ORIENTATION BY MEANS OF LONG RANGE ACOUSTIC SIGNALING IN BALEEN WHALES*

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Introduction

With very few exceptions, whales are social animals. Even though they may be widely dispersed at some seasons, most species congregate in herds during some portion of the year. As a general rule, small, toothed whales form the largest herds, which frequently contain hundreds, and exceptionally tens of thousands, of animals, whereas the much larger baleen whales, when found in herds at all, most often travel in bands of less than 20 animals, with only occasional reports of herds of up to 1,000 animals or more.[1] There has been considerable speculation on the functional significance of herd behavior in whales, but it seems unlikely that we will get any closer to understanding the role of herd behavior until we know more about what constitutes a herd.

In general usage, the word "herd" seems to mean a group of animals that are in close enough proximity to offer visible evidence to an observer (usually on the deck of a boat) that their behavior is linked (i.e., they are swimming in the same direction, or breathing in rough synchrony, or feeding in the same area or resting together, and so on). But this is a visual judgment of what may be principally an acoustic phenomenon, and therefore is more than likely to be inappropriate. Since sound is conducted in the ocean so well and light so poorly, a functional social group of whales may be held together by sound rather than sight and may stretch far beyond the horizon visible from a boat, or even from an airplane, and what appears to be a lone individual may in fact be an animal traveling in company with one or many companions some miles away–by our definition, a whale in acoustic contact with another whale is not alone.

This paper is concerned with baleen whales. Baleen whales are reticent laboratory subjects. In the absence of direct experimental evidence we might be able to get some idea of how far apart they can be and still be in acoustic contact by calculating how far their sounds might travel before being lost in the background noise of the ocean. Such calculations, while based in part on measured values, are also based on assumptions and remain theoretical. However, because of the exponential nature of acoustic phenomena, they are probably not entirely misleading.

In this paper we will try to show what kind of useful range at least one sound made by one baleen whale species, the fin whale (*Balaenoptera physalus*), might have and will suggest that its function includes long range signaling. We have chosen fin whales because they make exceptionally loud, low frequency sounds that have been the object of considerable study in recent years.

It must be borne in mind throughout this paper that we are *not* postulating meaningful communication of complex information among distant whales. Our remarks are concerned solely with simple signaling of place, for purposes of closing range and nothing more–in human terms, a message containing no more information than "there is a fin whale here." Our thesis is that fin whales, and

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perhaps some other large whale species as well, may be in tenuous acoustic contact throughout a relatively enormous volume of ocean and that such contact might be of use for finding each other or for joining, or keeping together in, widely dispersed herds.

CETACEAN SOUNDS

If the following discussion is to have much meaning, the sounds made by fin whales must be placed in the context of other whale sounds. Whale vocalizations have been reviewed by Tavolga,[2] Schevill,[3] Schevill and Watkins,[4] and Backus.[5] All cetaceans with which man has had more than passing contact have been found to make some type of sound. In general the sounds made by toothed whales (odontocetes) fall into three categories: 1) "impulsive sounds", i.e., broad-band clicks; 2) "squeaks" or "whistles," which are narrow band; and 3) "complex sounds," being some combination of these two categories. Besides broad-band clicks, which can contain any frequency, marine odontocetes are not known to produce sustained frequencies much below 500 Hz, and most of their vocal activity is at frequencies above 2,000 Hz.

Baleen whales (mysticetes) on the other hand, seem principally to make sounds with fundamental frequencies below 2,000 Hz, although some recent evidence by Beamish and Mitchell[6] tentatively indicates that blue whales (*Balaenoptera musculus*) may be able to produce fundamental frequencies in the ultrasonic as well as the sonic range.

Perhaps the most spectacular mysticete vocalizations known come from humpback whales. The work of Payne and McVay[7] has indicated that prolonged vocalizations of humpback whales occur in complex sequences, usually lasting from ten to 15 minutes, and may be repeated more or less exactly for several hours at a time, with no breaks longer than one minute. Without intending to imply any function for these repeating vocalizations (age and sex of the whales are unknown), we have called them "songs," in the same sense that this word is applied to the many repetitive, patterned sounds of birds, frogs, and insects—regardless of the functions served.

There seem to be several "song types" that are adhered to by different individuals, although there is much individual variation. Although the function of the songs is unknown, they have impressed many human hearers with their surprising complexity, and many people seem quick to want to ascribe some advanced communicatory function to them. It is well to remember, however, when trying to assess their function that these sounds are, within fairly narrow limits, monotonous, and any one who advances a theory that is to explain the songs satisfactorily cannot afford to overlook this fact.

Humpbacks are not the only baleen whales producing repetitive, or monotonous, vocalizations. There is some evidence from Cummings and Phillippi[8] that right whales (*Eubalena glacialis*) do so as well. But perhaps the most precisely repeating sounds yet ascribed to a mysticete are the 20 Hz signals thought by Schevill and coworkers[9] to be produced by fin whales. We will consider them in some detail here.

20 Hz Sounds

Occurrence, Timing and Source

A group of remarkably loud and repetitive naturally occurring sounds, with their principal energy centered at frequencies near 20 Hz, has been the subject of considerable study.[10–15] Although the signals in this group are often referred to collectivley as "20 Hz signals," they are diverse in form and can be imagined to have their origins in several animal species (usually thought to be whales). On various occasions Patterson and Hamilton[12] have heard each of the various pulse types (subsequently described) change to one of the other types, and this suggests that all can be produced by one species, although, of course, this is not proof that such is the case. About all that can currently be said about the origin of 20 Hz sounds is that at least one of the animals producing at least some of the sounds is the fin whale. This determination was made by Schevill and colleagues[9] from several lines of evidence including 1) a recording of 20 Hz sounds from a stranded fin whale, and 2) successful "homing" on several 20 Hz sources that proved each time to be one or more of this species.

Schevill and colleagues unfortunately do not describe the 20 Hz signals they heard while in the vicinity of fin whales, but their general comments suggest they were usually short signals similar to those reported by Patterson and Hamilton,[12] who called them "blips." These are very loud, nearly pure tone pulse trains, centered at about 20 Hz. They last about one second and are repeated at very regular intervals several times per minute. Trains of pulses are made for about 15 minutes and then followed by a silence of about 2½ minutes, a spacing that suggests the sounding-breathing cycle of a whale. The most common spacing of pulse trains reported by Patterson and Hamilton was 12 seconds. They also reported paired pulses, which they call "doublets"; these consist of a large amplitude pulse followed by a smaller amplitude pulse, the pair repeating every few seconds. These authors recognized several categories of doublets by their interpulse and interpair intervals, naming them, for example, the "22–15 second type," the "9–12 second type," and so on. When using the term "20 Hz" sounds in this paper we will mean sounds of the kinds described by Patterson and Hamilton.

Intensity

Walker,[10] Patterson and Hamilton,[12] and Northrop and coworkers[15] were all able to track 20 Hz pulse sources with hydrophone arrays and thus determine the position of the source. Once the distance from hydrophone to a source was known, it was possible to determine what has proven to be the most interesting aspect of the 20 Hz signals: their exceptionally high intensity. Because they are so loud, research on 20 Hz sources was first entered intensively with the certain feeling that these sounds could not be natural and thus might have military implications.[10,12] There were even speculations that such intense pure tones could not originate in the water, e.g. this quote from Patterson and Hamilton:[12] "When these signals were first called to our attention, we could not visualize such a regular, large amplitude, low frequency signal having a natural origin in the ocean. Accordingly a search was made for similar signals in other geophysical media. Recorders were set up in this frequency band to monitor the geomagnetic field, airborne acoustic signals and seismic signals in the Earth. The program was soon abandoned because with the hydrophone recorders overloading on the 20 cps signals the other monitors showed no signals above background noise." These same authors also note at first, "in the press of other work the repetitive [20 cps] signals were recorded unnoticed apart from an occasional passing thought that the hydrophone amplifier was intermittently motorboating."

Apparently Walker,[10] at first, also had similar, incredulous feelings about such loud sounds being made by animals in the ocean for he notes that after many tests "it was concluded that the pulses originated neither from deep within the Earth nor from the action of breaking surf on continental shore lines."

We are dealing then with an animal sound so loud that it was at first thought to be everything from surf on distant shore lines to faulty electronics, including sources not even in the ocean– How loud then are these sounds?

The calculations by Walker[11] seem most reliable. He used a 3-hydrophone array, about which he notes: "The receiving system had been carefully calibrated and the transmission characteristics for the region were well known." Most of Walker's roughly 150 measurements of source level (for 20 Hz sounds of the kind described by Patterson and Hamilton) fell between 70–85 decibels (dB) re 1 dyne/cm^2 at 1 yard with most of his readings near the higher values and a few readings well above 85 dB.

Patterson and Hamilton also used a 3-hydrophone array, but the amplifiers in their array were not calibrated, so they could not make direct determinations of source intensity once they knew distance to the source. However, by comparing the ratio of signal strength to background noise levels over the bandwidth involved (assumed to be the same as previously measured ambient noise values for a nearby location) they found, in roughly 400 measurements, that 66% of the values fell between 73 and 81 dB re 1 dyne/cm^2 at 1 yard.

Northrop and associates[15] used an array consisting of a pair of hydrophones. This technique allows reliable determination of intensities only for sources on or near the axis of the pair. The range of their 20 such measurements (these were Pacific Ocean 20 Hz sounds) is 65–100 dB re 1 dyne/cm^2 at 1 yard.

The following discussion makes use of the value of 80 dB re 1 dyne/cm^2 at 1 yard, unless otherwise stated, since it is in keeping with all determinations and is near the median determined by what appears to be the most reliable data, Walker's. We will assume that some whales make 20 Hz sounds at this intensity some of the time, but we are aware that they make softer as well as louder sounds.

Bandwidth

Of equal significance to the loudness of these pulses is their remarkable purity of frequency. Spectral analysis of 20 Hz pulses by Walker[10] indicates that the energy is confined in a band 3 Hz wide. Cummings (personal communication) notes that the energy lies in a 4 Hz band width. Patterson and Hamilton[12] refer to a 1/5 octave band centered at 20 Hz, which, at this frequency, means energy in a band ca. 3 Hz wide.

Considerations Underlying Calculation of Transmission Loss

We have seen something of the characteristics of the signal under consideration. The central argument for the possibility of long range signaling by some whales rests on knowledge of the signal, the receiver, and physical principles of oceanic sound transmission. The minimum quantitative data adequate to permit rough calculation of maximum signaling range are: 1) frequency, bandwidth, duration, and intensity of the signal; 2) oceanic attenuation losses (which are frequency-dependent); 3) geometrical spreading losses (which are frequency-independent) and reflection losses (frequency-dependent); 4) directional characteristics of source and receiver; 5) receiver sensitivity; 6) background noise; and 7) lowest signal-to-noise ratio (S/N) acceptable at the receiver. We will consider these parameters one at a time.

1) *Signal*: Frequency 20 Hz, bandwidth 4 Hz, duration 1 second, intensity 80 dB re. 1/dyne cm^2 at 1 yard. (= 154 dB re .0002 dynes/cm^2 at 1 yard).

2) *Oceanic Attenuation Losses*: While spreading out after leaving the source

(discussed under the following heading), some of the sound energy is lost to heat along the way. This is called attenuation and it is proportional to the distance traveled times a measured attenuation coefficient α. Whereas geometrical spreading loss applies equally to all frequencies, attenuation loss is proportional to frequency. FIGURE 1 shows α vs. frequency. At 20 Hz α is approximately 0.0003 dB/1,000 yards, a remarkably low value. It means that a transmission distance of 10^7 yards, or approximatley 5,600 miles, is required to reduce by 3 dB (i.e., to half the power) the sound energy lost to attenuation! Therefore, at 20 Hz attenuation loss can be ignored as long as we are discussing spherical propagation.

3) *Geometrical Spreading*: We will consider two cases, spherical and cylindrical spreading. Spherical spreading is the simplest case: we assume that the signal strength at range r will be inversely proportional to the square of the range r. Thus the transmission loss (TL) in decibels is calculated as follows: TL = 20 log r. Were the ocean an unbounded, lossless, homogeneous medium this model would suffice but the ocean is a relatively thin sheet (i.e., shallow in relation to its surface area). And so at distances from the source considerably greater than the depth of the ocean the transmission of sounds includes multiple reflections from surface and bottom. Under such circumstances sound energy is spread over the outer surface of an expanding cylinder (of small height in proportion to the radius) rather than over the surface of an expanding sphere. Since the surface

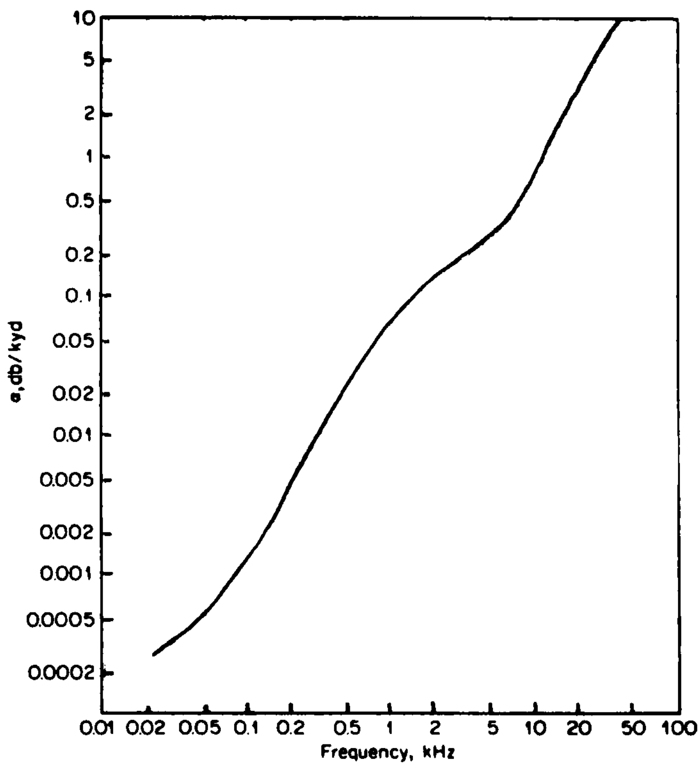

FIGURE 1. Attenuation coefficients. Note the remarkably low attenuation of frequencies below 100 Hz. (After Urick,[22] reproduced by permission of McGraw-Hill Book Co.)

area of a cylinder is directly proportional to its radius, whereas the surface area of a sphere is proportional to the square of its radius, transmission losses at a given range r are far less with cylindrical than with spherical propagation (geometrical spreading loss is 20 log r for spherical spreading but only 10 log r for cylindrical spreading).

Cylindrical spreading between parallel planes reduces geometrical spreading losses, but it introduces reflective losses. There is always some energy lost with any reflection. Such losses are severe at high acoustic frequencies but they may be relatively insignificant at frequencies as low as 20 Hz. There is a form of ducting of sound energy in the ocean in which refraction rather than reflection is responsible for cylindrical spreading (thus there are no reflection losses). This channeling results from the variations in speed of sound conduction with depth. Several ducts are recognized, but we will first consider just one, the deep sound channel, or sofar channel, as it is also called.

The speed of sound in the ocean varies directly with temperature and pressure. In mid-latitudes the speed decreases with depth (a decrease of water temperature with increasing depth is the overriding influence) until near isothermal water is reached, whereupon speed of sound increases once more (increased density of water due to increased pressure now becomes the controlling influence). In mid-latitudes in the Atlantic the speed minimum occurs at a depth of about 3,600 feet. Above and below the depth of minimum speed (that depth is the "axis" of the channel), the speed gradient continually bends any sound ray toward the depth of minimum speed. A fraction of any sound radiated at or near the sound speed minimum is trapped within this deep sound channel and finds a transmission path to great ranges without acoustic losses due to reflections from the surface or bottom. A ray diagram for sofar transmission from the original paper by Ewing and Worzel[16] is shown in FIGURE 2. It depicts ray paths at 1° intervals around a source at channel axis depth. The ray paths show the refracted propagation paths followed by sound energy leaving the source at angles near the horizontal (angles too steep to be trapped in the channel are omitted). It is apparent that the sound energy is not spread uniformly over the duct, that it is concentrated near the axis, and that some sound energy is well outside the main duct. As a result, the ocean is not uniformly insonified, and indeed, some part of the ocean volume contains no sound energy from the source, and in the remaining volume the sound intensity varies markedly with both depth and horizontal position, with time, and with motion of the source. Sounds that take the most indirect path, the path showing the greatest refraction away from the axis, arrive at a distant point first even though they have traveled farthest. This is because they travel most of the time in water that conducts sound fastest. Sounds traveling the shortest, slowest path, right down the channel axis, arrive last but are loudest. Thus an abrupt sound like an explosion, even though it lasts for only a fraction of a second at the source will, at remote distances and near the channel axis, be heard as a gradually increasing roar lasting several seconds but stopping abruptly as the final, loudest sounds go by. (The rate of increase of this roar is inversely proportional to distance and can be used as a rough indication of range.) This time-stretching lengthens a signal by about 10 seconds per 1,000 miles traveled, making it difficult or impossible to recognize the original characteristics of very distant signals. Such distortion prevents the transmission of any but the simplest messages at extremely low data rates.

The greatest ranges via sofar transmission will occur when source and receiver are both at channel axis depths. But in low latitudes this would require a whale

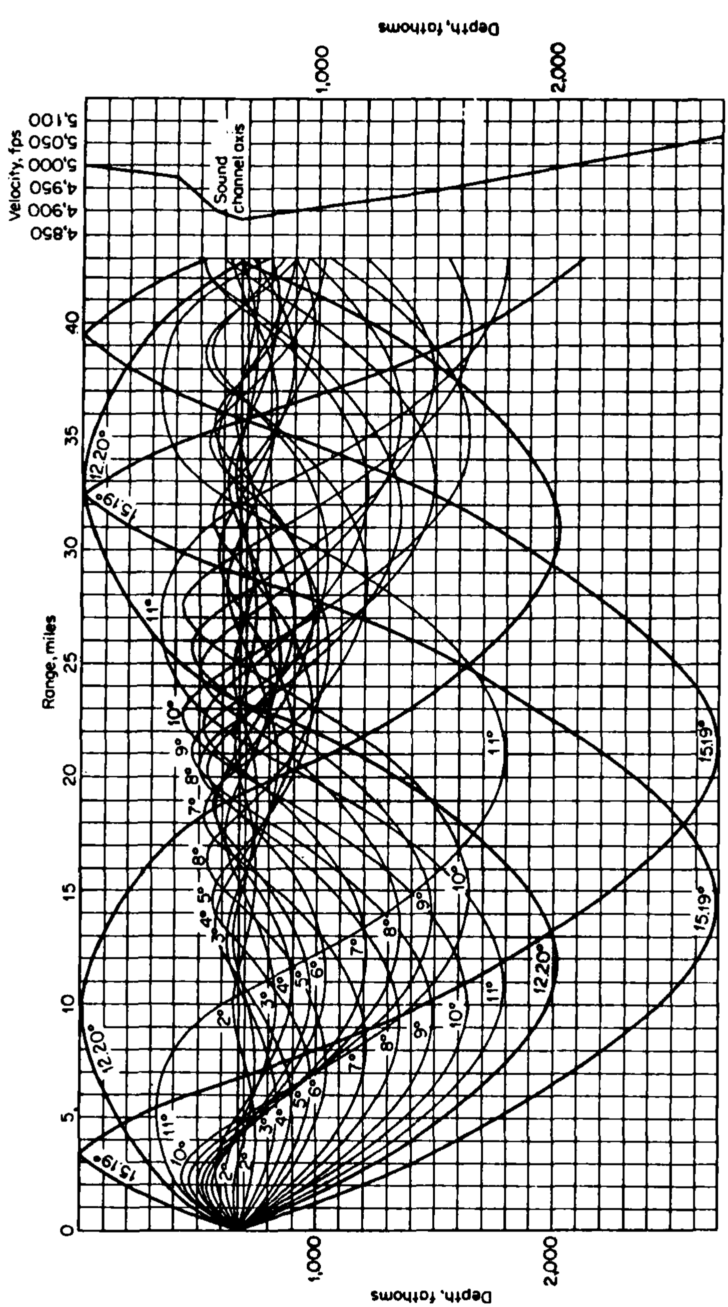

FIGURE 2. Ray diagram of transmission in the deep sound channel for a source on the axis. (Ewing & Worzel,[16] in Urick.[22] Reproduced by permission of the Geological Society of America, courtesy McGraw-Hill.)

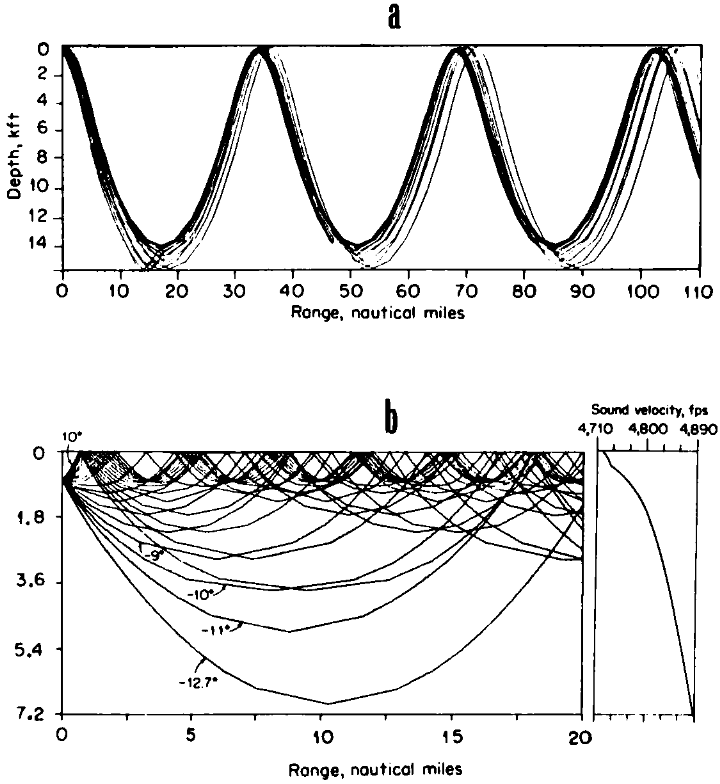

FIGURE 3. Ray diagrams showing rays at 1° intervals. Rays leaving the source at steep enough angles to reflect from surface and bottom are omitted. a) Source at a depth of 300 feet in the deep sea. Note that reception near the surface is only possible at intervals of 30–35 miles. b) Transmission in the Arctic. The velocity profile is shown at the right. Under solid ice, measurements indicate that frequencies near 20 Hz are transmitted best; owing to the loss of higher frequencies (due to scattering from the rough undersurface of ice), and of lower frequencies (due to the fact that such long wavelength cannot be transmitted in the duct). (From Urick,[22] reproduced by permission of McGraw-Hill.)

diving to depths of 3,600 feet and more. There is good evidence that sperm whales (*Physeter catadon*) reach such depths and perhaps beyond,[17] but all sounds recorded so far from this species are many octaves higher than 20 Hz (at frequencies that suffer drastic transmission losses by attenuation), and until it is shown that sperm whales make lower sounds, it is hard to see how signaling via the sound channel would be of much help to them.

The literature on whaling dramatizing its adventurous aspects abounds with supposed feats of deep diving by many species of whales (as indicated by how many fathoms of line were taken by harpooned whales). But even if such reports proved true, it is one thing to dive to a depth of 3,600 feet and another to make loud sounds once there. Patterson and Hamilton[12] attempted to measure the depth of 20 Hz sources with a 2-hydrophone array, but equipment failures limited them to a single very rough datum. It did indicate, however, a source depth of at least 1,200 feet (of course, the source was also producing sounds at that depth, although how loud they were is not stated). Sounds are certainly produced at much shallower depths,[10] but until it can be demonstrated that fin whales can dive to channel axis depths and make their sounds once there, it would be unwarranted to assume that they do so. However, both source and receiver can be at relatively shallow depths and still gain some of the benefits of the sofar channel.

FIGURE 3–a shows computed ray propagation paths through deep water for a source at a depth of 300 feet in latitudes where the sound channel axis is at 4,000 feet. Such computed curves enable one to predict that in deep water in these latitudes sounds from a near-surface source will only be audible to a near-surface receiver at intervals of 30–35 nautical miles. (It is also obvious, since ray paths are very similar, that time-stretching and thus signal garbling will be considerably less than with an on-axis source and receiver.) Experimental confirmation of this prediction is reported by Hale.[18] He made a series of measurements with a shallow hydrophone at increasing ranges from a shallow source. He found signal intensities at 30–35-mile intervals that in some cases were 30 dB higher than signal intensities expected by simple spherical spreading. (Less spectacular values were more common, however.) It is not clear how far from the source such regular concentric rings of improved signal intensity (called convergence zones) occur, but Hale found them well developed up to 400 miles away (FIGURE 4). Beyond that range he found definite evidence that the simple, easily predicted and regularly occurring zones deteriorated " . . . with evidence of overlapping zones and sporadic variation of intensity." Since he was interested in demonstrating the regularity of this acoustic transmission phenomenon, he terminated his observation at 400 miles when the phenomenon became less predictable. It is well to note, however, that the signal energy was not destroyed, it did not vanish, but that at 400 miles the locations of overlapping rays (i.e., of increased signal intensity) simply became less predictable. Therefore, the range at which the deep sound channel no longer contributes to long-range transmission between a near-surface source and a near-surface receiver is still an open question. We would suspect that beyond 400 miles the effect would still be apparent for some distance but at much reduced intensities and much less regular intervals until there is a final change to cylindrical propagation.

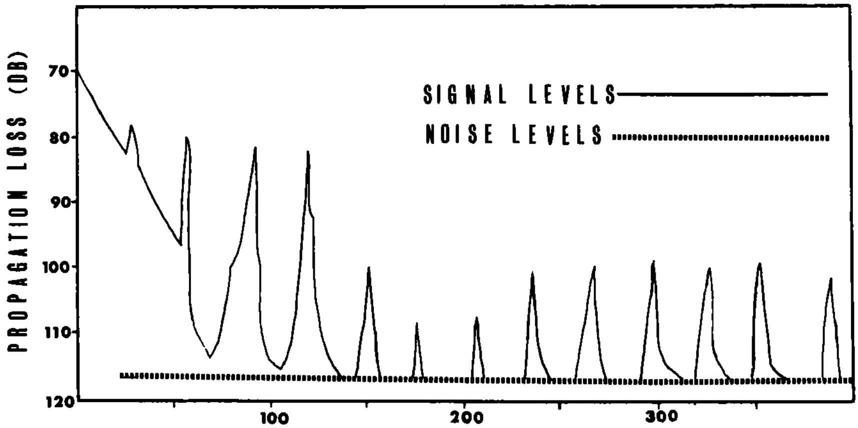

FIGURE 4. Convergence zone propagation. Low signal levels at zones around 200 miles were caused by a sea mount which temporarily obstructed the acoustic path. (From Hale.[18])

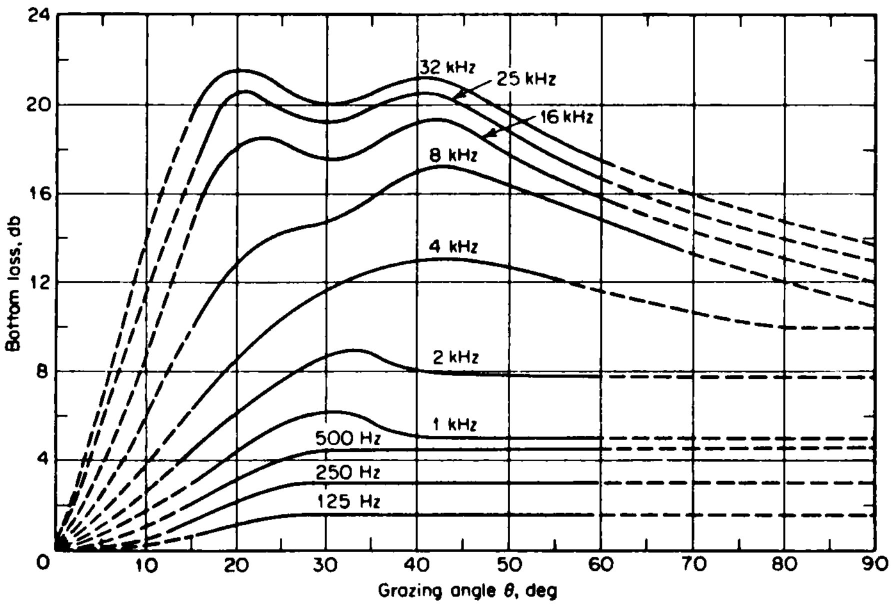

FIGURE 5. Bottom loss versus grazing angle at various frequencies. Note that at the lowest frequencies reflection losses are almost independent of the angle at which the sound is propagated relative to the bottom. (From Urick.[22] reproduced by permission of McGraw Hill.)

Such a system even in its most well-defined form would be of little use as a communication channel if one of the requirements were a high probability of successful contact at any given moment. But, if the signal were highly monotonous and of use for little more than taking a bearing in order to close range, then it would be of slight consequence whether or not reception were intermittent (even human navigators must often wait several days for the weather to clear in order to take a sight, yet this does not make celestial navigation useless). There is another way the sound channel might be of use to whales without requiring that they be able to dive to its axis in mid-latitudes. The slope of any island, continent, or sea mount passing through the sofar channel must reflect some of the energy into the channel from appropriately located sources near the surface. The converse is known to be true–that sounds from the channel follow up slopes and can be heard at lesser depths. If the reflecting slope were an island or sea mount, then direction to a source might be determined by swimming around the island until the sounds were loudest. But of more interest is the possibility that reflections provide a means for a shallow whale to inject its sounds into the channel. (It *will* occur sometimes whether or not the whale intends it.) Then passive listening at relatively great depths would still be useful even if whales could not make sounds at such high hydrostatic pressures as occur at axis depths.

The need for a reflection (or perhaps two) in this system raises the question whether the reflective loss would be worth the refractive gain. But reflective losses are frequency-dependent, and one of the advantages to a whale of "speaking" at 20 Hz is that such very low frequencies suffer only slight losses, even when reflected from highly absorbent muddy bottoms.[19] Marsh[20] gives data for reflective losses only at higher frequencies, but the trend is obvious (FIGURE 5).

From the aforementioned considerations it seems reasonable to assume that source and receiver need not be on the sofar channel axis in order to gain some advantage from it. However, we will still resort to calculations of transmission loss based upon on-axis sources and receivers in order to show an upper limit. This is chiefly because there is no adequate general theory for predicting transmission losses under conditions of off-axis signal and source except for the special case of convergence zones, where for quite shallow sources and receivers and for ranges out to the first 10 or so zones, there is a constant improvement in signal over that to be expected from spherical spreading, of 5–10 dB for each zone. Even though our calculated values for sofar signaling will certainly give overestimates of range (unless fin whales prove to be signaling on-axis), we will, by later reexamining several of our other assumptions, point out that ranges approaching the upper limits we have indicated may occur or may once have occurred.

The formula we have used for determining range was arrived at by the following reasoning: FIGURE 2 shows that only the sound leaving a deep source between an angle of approximately $\pm 12°$ from the horizontal is eventually trapped in the sound channel. At one yard from a point source the sound energy that will eventually be trapped is distributed over a portion of a spherical surface:

$$4\pi \sin \theta \text{ yards}^2 \quad \text{where } \theta = 12°$$

At a long range r, this same sound energy will be channeled through a duct of height H and surface area, $2\pi rH$.

Referring to FIGURE 2, if H is estimated at 1,500 yards (100° to 2,500 yards depth), then the transmission loss in decibels due to geometrical spreading is:

$$TL = 10 \log r\left(\frac{2\pi H}{4\pi \sin\theta}\right) = 10 \log r\left(\frac{H}{2 \sin \theta}\right) =$$

$$10 \log r + 10 \log \frac{H}{2 \sin \theta} = 10 \log 7.2 + 10 \log r$$

Attenuation must now be added because of the ranges involved and in Final Form the equation is:

$$TL = 10 \log 7.2 + 10 \log r + \alpha r \times .001 \, [\alpha,] \text{dB}$$

(The answer is in kiloyards, hence the multiplier .001).

Note that $H/2 \sin\theta$ is called the transition range and may be viewed as the range at which geometrical propagation changes from spherical to cylindrical. The two straight lines in FIGURE 6 show the different rates of transmission loss for cylindrical and spherical spreading. Cylindrical transmission losses (10 dB per decade of distance) only begin at ranges beyond the transition range. Up to that distance transmission losses are spherical, 20 dB per decade of distance. (Transmission losses are considered to be 0 at a distance of 1 yard since that is the distance at which sound intensities are traditionally measured).

Although the transmission loss above is a correct estimate of the loss of signal energy with distance, the relationship between signal intensity and energy must be kept in mind. The signal is stretched in time as the pulse propagates, and the intensity of a signal spreading cylindrically will decrease more than the inverse first power of the range. As it is difficult to be sure of the extent to which the ear is sensitive to the signal energy, i.e., the integral of intensity times duration, or to intensity alone, the estimates of very long ranges with cylindrical propagation should be treated cautiously.

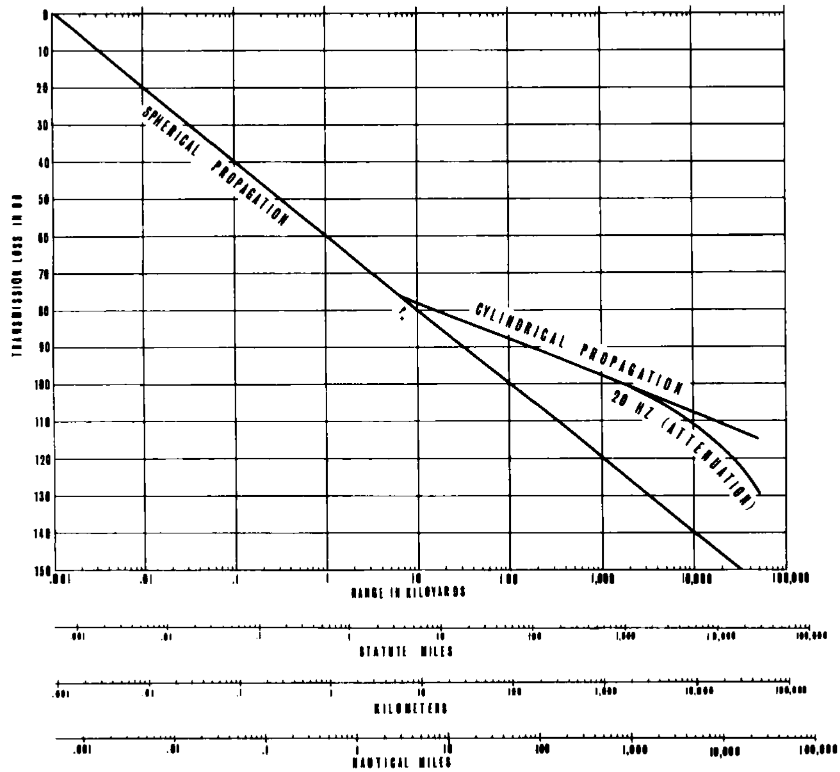

FIGURE 6. Calculated transmission loss versus range for two cases of propagation in deep ocean: 1) spherical and 2) Sofar signaling where propagation becomes cylindrical once transition range, r_o, has been reached via spherical spreading. (Source and receiver both on the axis of the channel.)

The transition range of 7.2 kiloyards arrived at by this calculation is in adequate agreement with measurements made by Webb and Tucker.[21]

The Arctic represents a third type of channeling–in some ways a hybrid between simple multiple reflections from surface and bottom and the pure refractive propagation without reflective losses found in sofar signaling. In polar seas there is no appreciable overlying layer of warmer water as in mid-latitudes, and so the sound speed is at a minimum at or very near the surface. (Speed of conduction is principally affected by density considerations and, to a much lesser degree, by salinity.) Propagation thus involves both refraction and reflection: refraction of all rays forming angles with the surface of less than about 12–13 degrees until they recurve back to hit the undersurface of the ice, and then reflection from that surface (FIGURE 3–b). Besides making very great ranges possible, one pecularity of under-ice transmission is that both high and low frequencies are rapidly attenuated, the low because they are of too great a wavelength to be effectively trapped in the channel, and the high by reflection losses from the rough surfaces of the under-ice. Thus in the Arctic, beneath solid ice cover, the best frequencies for long distance propagation have been found to be in the single octave 15–30 Hz.[22]

The measurements referred to here were made beneath solid ice, so we cannot use equations derived from them to predict transmission losses under scattered ice. However, it seems safe to assume that the kind of discontinuous cover represented by diffuse pack ice would have a similar, though less pronounced, filtering effect on high frequencies. Fin whales are found in deep water on all sides of pack ice fields that often extend for hundreds of miles, particularly in the Antarctic Ocean during spring.[23] Presumably they must occasionally travel many miles to find a lead to get through the pack, for under some conditions they are stranded by pack ice.[24] If a fin whale found itself getting increasingly boxed in by wind-drifted pack ice, it might be of vital advantage to it, in choosing the appropriate escape direction, to be able to hear even quite distant companions toward which it could pick its way to safety before the pack was too dense to afford suitable breathing spaces. The ability to produce sounds at frequencies that are so peculiarly well suited to long range transmission under rough ice is of obvious advantage.

4) *The Directional Characteristics of Source and Receiver*: It seems reasonable to assume an omnidirectional source since the wavelength at 20 Hz is about 250 feet, and even large fin whales are barely more than 1/3 as long. Walker[10] notes both the meandering paths taken by 20 Hz sources and the remarkably constant amplitudes of their signals, even over prolonged time periods—an unlikely pair of observations unless the source were omnidirectional.

In the case of the receiver the question of directionality is more difficult to assess. It seems reasonable to expect that a whale could monitor a signal arriving from a given direction by selecting its characteristic phase lag between the two ears, and by suppressing signals lacking the appropriate lag, thus gaining some measure of directionality (similar to a phased hydrophone array). A similar mechanism, supported by compelling evidence, is postulated by Batteau[25] to explain the "cocktail party effect" in humans (the ability to follow a conversation buried deep in noise if, and only if, directional cues are present). Similarly, the remarkable performance by bats in detecting signals in noise are now thought to be explainable by binaural, directional hearing.[26] In spite of the possibility of some receiver directionality we will conservatively assume both source and receiver to be omni-directional.

5) *Receiver Sensitivity*: There are, as yet, no measurements of sound spectrum versus sensitivity in baleen whales. We would, however, expect a fin whale to have adequate hearing and to have its greatest sensitivity somewhere near frequencies of 20 Hz. We assume this because other animals that are highly dependent on hearing show a rough congruence between their "speech" and hearing spectra.[27]

In terms of absolute threshold it seems most unlikely that a fin whale would need the kind of ultrasensitive hearing found in many terrestrial mammals. (Man's absolute threshold of .0002 dynes/cm^2 is an example.) The ocean is a very noisy place and, therefore, in theory an acoustic system will always be limited by noise before it is limited by sensitivity, except under the very calmest conditions and at the very highest, ultrasonic frequencies (FIGURE 7). At the frequency in question, 20 Hz, the lowest background spectrum noise level reported by Wenz (FIGURE 7) is -45 dB re 1 dyne/cm^2 at 1 yard. (A still lower 20 Hz, spectrum, noise level, -55 dB, has been recorded but only during quiet periods and beneath the frozen Arctic Ocean,[28] and it need not concern us here). If 20 Hz was a fin whale's frequency of greatest sensitivity and if fin whales could just detect a 20 Hz sound at -45 dB, their detection threshold would be about 30 dB higher (less sensitive) than a human ear at its most sensitive frequency. Even if a fin

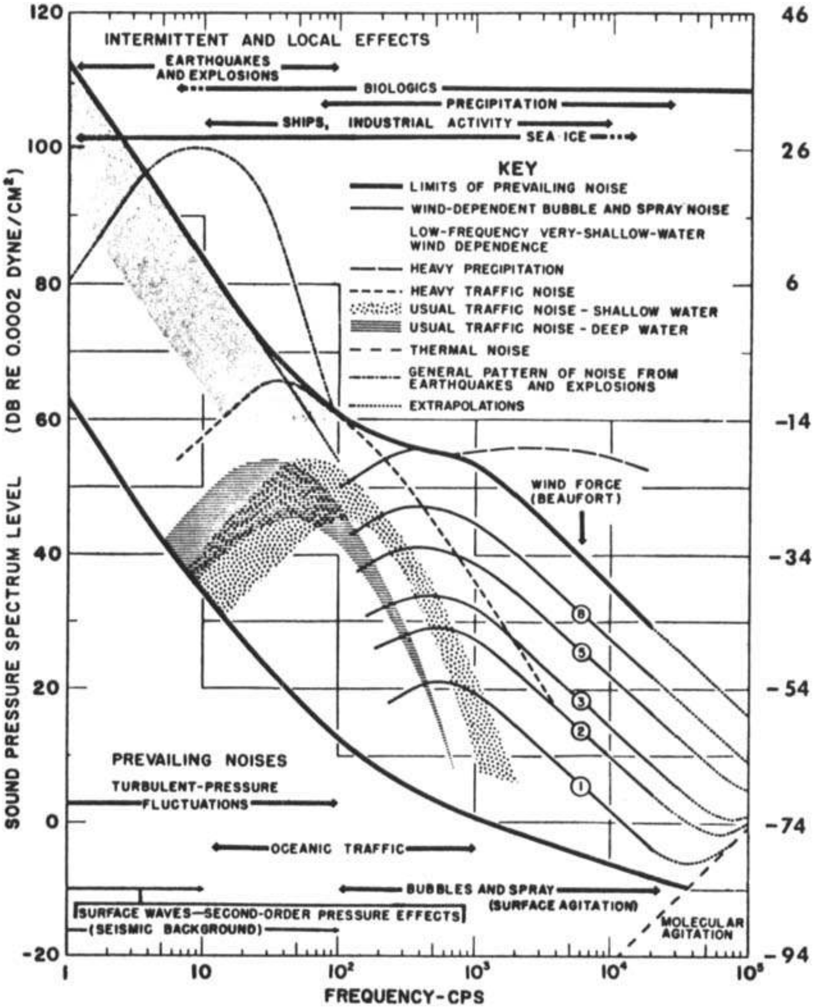

FIGURE 7. A composite of ambient-noise spectra, summarizing results and conclusions concerning spectrum shape and level and probable sources and mechanisms of the ambient noise in various parts of the spectrum between 1 Hz and 100 kHz. The key identifies component spectra. Horizontal arrows show the approximate frequency band of influence of the various sources. An estimate of the ambient noise to be expected in a particular situation can be made by selecting and combining the pertinent component spectra. (From Wenz,[29] reproduced by permission of Pergamon Press.)

whale could detect signals at a signal to noise ratio of —15 dB (see subsequent discussion), and, therefore, on calm days required a more sensitive ear, it could do it, in theory, with an ear that was still 15 dB less sensitive than the human ear at its best detection threshold. We do not feel inhibited about assuming that fin whales have adequate sensitivity at 20 Hz to make possible the ranges we have calculated.

6) *Background Noise*: The most ancient ancestors of baleen whales probably

first appeared on earth about 27 million years ago (give or take a few million years). About ± 15 million years ago, the ancestors of modern fin whales appeared. Propeller-driven ships and the noise they generate have been around for about 150 years–about 1/100,000th as long. If we are really interested in knowing what function 20 Hz signals evolved to serve, we can only hope to do so if we look at the conditions under which they evolved. (Otherwise, we will be in the same boat with the man who was horrified to find out that in pre-Columbian times Indians had been content to drink Hudson River water.)

The point here is crucial to the whole argument for long range signaling by baleen whales. As can be seen from FIGURE 7, the most prominent of the prevalent noise sources in the frequency band from 5–200 Hz is from ship traffic.[29] Even moderate shipping produces a roar equivalent in other bands to steady winds of 35 knots. In the most remote areas, hundreds and even thousands of miles from the nearest shipping lanes, traffic noise is still prominent in this frequency band.

Before the advent of propeller-driven ships (i.e., during 99.999% of the time fin whales were evolving) there was absolutely no sound from propeller-driven ships. At 20 Hz the whole ocean was as quiet as it gets nowadays in the most remote areas–and perhaps a good deal quieter. This is not to say that it was noiseless. Ocean noise must always have increased as frequency decreased. But, we must note the position of 20 Hz once we remove shipping noise from the average deep-water ambient-noise spectrum (FIGURE 8). It lies just below the lowest frequencies generated by wind noise. It is, therefore, the highest frequency one could employ to build a long-range signaling system free from all weather noise except for that generated by the very worst storms.

Of course, as things presently stand, 20 Hz is a poor choice for a signaling

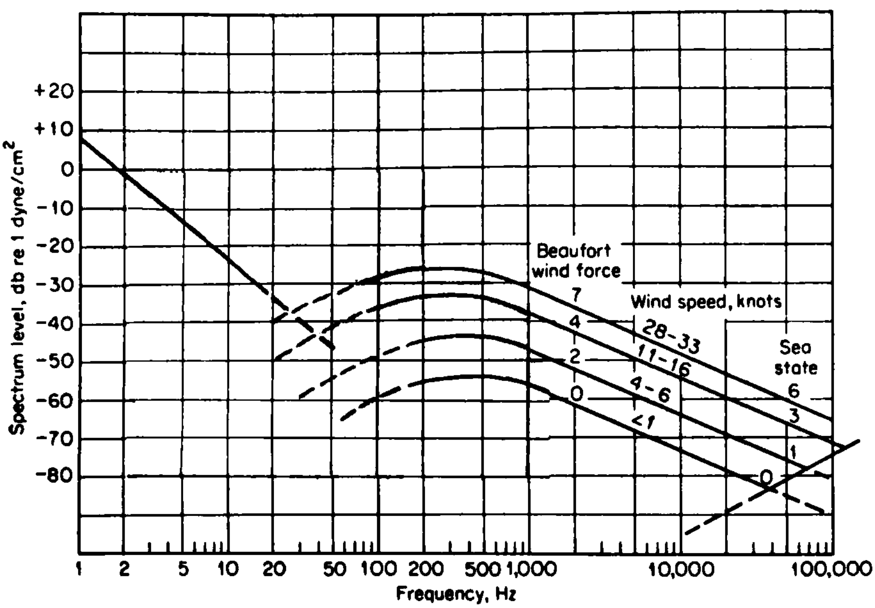

FIGURE 8. Average deep-water ambient noise spectra with components due to shipping removed; the assumed condition of the ocean during all but the last 150 years of fin whale evolution. (After Wenz,[23] reproduced by permission of McGraw-Hill.)

system since it lies almost at the peak of traffic noise. Therefore, our calculations will be made at three different 20 Hz noise levels for which we will assume the following spectrum values (all re 1 dyne/cm^2): contemporary noise background with moderate shipping, −25 dB; average pre-propeller ocean background, −35 dB; quiet pre-propeller ocean background, −45 dB. The spectrum value of sound pressure is the pressure measured over a band 1 Hz wide.

Because 20 Hz sounds have their energy distributed over a 4-cycle bandwidth, we will have to listen over a bandwidth of at least 4 Hz if we wish to intercept all the energy in the signal. When we widen the bandwidth, we also let in more noise, 6 dB of it, four times the power). Therefore, all of our noise levels must be increased by 6 dB to −29, −39, and −19 dB, respectively. The assumption that a whale can search a band as narrow as 4 Hz wide (1/3 octave at this frequency) is supported by the following: At frequencies of maximum sensitivity for humans the critical bands are slightly less than 1/3 octave wide.[30] (For a discussion of critical bands, see the following section). As further support, humans are able to distinguish frequency changes of 3 Hz at all frequencies below 1,000 Hz, and to distinguish less than 1 Hz at the very lowest frequencies.[31]

7) *Lowest Signal-to-Noise Ratio Acceptable at the Receiver*: Again, there is no direct information to guide us in selecting a criterion, so we will pick 0 dB S/N because humans do well in retrieving signals at 0 dB S/N in a wide variety of circumstances (see following section). As we will see shortly, 0 dB may be unrealistically conservative.

Computation of Maximum Detectable Range

We will attempt to compute the maximum possible range at which one fin whale might hear another. By way of summary, the signal is assumed to be at 20 Hz with a 4 Hz bandwidth and a bandwidth intensity of 80 dB re 1 dyne/cm^2 at 1 yard. It lasts for one second and is repeated every few seconds. It is produced by an omnidirectional source at an unknown depth in deep ocean (20 Hz has a measured attenuation of 0.0003 dB/kiloyard, which means we can ignore losses due to attenuation below 1,500 miles.)

We will compute two types of attenuation loss: 1) spherical, the worst possible case in deep ocean, and 2) channeling by the sofar channel, the best case. We will assume a receiver and source at axis depths simply because there is no adequate general theory for computing losses at off-axis depths and we wish to define an upper limit of ranges. We therefore realize that the sofar values will represent the most favorable possible case.

We assume an omnidirectional receiver of adequate sensitivity tuned to a 4 Hz bandwidth (⅓ octave) centered at 20 Hz. Noise background is the level of noise in a 4 Hz bandwidth also centered at 20 Hz, and we will calculate for three values of noise: moderate shipping in the 20th century, —19 dB; average pre-propeller background, −27 dB; quiet pre-propeller ocean, −39 dB. We will require a O dB signal-to-noise ratio (S/N) for detection.

The equations used are: TL = 20 log r for spherical spreading (ignoring attenuation since it is less than 1 dB at ranges less than 1,500 miles); and TL= 10 log 7.2 + 10 log r + α r × 10^{-3} kiloyards for sofar signaling. Realizing that signal level minus noise level equals the maximum possible transmission loss for reception at 0 dB signal-to-noise level (for example +80−(− 19) dB = 99 dB), we then substitute the computed transmisson losses in these formulas and compute the ranges, or look them up in FIGURE 6. The results are shown in TABLE 1.

As we have pointed out before, the sofar ranges should be taken as the maxi-

TABLE 1

CALCULATED MAXIMUM RANGES AT WHICH FIN WHALE, 20 HZ SOUNDS REACH O dB S/N UNDER THREE DIFFERENT BACKGROUND NOISE CONDITIONS*

Background Noise Conditions	Backgr. Noise Level in dB in 4 Hz Band	Max. Transm. Loss for 80dB Signal (80 — Noise Level)	Range in Kiloyards	Range in Naut. Miles	Area of a Circle with Radius Equal to Range (Sq. Miles)
20 Hz — Spherical Spreading (Minimum Range) Deep Ocean					
This century (moderate noise)	−19	99	90	45	6,400
Pre-propeller ocean (average noise)	−29	109	280	140	62,000
Quiet, pre-propeller ocean	−39	119	900	450	636,000
20 Hz Sofar Signaling Conditions (Maximum Range) Deep Ocean					
This century (moderate noise)	−19	99	1,050	525	866,000
Pre-propeller ocean (average noise)	−29	109	7,000	3,500	38,000
Quiet, pre-propeller ocean	−39	119	23,000	11,500	no ocean big enough

* "Pre-propeller ocean noise" refers to derived, ambient, ocean noise conditions prior to ships. Maximum ranges calculated for spherical spreading losses probably represent the minimum propagation distances to be expected under assumed conditions. Ranges determined for Sofar Channel propagation represent upper limits that may be approached but are probably not reached, due to considerations outlined in the text.

mum upper limit under the specified conditions, since there are bound to be losses that we cannot calculate, both as a result of off-axis location of source and receiver, and due to signal stretching. In the convergence zone case if both source and receiver are very close to the surface, then there will be intermediate areas (at first averaging a spacing of 30–35 miles and later at more irregular distances) in which the signal will not be audible even at very short ranges.

Only two of the figures in TABLE 1 can be tested by direct measurement — the ranges expected under modern noise conditions. Northrup and colleagues[15] tracked 20 Hz signals to ranges as great as 100 miles, Walker[10] tracked them to 35 miles, and Patterson and Hamilton,[12] to about 12 miles. The differences in these ranges almost certainly reflect local noise conditions as well as different filter widths at the input. The results straddle our predicted range; in fact, they average a rather better performance than we predicted since we have specified an S/N of 0 dB, and these authors used arrival time measuring techniques that require a signal-to-noise ratio of a few (<10) dB.

A further confirmation comes from the work by Webb, who has carried out low-power, long-range signaling experiments in the sofar channel. Instead of using explosives for sources, he used tones of 380, 550, and 780 Hz and found the detectability of the received signals to be in good agreement with the value predicted, using a calculation analogous to the one mentioned.[21,33] For all of these reasons we believe our calculations are a fair reflection of reality.

Several considerations may offset in part the losses inherent in off-axis signaling in the sofar channel: 1) There is good evidence that some signal source levels are 5 or more dB higher than we have assumed. 2) The receiver may be directtional. 3) Lower noise conditions might exist – something that would be unwise to count on in designing a system demanding reliability but which nevertheless ought to be strongly entertained when the task is to calculate maximum possible range. 4) Sequences of pulses might be suitably integrated at the receiver, thus providing signal energy greater than that from single pulses. Unfortunately, we know of no acoustic research on other animals that would indicate a time base long enough to make such a mechanism very plausible. A signal retrieval system relying on a monotonously repeated signal, such as that from a whale or from a ship's propeller, would require sampling times on the order of minutes or even hours if it were to detect signals buried very deep in noise. Should it exist, however, then one whale's sounds would, even today, be audible by another whale that knew its "signature" from anywhere within the same ocean basin. At a far simpler level of analysis there is still something to be gained from a repetitious signal containing a very simple message. If the message contained by a signal is redundant, then it need not be detected all the time or even a large fraction of the time. In fact, in the extreme, a single detection, even if thousands of repeats had gone unheard, would be sufficient for a whale seeking to rejoin a herd or mate, to choose the general direction in which to swim. (Of course, receipt of more than one signal would add confidence to the decision.) 5) There may be some summation of signals from animals in close proximity that would make it possible for a distant whale to detect a herd at ranges too great for it to detect individuals. Kibblewhite and coworkers[14] present what they believe to be an example of such summed signals, but unfortunately it seems to us more likely to be a single whale (or pair) of another species. 6) The whale might be making sounds in suitable conditions to have Arctic transmission provide long ranges. 7) The 0 dB signal-to-noise ratio we specified for a just detectable signal may be much too conservative. By choosing 0 dB we are really only saying that since baleen whales have well-developed ears and a large region of a large brain given over to acoustic function,[40] they are probably at least as good at detecting a signal in noise as is a human being – an animal that presumably does not rely so much on ears for its livelihood as does a whale. (Acoustically speaking, human beings are not exceptional; for example, they are only marginally capable of crude echolocation of large objects and cannot approach the performance of a bat, seal, or porpoise in selecting among objects on the basis of their acoustic properties alone.)

With broad-band "white" noise (20–4,000 Hz) for masking, Miller[34] found that humans could correctly identify 50% of the words on a list when intensity of masking noise and speech were the same (0 dB S/N). However, many factors can improve this performance. For example: The subjects in Miller's tests were required to pick words that were outside any context. Each word was a separate problem that gave no clue to predicting the next. The subjects were searching for a signal with almost no redundancy, which is hardly analogous to the problem faced by a fin whale in detecting what must be one of the more redundant signals in nature. Later work by Miller and coworkers[35] gives an insight into what kind of improvement is possible in detecting a signal in noise if the choices are limited, a case that seems closer to the task faced by fin whale. They made tests with limited vocabularies containing no more than 2, 4, 8, 16, 32, etc. words. The task was to pick the one correct word from a known list of words. In all cases the percentage of correct words chosen fell to chance level only when the signal-to-noise ratio was − 18 dB. At S/N of −9 dB the percentage of time subjects could choose the correct word out of a limited vocabulary was 90% for a two-word vocabulary, 85% for an eight-word vocabulary, 82% for a six-word vocabulary, and 62% for a 32-word vocabulary. This suggests that if a message is somewhat predictable (i.e., one of a few expected alternatives), it can be detected deep in masking noise.

We have been discussing speech, but a closer analogy to the problem faced by a fin whale might be that faced by a human in detecting pure tones in noise. (Actualy, a whale's signal should be intrinsically easier to find in noise than a pure tone, since 20 Hz signals are not pure tones and information theory indicates that the detectability of a signal is improved by some complexity.) Much work has been done in this area in connection with masking of pure tones by a "critical band of noise." Bilger and Hirsh[36] define the critical band as ". . . that band of frequencies in a noise beyond which broadening the band will not further increase the masking of a pure tone in the center of the band." Their measurements of signal-to-noise ratios at which a tone is barely masked by a critical band show a spread from −5 to −12 dB depending on frequency of the signal. Greenwood,[37] in a similar set of measurements, found a span from −3.5 to −8 dB. In both of these examples intensity of the masked tone is measured in terms of spectrum level SPL (the sound pressure level in a frequency band 1 Hz wide), whereas intensity of masking noise is given in terms of band level (the intensity in a frequency band greater than 1 Hz wide, in this case, as wide as the critical band).

Detectability of a signal is also dependent upon duration of the signal. The work of Garner and Miller[38] shows that the signal-to-noise ratio necessary for detection decreases by about 15 dB as a signal is lengthened from 12.5 msec to one second. Beyond one second there is no significant improvement, the signal-to-noise ratio having reached an asymptotic value, an interesting coincidence when compared with the one-second duration of 20 Hz pulses.

All of these lines of evidence indicate that there must be any number of adaptations that might very significantly improve a whale's ability to detect a signal in noise and that each slight improvement would exponentially increase the area within which a listening whale could detect another of its kind. For example: if a whale can detect signals at a —9 dB S/N rather that at the 0 dB we have worked with, then in pre-steamship days it might haved detected sounds arriving via spherical propagation from sources as far away as 1,300 miles rather than the 450 miles we calculated earlier. This means that rather than hearing other fin whales anywhere within an area of 610,000 square miles, it could monitor an area of 5,300,000 square miles. An ability to detect sounds at a signal-to-noise ratio of − 15 dB would double this range, to 2,600 miles, and quadruple the area sampled, bringing it to 21,200,000 square miles. (To put these figures into some context, the area in square miles of the Atlantic Ocean is 33,420,000; of the Pacific it is 64,186,300; of the Indian, 28,350,300; and of the Arctic, 3,662,200.)

If we consider propagation by the sound channel and adhere to pre-ship noise conditions, the results are even more impressive, for now it will take only a 3 dB improvement to double range and quadruple area monitored, and a 6 dB improvement will quadruple range and multiply area by 16. (Incidentally, there are no deep water paths following great circle routes that are longer than about 15,000 miles.)

Of course, since we do not postulate that whales produce sounds at channel axis depths, the ranges would serve only to indicate the extreme upper limit and would almost certainly not be realized unless whales could dive to channel axis depths and make their sounds once there. However, such calculations clearly indicate that there should be a strong selective pressure favoring even the slightest improvement of signal detection ability since the area thus opened up for signaling or monitoring would be so dramatically increased.

With the exception of a few simple mechanical strategies, such as making the receiver directional, the minimum signal-to-noise ratio necessary for detection can only be lowered at the expense of considerable computing cost. Whales have remarkably large brains, a fact that has led some students of cetaceans to postulate an advanced form of intelligence. It may be of little value to substitute one hypothesis for another, but we find it easier to see a selective advantage in having a sophisticated computer for detecting signals deep in noise than to see how a mammal with no means such as hands to manipulate objects in its world could gain an advantage over the competition by being able to swim about the oceans entertaining advanced, philosophical thoughts.

When trying to assess the value to a whale of an improved ability to deal with ocean noise in its environment, it is well to reexamine what is meant by "ocean noise." Urick[22] defines ocean noise as ". . . that part of the total noise background . . . which is not due to . . . some identifiable localized source of noise. It is what is 'left over' after all identifiable noise sources are accounted for." Accounted for by what computer? Ours, or the animal's in question? It may be just as erroneous to assume that an animal's noise background is like our own as it is to conclude that bats are silent because we cannot hear their cries. For example, when the Navy measures ocean noise, the sounds made by whales are included as part of the total noise. In order words, one man's signal is another man's noise. We must periodically remind ourselves that ocean noise is not entirely "white" noise generated by a random-noise generator, but only a good approximation of "white" noise. It is, in part, the jumbled totality of discrete, familiar signals. From which it follows that if a mutation appears enabling an animal to identify more "noise" sources than its fellows, it will be working at a lower noise background than are its fellows.

What If The Theory Is Correct?

The thought that an animal other than man might signal by sound over hundreds or even thousands of miles may seem alien, but it is really no more remarkable than signaling by radio. The fact that a hand-held transmitter putting out a few watts can be heard across a continent *under some conditions* is explained by a phenomenon very similar to cylindrical sound propagation—the energy of the radio is not allowed to spread, but is confined in a duct, in this case an atmospheric, rather than a marine duct. Of course there are many days during which the same small transmitter will not function beyond ten blocks. We are still content with the analogy, however, since we expect that on many days in the ocean even close whales will fail to hear each other. But we must also realize that there is a case on record of a four-pound shot of dynamite that was detonated near Australia and heard off Bermuda, a distance of 12,000 miles.[19] And without being on the axis of the sofar channel, sound sources are sometimes heard, even in these noisy times, at ranges of hundreds of miles. Let us for a moment assume that the theory of long-range signaling is right and then try to cope with some of the questions that will arise if it is:

1) If such a system is so good, why don't more species use it? Small animals could probably not make loud enough or low enough sounds; even if they could, they might not have sufficient ear separation to obtain a useful bearing on an incoming sound (see following section). Also, the signal that assembles a herd

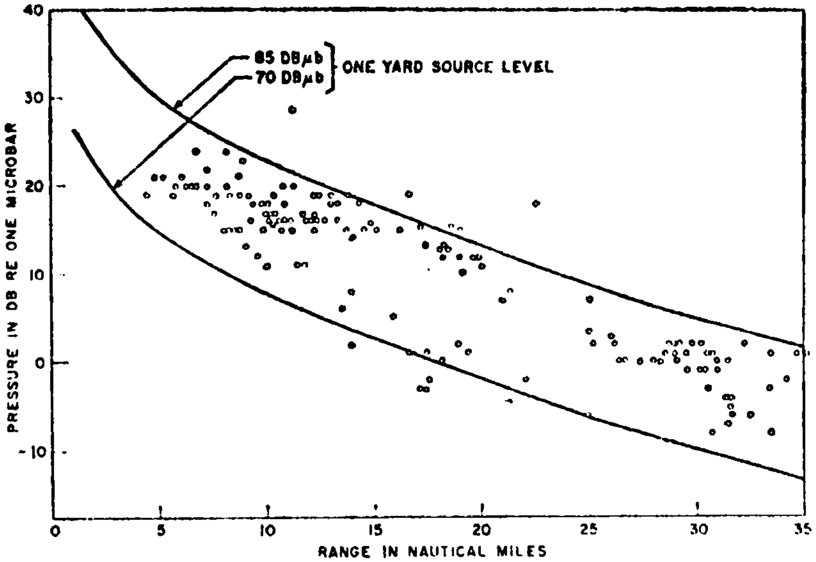

FIGURE 9. Received pressure levels re 1 dyne/cm² (= 1 microbar) versus computed source levels for 20 Hz sources. Hydrophones in shallow water (less than 300 feet). (From Walker.[10])

of animals must not also assemble its predators. Therefore, truly long signaling would only be expected to evolve in animals that were reasonably independent of predators, such as, for example, large whales. We feel, in fact, that some of the other very loud, low signals reported[13,14] at different frequencies below 100 Hz and at different (usually longer) durations than fin whale sounds were probably made by other baleen whale species.

2) Why haven't others recorded very long ranges for 20 Hz sounds before? The signals are in the peak of traffic noise and inaudible to most humans; thus one must interpose some form of translation between the signal and one's ears. The usual strategy is some form of visual display requiring several dB S/N for detection. For example, Walker's graph showing signal strength versus range indicates that at the greatest range at which he was able to detect fin whales, 36 miles, there must often have been 10 or more dB S/N (FIGURE 9), unless he was in an unusually high noise background, which would make 35-mile ranges unlikely.

Another reason why this theory may not have appeared earlier is that people are not used to thinking in terms of *unreliable* acoustic systems. Acoustic work done by the Navy often requires the most rigorously certain identification, since the fate of civilization as we know it may lie in the correct recognition of a "peculiar source." But on the other hand, what, after all, are a few noisy days in the life of a whale? If it doesn't hear its companion today, might it not tomorrow or the next day or the next week? If it wanted to join a distant companion, it would take several days to swim the distance anyway.

Of prime significance is that the source most often used in acoustics research is the explosive charge. This is particularly true in sofar work in which range is most often the parameter being measured and in which, therefore, a pulsive signal is desirable, as well as frequencies high enough (higher than 20 Hz) to measure an abrupt onset or offset for accuracy in range computation later. This means that few investigators are familiar with the characteristics of low-frequency sustained signals of modest power. We have seen that Patterson and Hamilton,[12] upon discovery of the 20 Hz sounds during their sofar research, were at first incredulous, and then sought an extra-oceanic source.

3) With what accuracy, if any, could an animal the size of a whale determine the direction to a 20 Hz sound? Let us once more start with humans. Although we can find no measurements of the ability of humans to detect direction at frequencies as low as 20 Hz, the trend is very clear. Mills[39] has studied the minimal audible angle, which he defines as "the angle formed at the center of the head by lines projecting to two sources of sound whose positions are just noticeably different, when they are sounded in succession." His results clearly show that man's best directional hearing occurs at frequencies below 1,000 Hz where phase alone is almost certainly the cue used. As frequency is lowered in this range, the ability to detect interaural phase differences improves. Mills' lowest datum (250 Hz) shows a minimum phase discrimination ability of 1.5°. This yields a minimum audible angle of 3.5°. When conditions are most favorable for making temporal discriminations, the interaural difference in time discrimination is about 10 μsec. Because of the difference of speed of sound in air and water it makes more sense, for comparative purposes, to express the separation of ears in terms of time rather than distance. The minimum acoustic path between human ears is 650 μsec. That for an adult fin whale of average size is harder to come by since the path taken by a sound wave in traveling from the body surface to the cochlea of a whale is the subject of almost as many theories as there are investigators.[40] Although the interaural acoustic path length is not known, the minimum distance between stapes footplates can be measured, and if we can assume acoustic isolation between the cochleae and no medial joining of acoustic paths, then it measures about 600 μsec for an average adult fin whale. (Another advantage of being large for an aquatic animal is that it makes fair acoustic separations possible in spite of the high speed of sound in water.) This indicates that if a fin whale could detect phase differences as well as people can, it would do very well indeed, even at such a low frequency as 20 Hz.

4) Is it not more likely that 20 Hz pulses are principally used in sonar? We, of course, feel that they would provide valuable information about range (within 250 feet, their wavelength) and major features of the ocean (the bottom, sea mounts, and perhaps large shoals of fish or even swarms of krill), but if this is their principal use, the repetition rate seems too great for such a loud, low sonar. We know that animals producing 20 Hz sounds often meander slowly about in a restricted area for long periods while vigorously pulsing.[10,12] If the pulses are the signals for a sonar, it must be a very long-range one, and when the animals are hardly moving, what new information would be gained by such relatively rapid repetition rates? If there was not such good reason to believe that the sounds are omnidirectional, then one could believe in any pulsing rate, however rapid, as the animal directed its beam about, investigating in different directions. But unless the ears are made directional by phasing in some way, there is not much to be gained by pulsing loudly 100 times over the same canyon or plain. In addition, the unchanging pulse rate makes these sounds differ from known animal sonar systems, which vary dramatically in pulse rate depending upon the activity of the animal. However, it is easy to see how a fairly fast and steady repetition rate could evolve in a communication based on such loud sounds, for whenever an animal becomes silent, it "vanishes" from the rest of the herd.

6) What use would it be for whales to contact each other at great range?

Marine species that roam widely over a great range often rendezvous in vast numbers either annually or once in a lifetime at precise times and places (salmon, sea turtles, penguins, seals, and others). The advantage of such congregations is traditionally considered to be that they bring members of the same species together in time and space. However, there is another way of looking at it, which is seldom stressed enough: having a fixed, annual, or once-in-a-lifetime, rendezvous makes it possible for the species *not to be together* at other seasons, to spread out away from each other and to cover the maximum possible area, exploiting resources whenever and wherever encountered. A disadvantage of such a rendezvous system is that if an animal is to get its genes into the population it must leave whatever feeding areas it may have encountered at a specific time and join the breeding concentration. A second disadvantage of a large percentage of a species assembling at a large, fixed rendezvous site must be that when food supplies in the vicinity of the site fail, a large proportion of the population will probably die (even though food in the areas they left in order to join the rendezvous may be abundant).

Another mechanism that ensures breeding in widely ranging species is the nomadic life in which herds of animals move about together, keeping in close enough contact to rejoin at will. They are not tied to a specific rendezvous spot, and when good feeding conditions are encountered, they can linger as long as the conditions last. They may show some trend towards an annual drift, but they do not have to be in some given spot at some given time in order to breed. (Porpoises, tuna, mackerel, and many other shoaling fish are probably examples.) Since food supplies at any destination have to be good enough to suport the whole group, such animals might be expected to be fast swimmers, always on the move, patrolling a given beat at irregular intervals or wandering fairly widely.

As the size of, and numbers in, a herd increase, the area it needs to patrol for food must also increase, and any adaptation that improves the maximum effective signaling distance should be immediately favored by natural selection. There seems to be nothing that would limit this process, i.e., nothing that would select against an improvement in signaling range, for surely the wider the herd can be spread and still keep contact, the fewer the constraints it will face in encountering and exploiting every possible food source in every shifting and unpredictable location. Thus the trend to improve range would be limited only when the boundaries of the inhabitable range had been reached. Beyond that there would be no selective pressure to favor an increased ability to signal over greater ranges, and the system would reach equilibrium.

If there were a quantum jump from simple signaling to meaningful communication, there could be strong pressures to improve signal-to-noise ratios, but a shared communication channel becomes self-defeating after a while (like a cocktail party again), and it is most important to recall that all whales share one channel. Thus what one whale would hear from the center of a herd might be a summed roar emanating unevenly from various directions with closer individuals standing out against the jumbled background.

We postulate then something that might be called a "range herd," a new form of herd structure in which the population lives in tenuous contact throughout large portions of its range (perhaps over their whole deep-water range in any one ocean), a system in which set rendezvous sites are not necessary, and in which individuals, when in deep ocean but far from the center of the herd, are, in an acoustic sense, a part of it.

If one is skeptical about the advantages of such a system, let us make up a very simple law for the herd to follow: When a whale is well fed, it vocalizes; when searching for food, it remains silent. With such a system in effect a hungry whale could find the best concentrations of food by heading for the loudest and/or the most jumbled sounds. Such a system would allow maximum exploitation of the whole ocean by a single whale species through long-range signaling.

If some such simple signaling system as we postulate existed, the behavior of the animals that possessed it might show certain attributes. A demonstration that fin whales have such attributes would not prove the existence of range herds, but it would lend support to the idea. Such traits might include very informal migrations showing broad trends controlled more by seasons than by any adherence to precise schedules, places, or groupings (other than family); ability to migrate to different destinations in different years; ability to collect into large herds at unpredictable locations and seasons; and in fact anything that seems to involve a high element of unpredictability should suggest an underlying system of communication. With this in mind let us examine what is known about fin whale migrations.

Migratory Behavior

It is generally stated that baleen whales feed principally in summer in cold waters during annual blooms of food organisms, and then migrate during the winter to warmer waters for calving.[1,41,42]

While this observation is reliable and useful as a broad generalization, there is also evidence for several species of baleen whales that some part of the population may be found in any ice-free portion of their whole range during any season. At the time of the early Discovery II expeditions (from 1933–1939) sightings of baleen whales were recorded in the Antarctic Ocean in all months of the year. These data were later used by Macintosh and Brown[43] to estimate the numbers of whales present in ice-free Antarctic waters month by month. Their figures (FIGURE 10) indicates that populations of fin, blue, and humpback whales in the ice-free Antarctic fluctuate between roughly 10,000 individuals in the dead of winter and 200,000 in mid summer, but that at no time is the Antarctic Ocean devoid of whales. Although more recent methods of age determination and current population models might be expected to modify the absolute estimates given here, it seems unlikely that the relative proportions would be seriously changed. Thus we see that many baleen whales must linger in the Antarctic throughout the winter, even though most of them move to lower latitudes.

To consider specific cases: At a few shore stations that operate all year, whales are present in the catch throughout the year. For example, in the 1920's, before overexploitation caused a dramatic decline in population, fin whales were sighted year round off Spain and Portugal even though the peaks of the fin whaling season were only in May and October.[44] In Japanese and Korean waters fin whales were killed in every month of 1938; and in the same year fin whales were taken every month except January off the coast of western Norway. In the waters around the South Shetland Islands and South Georgia, fin whaling was successful in all months except June and July during 1925–26, even though operations were much reduced outside the months of December to April.* There are numerous other examples throughout the literature of seasonal sightings of fin whales far outside their areas of principal abundance.

Most of our knowledge about geographical distribution of baleen whales comes from research related to the activities of whaling. Since that industry prefers, for

* Data tabulated by Tomilin, based on reports of the Bureau of International Whaling Statistics.

obvious reasons, to operate in regions of high concentration of whales, and at seasons favorable for running ships, it is inevitable that our impression of fin whale distribution will exaggerate the importance of dense concentrations and therefore, underemphasize the importance of "widely scattered" individuals at the same season outside "whaling grounds," or in different seasons on the grounds. It is unlikely that future discoveries concerning fin whale migrations will very much simplify this picture. The industry has only been able to profit by discovering the main predictable concentrations of whales, and it is a fair bet that future data on the distribution of whales will contribute more examples that do not conform to a pattern of predictable annual concentrations than examples that do!

Unlike most terrestrial animal migrations, baleen whale migrations do not seem to be primarily linked to feeding. There is considerable evidence that in winter large baleen whale species feed only at widely spaced time intervals.[45-47] The usual explanation offered is that suitable food is scarce in winter even at low latitudes. However, fin whales may fare better than some other species since they are known to feed on shoaling fish (in some areas they are called "herring whales"), and it seems unlikely that they would have to starve for a whole winter regardless of what latitudes they were in. Because they have broad food preferences, the prospects for fin whales in finding food may not be much affected by whether or not they migrate, and their capacity for long starvation may enable them to survive the universal low abundance of food in winter.

The most popular explanation of baleen whale migrations in terms of survival value involves the thermal requirements of the newborn calf.[41,44,45,48] Most calves are born at the time when most fin whales are thought to be in warm waters. The data tabulated by Tomilin,[44] for 21,450 fin whale embryos taken from females captured in the Antarctic between 1925 and 1948, show a peak in births during the winter months. Laws[49] shows a curve based on similar evidence, indicating April and May (southern hemisphere) as the peak season. The assumption is that the newborn calf, with its thin blubber coat and relatively great surface-to-volume-ratio would require warmer waters than the adults. Kanwisher and Sundnes[50] criticize this theory strongly on theoretical grounds. Their calculations indicate that the young of the largest species of whales are born with ample insulation for the coldest oceans. They also calculate that the layer of blubber in which the adults are wrapped is far more than is necessary for protection against heat loss and concur with the calculation of Parry[51] showing that half of a large whale's blubber could maintain its basal metabolism for four to six months without feeding. Kanwisher and Sundnes therefore postulate that the primary function of a thick blubber coat is probably related to its potential as an energy reserve during lean times.

We now face a dilemma, for if migrations have not evolved primarily to ensure a continuous food supply or to avoid thermal stress on newborn, what selective pressures did shape them? The answer is by no means clear, but the temporal coincidence of migration to warm waters with the time of year when births are most numerous strengthens the suggestion that the two phenomena are functionally linked.

The above considerations indicate that it may not be necessary for all individuals in all stages of development to participate in every migration every year, an opinion that is shared by Clarke.[48] Simply stated: Why swim several thousand miles in one year if there is no need to do so? In fact, a large fraction of the total population may not be directly in need of the benefits that would accrue from migration every year; if those benefits are really only necessary to new mothers and their calves, the portion of the population for which migration to the warmer waters is less crucial might be large. It might at least include weaned but not sexually mature "adolescents" of both sexes, reproductively senile individuals of both sexes, and sexually mature females not in the terminal stages of pregnancy. Since female fin whales are thought to give birth, on the average, once every other year,[1] the need to visit warm waters may not much exceed half of their reproductive lives. Thus, even reproductive females might need to visit the calving grounds during only half of their reproductively active lives.

Although there is some evidence indicating favored migration routes,[45] fin whales are widely spread in winter (the height of the breeding season), there being no known large concentrations.[42,44,45,48] This is in contrast to the pattern observed in other baleen whales, which aggregate in large close groups during calving. (The well-known breeding grounds of grey whales in Scammons Lagoon is an example.) The movements of fin whales are complex and apparently unsynchronized in summer too. For example, observations by Hardy[52] indicate that fin whales may have different migratory destinations in different years since blooms of krill shift widely from year to year, and yet the whales tend to be found in the appropriate food-rich areas, rather than in areas that may have had abundant stocks last year but are now vacant. Tens of thousands of square miles of ocean that were ice covered last year may be quite clear of ice this year and thus freshly accessible for exploitation. If individuals are to profit by such newly opened food areas in time to harvest an annual bloom of food, they would be greatly helped by some form of sounds made by well-fed individuals.

To add to the picture of inconstant migratory habits, analysis of tag recoveries demonstrates that some fin whales wander broadly even in summer, since tagged whales are often recovered on feeding grounds far removed from those on which they were marked—as far away as the opposite side of the Antarctic continent. To quote Mackintosh:[45] "The overall picture is one of apparently disorderly movements in which it is hard to see the whales following any definite rules."

The more one examines what is known about their migration, the harder it becomes to fit fin whales into the usual, comfortable concept of a migratory species shuttling on schedule twice each year between definite fixed destinations. Although there are clear trends, there are also many exceptions and one is forced to consider rather more haphazard models, involving, in addition to a main annual trend, local opportunistic movements in response to a fluctuating yearly food supply. Summer feeding herds may well be composed of somewhat different individuals from year to year, with a few individuals wandering considerably over the summer feeding grounds. In winter there seem to be even less well-ordered patterns, with some individuals remaining on the feeding grounds, some going all the way to lower latitudes, and others scattered throughout the area between. Even in the lower latitudes towards which the main surge of the population is presumed to go there are no clear concentrations in predictable places, and a smaller proportion of the population than usually imagined would be found going all the way to the warmest waters for calving.

In spite of how little is known about the distribution of fin whales, one line of evidence clearly points out that their migratory behavior is much at variance with that of other migratory marine mammals, namely, that conception is at a minimum when fin whales are known to be concentrated,[49] and at a maximum when they are thinly dispersed over millions of square miles of ocean (FIGURE 10). This is not the usual marine mammalian pattern. Unless we postulate long-range communication, then how do fin whales find each other during the mating

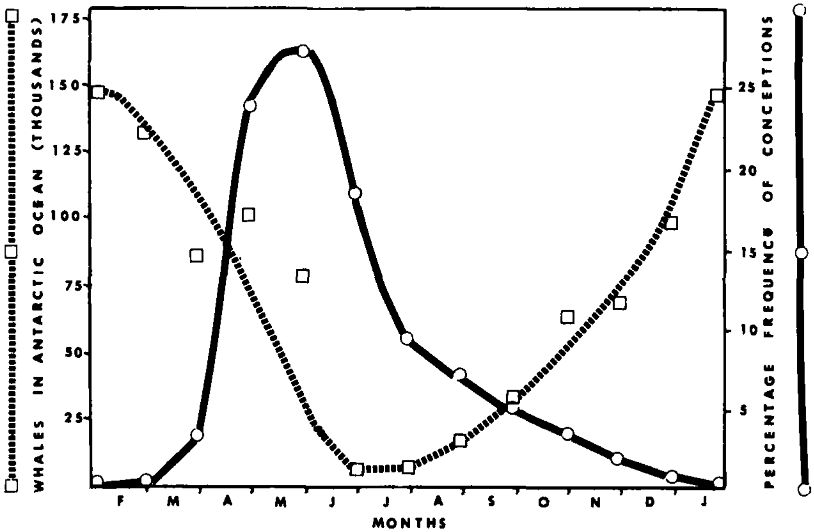

FIGURE 10. Monthly percentage frequency of matings leading to conception (from Laws[50]); and estimated seasonal variation in numbers of fin whales in ice-free Antarctic waters (after Mackintosh and Brown[43]). Note that during the time of maximum concentration of fin whales mating has almost ceased.

season? And how do they manage to concentrate at different migratory destinations in different years? And, if all animals do not join the seasonal exodus every year, how does a dropout rejoin a concentration? Or for that matter how do concentrations form at all without requiring many months or years for chance accumulation? (Herds of 500–1,000 have been seen at one time.[44])

Should the sounds made by fin whales carry far enough so that even widely separated whales are in fact part of the same herd, then perhaps some of the "apparently disorderly movements" or even their extraordinary feats of navigation, such as the ability to concentrate at different migratory destinations in different years, would appear less mysterious.

Wenz[53] reports slight (ca. 3 dB) periodic variations in 20 Hz ambient noise levels throughout wide areas of the ocean. The peaking of the fluctuations occurred at the same local time each day. We feel that at least some of the energy responsible for these regular variations in 20 Hz noise level may be contributed by fin and/or other whales. Payne has confirmed an observation, originally made by Perrone (personal communication), that there is a pronounced diurnal cycle in the vocal activity of humpback whales (*Megaptera novaeangliae*) in the Bermuda area. If fin whales are also predictably more vocal at certain hours, Wenz's observed increased 20 Hz level may represent summation of very distant sounds from animals, which, though vocal at any time, were at their most vociferous just before midnight each day. Although Patterson and Hamilton show data for two years, the sample is not large enough to show statistical significance for slight trends. However, in both years 20 Hz pulse activity does increase during the late afternoon and early evening, reaching a peak shortly before or after midnight.

What other possibilities are there? The 20 Hz noise is at the right frequency to have derived from ships. But such could not be the case because of the predictable and widespread diurnal rhythms, which have no analog in shipping.

We suspect it would be interesting to look for evidence that 20 Hz ambient ocean noise receives a significant input from the cries of fin whales and/or other species, at least in areas where they are still fairly plentiful.

We ourselves, using a vertical hydrophone array, plan to track fin whales in the vertical plane in order to see what depths they are at while singing. Any evidence that they reach channel axis depths would have obvious interest. We also hope to try tracking fin whales at somewhat greater ranges than achieved hitherto by employing more sophisticated signal processing techniques, to see if we can get some idea of what areas they roam over.

What If The Theory Is Incorrect?

We are not the first to speculate in print on the possible function of 20 Hz sounds. Explanations have included acoustic artifacts, heartbeats, signals strong enough to stun a predator, sonar, and sounds for more local, general signaling. We, of course, recognize the great likelihood that such sounds could, and almost certainly do, serve several purposes, and that other fainter sounds accompanying them would only be useful at limited range. We do not wish to be interpreted as saying that the one function of 20 Hz sounds is for long-range signaling. If it were, for instance, useful as a means of orientation when animals travel towards a new destination, we would think it most unlikely that it replaced other navigational systems, but rather, augmented them. In other words, we do not feel that these sounds are the only means by which whales maintain contact, but rather, one of several, and the one working at greatest range.

Our theory is that the signals evolved in a quieter ocean and that the principal selective pressures all tended towards a signal detectable at great range. If we are wrong, then any alternative theory ought to explain why 20 Hz sounds are so loud, so constant in repetition rate, so pure in frequency, and so narrow-band. It must also explain why they may go on for many hours at a time, even though the animal producing them is simply meandering about in a relatively small area. An alternative theory should not overlook the fact that the frequency, 20 Hz, has particularly low transmission losses under ice, has an exceedingly low attenuation with range, has almost no losses from reflection off the bottom, and is the highest frequency that would be independent of wind-generated noise. Finally it must explain how whales find each other near the height of mating season when they are (inconveniently) most thinly distributed, and how an individual rejoins a herd, and how 500 to 1,000 fin whales ever happen to come together at one place and time when normally they are found as singles or in small herds.

Summary

1) The term "herd," as applied to whales, is challenged since it usually represents a visual judgment of a social unit that is probably held together by acoustic means. Thus, whales that appear to be traveling alone are perhaps really members of the same widely spread herd. This raises the question how far apart members of whale herds might be and still be able to keep contact.

2) The 20 Hz sounds made by fin whales are used in a calculation of maximum signaling range in deep ocean. (They are selected because they are loud and monotonous.) Two different types of sound propagation are considered, spherical, and cylindrical propagation in the deep-sound channel. Since fin whales are not known (or suspected) to make sounds at sufficient depths to utilize the most

favorable portions of the deep-sound channel (the axis), other, less favorable, paths that are accessible from near the surface are described.

3) Our calculations indicate that in modern deep-ocean, ambient, noise conditions and in areas of moderate shipping traffic, 20 Hz fin whale sounds should be audible at a signal-to-noise ratio of 0 dB out to ranges of 45 nautical miles when the sounds propagate by spherical losses and to ranges of 525 miles when propagated via the deep-sound channel. It is pointed out that ranges of 700 miles represent an upper limit that is approached but not attained.

4) It is noted that since modern ambient background noise in the ocean is principally due to ship traffic and that propeller-driven ships have been present for roughly 1/100,000th the time that fin whales have been evolving, it is more than likely that whatever their function, 20 Hz sounds were designed for a set of noise conditions that no longer exists. If these conditions are assumed to correspond with current ambient noise levels in remote areas, our calculations of maximum transmission range increase to 140 miles by spherical propagation and 3,500 miles by cylindrical propagation in the deep-sound channel. In both cases this assumes average background noise; still longer ranges are calculated for quiet conditions prior to the advent of propeller-driven ships.

5) A series of arguments is presented pointing to the conclusion that many different factors might reasonably extend these calculated ranges by lowering the assumed signal-to-noise ratio at the receiver.

6) Since circles with such large radii would encompass millions of square miles, it is concluded that fin whale herds prior to propeller-driven ships might be thought of as "range herds," that is, a single herd covering the entire deep-water range of the species in any one ocean. Observations that fin whales lack fixed breeding rendezvous, taken together with evidence that they are most closely concentrated (for feeding and not breeding) at times when mating is nil, would point to some special mechanism by which pairs meet. A review of the migrations of fin whales, particularly the many exceptions to any stereotyped rules, is given in support of the view that fin whales can come together at will even when spread out over their entire range.

7) The many advantages of 20 Hz as a frequency ideal for long range signaling (and the many disadvantages for its use in sonar) are reviewed. It lies just below storm-generated noise, meaning that any communication system that employed it would be free of disruption by storms. Almost no energy is lost by reflection of 20 Hz sounds from the bottom; it has remarkably low attenuation with distance (3 dB in 5,600 miles), and is in the best octave for long-range propagation under polar ocean conditions.

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DISCUSSION

DR. TAVOLGA: It seems to me that Dr. Payne finds himself in a similar situation to mine, in that the information seems to be there, but it's not clear whether or not it's being used. On the question of the information getting to these distances of hundreds of miles or so, this is a very elegant extrapolation. I would feel happier if there were some data points at the end of this extrapolation. Since we are, shall I say, unhampered by any evidence on the hearing capacities of these whales, we can assume that the whales are hearing this. But perhaps you are in a better situation than I am. Do you have any evidence that they are using this information?

DR. PAYNE: No, not yet. Let me comment on your two points. Nobody knows if fin whales can hear these signals at all, though it is hard to explain their characteristics on other than acoustic grounds. It is hard to demonstrate that large species of whales can hear anything, though we do know that they can hear something, as evidenced by their rapid diving when you bang on the side of a boat. If you recall the curves, I showed fin whales would require a sensitivity 15–40 decibels less good than a human, at his frequency of maximum sensitivity, to hear 20 Hz sounds at the distances we are claiming. In other words they could be quite deaf by human standards and still not have that affect our arguments in the least. That is because we are talking about signal-to-noise ratio; we're not talking about ability to detect a small signal.

You say it's unfortunate there are no data points at the end of our extrapolation. Let me say only that there are dozens of such data points supporting just the kinds of calculations we have made. These points have been obtained by the Navy–in fact, marine transmission loss is one of the better measured acoustic parameters.

If we are wrong, any theory that's going to explain these sounds will have to include the fact that they're monotonous, that they're loud, that they're confined to a very narrow frequency range; that they happen to exactly correspond to one of the best places in the acoustic spectrum to get sounds a long way through the pre-ship ocean, and finally, they are at the frequency that gets through Arctic water best. Against some other theories is the fact that 20 Hz is not very useful for echolocation since you don't get better resolution than about 250 feet with a frequency that low and it's hard to have a directional transmitter or receiver.

DR. GEORGE GOUREVITCH (*Hunter College, City University of New York*): Dr. Payne, if the tremendous power of the acoustic signal these animals make might interfere with their own hearing, how would you explain this rather sizable energy that they produce?

DR. PAYNE: This same problem is faced and solved by many echolocating animals. Presumably there's some mechanism to avoid such damage, for example, increased tension on ossicular muscles during transmission, or some such. But, I don't think there is much controversy over the intensity of 20-Hz sounds and I don't think, for example, that anybody would wish to say that they were less than approximately 65 decibels in intensity, which is still a loud shout and must be coped with by the animal's receiver.