Communications

Against the Humpback Whale Sonar Hypothesis

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***Abstract*—A rebuttal to the article of Frazer and Mercado, who presented a sonar model for humpback whale song, is presented. This rebuttal considers the noise-limited form of the sonar equation, current understanding of humpback whale behavior and the characteristics of humpback whale songs, along with arguments from an evolutionary perspective. Arguments from all of these different aspects do not support the model of Frazer and Mercado.**

***Index Terms*—Acoustic noise, acoustic reflection, animals, sonar, sonar detection, sonar target recognition.**

I. INTRODUCTION

We read with interest the article by Frazer and Mercado[1] expounding on a sonar function for humpback whale songs. While they eloquently presented their case, we feel that there are some fundamental problems with their hypothesis. We would like to present our arguments against the Frazer–Mercado hypothesis. Our argument will encompass sonar theory, humpback whale behavioral ecology and evolutionary biology, and humpback whale acoustic observations. For the remainder of this paper we will use F&M in place of Frazer and Mercado [1].

II. USE OF THE SONAR EQUATION

We begin our critique by considering the noise limited form of the sonar equation used by F&M. This form can be found in Urick [2] and is

$$\mathrm{SE} = \mathrm{SL} - 2\mathrm{TL} + \mathrm{TS} - \mathrm{NL} + \mathrm{DI} - \mathrm{DT} \tag{1}$$

where

SE signal excess;
SL source level;
TL transmission loss;
TS target strength;
NL received noise level;
DI directivity index;
DT detection threshold, which is defined as the signal-to-noise ratio at which the signal can just be detected.

Some of the values used by F&M seem to be extremely favorable to their hypothesis. Using more moderate values in the sonar equation, the detection ranges of 4–6 km calculated by F&M will be drastically reduced, as we will proceed to show.

A. Source Level

F&M use a source level of 182 dB re 1 μPa, citing Winn and Winn [3] as a reference for a humpback whale source level of 175–188 dB re 1 μPa at 1 m. First, this is an incorrect citation and should be Winn *et al.* [5]. The only reference to song amplitude in the Winn and Winn [3] paper is as follows "The amplitudes of the low-frequency moans and snores are considerably greater than 55 to 60 dB re μbar." In the same paragraph, F&M cited Winn *et al.* [4] and others as having measured a source of 174–190. In fact, there are **no** source level data presented in Winn *et al.* [4]. Likewise, the F&M cited Payne and Payne [6] as a reference for source level. Again, there are no source level data reported in this paper. F&M also referenced Cato [7] as stating the "high source levels of the whales, up to 190 dB re 1 μPa." However, Cato [7] (a co-author of this paper) did not attach any source levels to his recording. Makris and Cato [8] actually reported "high source levels of the whales, up to 190 dB re 1 μPa at 1 m," but this was for whales in general such as the blue whales and the fin whales, not for humpback whales.

Frankel [9] used an array of sonobuoys configured in a line to localize singing humpback whales and to estimate the source levels of their songs. Measurements by Frankel [9] which are probably the most accurate to date, indicate a mean source level of 174 dB re 1 μPa ($\sim$300-Hz-bandwidth). Frankel's results were probably more accurate than the visual estimation of distance by Winn *et al.* [5]. Furthermore, Frankel reported mean source level and Winn *et al.* [5] provided range of estimated source levels. Finally, Winn *et al.* [5] results were broadband (20 Hz to 10 kHz) compared with Frankel's which were in a 300-Hz band. The spectrograms presented by Winn *et al.* [5] showed that energy was spread evenly over the 3-kHz band of the spectrograms, giving a level that would be 10 dB above that in a 300-Hz band, and 15 dB above that in the 100-Hz band used by F&M.

B. Transmission Loss

The transmission loss used by F&M came from a sophisticated theoretical model, rather than the empirical transmission loss measurement results of Frankel and Clark [10] conducted off the island of Hawaii, in waters frequented by humpback whales. Frankel and Clark [10] found that their direct measurement of transmission loss could be described by the equation

$$\mathrm{TL} = 17.6 \log r \tag{2}$$

where r is the range in m. Although (2) seems fairly simple and perhaps crude, it is based on real data taken in a real environment. Any transmission loss model is only as accurate as the environmental data that are used. In shallow waters, the critical factors are the acoustic properties, slope and topology of the bottom. These cannot be determined reliably without direct measurements; inferences from the geological properties of the sediment are generally unreliable. While transmission loss modeling provides insights into the way in which loss varies, we would argue that direct measurements are more reliable.

C. Target Strength

F&M referred to the target strength measurements of humpback whales performed by Love [11] which resulted in values between -4 and $+7$ dB. F&M chose a value of $+6$ dB in their calculations. However, Love's measurements were conducted at a frequency of 20 kHz, which is over 5–6 octave from the typical peak frequencies

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between 300–600 Hz of humpback whale songs. F&M supported their choice of 6 dB by modeling the whale's lung as a 2-m diameter sphere of air. In fact, what is known of the lung volume of baleen whales indicates that this is an overestimate. The fin whale, for example has a lung volume of about 2 m^3 (Slijper [12]). An air bubble of this volume would have a target strength of approximately 1 dB at 400 Hz and -8 dB at 2 kHz (Urick [2]). Since fin whales are larger than humpback whales, the lung capacity of the humpback whale would be expected to be no more, and probably less, than 2 m^3. Perhaps a more realistic and conservative estimate of target strength that should be used in the sonar equation is 0 dB rather than +6 dB used by F&M.

D. Noise level

The recordings of Helweg and Herman [17] in Kauai waters and Au *et al.* [13] in the waters of West Maui indicate that whales are continuously singing throughout the day and night. At any given instant, many whales can be heard singing in a manner that is commonly referred to as chorusing. Neighboring humpback whales themselves are the source of interfering noise for any sonar application, and since they sing basically the same or very similar songs, any "cocktail" party effect would not be a factor for a whale trying to hear an echo. Examples of two 1/3 octave band spectra of sounds aurally identified as humpback chorusing sounds are shown in Fig. 1. The chorusing sounds off Maui were measured by Au and Green [14] approximately 1–1/2 mil off shore using a DAT recorder. No humpback whales were visually observed by a shore-based team located on a hill using high power binoculars. The data represent a 40 s time period with the spectral analysis performed on blocks of data, each 93 ms in duration. The level of noise that was observed was similar along a 15-mil coast line in West Maui. This noise level does not represent a worst case situation but a rather typical one along the West Maui coast line where the density of humpback whales is relatively high. The standard deviation at the spectral peak of the 1/3 octave band level in dB was approximately 5.5 dB (Au and Green [14]). Also shown in Fig. 1 (dashed line) is the averaged 1/3 octave band noise level obtained with a remote sensor deployed off Kauai by Frankel and his colleagues from Cornell University. The remote sensor was placed on the bottom at 100 m depth off the northeast section of Kauai. The noise data were collected for 5 min every 6 h of a 10-day period from March 8 to March 18, 1998. The acoustic data were digitized with an *A/D* converter sampling at a rate 2 kHz. The dropoff in the Kauai data is due to the steep anti-aliasing filter set at 800 Hz. The difference in the amplitude of the chorusing data may be in part caused by the difference in the hydrophone depth. The Maui data were obtained from a hydrophone 7 m deep compared to the 100 m hydrophone depth for the Kauai data. Another reason for the Kauai data being some 10 dB less in amplitude could be related to the lower density of whales off Kauai than Maui [15].

F&M considered noise spectral densities of 64 dB re 1 μPa^2/Hz between 400–500 Hz in their sonar equation analysis. The noise levels are equivalent to 84 dB, in a 100-Hz band. However, Fig. 1 indicates that the 1/3 octave band noise level between 400–500 Hz should be more like 111 to 123 dB, and since a 1/3 octave bandwidth at 400 Hz is equal to 100-Hz, the equivalent noise spectral density is 91 to 103 dB re 1 μPa^2/Hz. The noise levels used by F&M are considerably lower than the actual noise levels in a humpback whale environment. For a humpback whale signal at 2 kHz, F&M used a noise level of 67 dB re 1 μPa^2/Hz. Our data in Fig. 1 indicate that a more realistic noise figure is 111 dB in a 1/3 octave band, or 104 dB in a 100 Hz band (a 7 dB adjustment is required to go from a 1/3 octave band level to a 100 Hz band level at 2 kHz). The equivalent spectral density value is 84 dB/Hz, which again is considerably higher than that used by F&M. For arguments sake, let us assume that the noise at 2 kHz off Kauai was about 10 dB below the Maui data in Fig. 1. We would then be using noise values between 94 and 104 dB at 2 kHz in our calculation of signal excess. These noise levels are still significantly higher than the 84 dB used by F&M. It is important to note that the noise levels used by F&M were inappropriately taken from the work of Frankel and Clark [10] and Frankel *et al.* [16] In obtaining their noise results, Frankel and Clark [10] purposefully excluded any part of the recordings that contained whale songs in an attempt to estimate the ambient noise level **without** any contribution from humpback whale choruses.

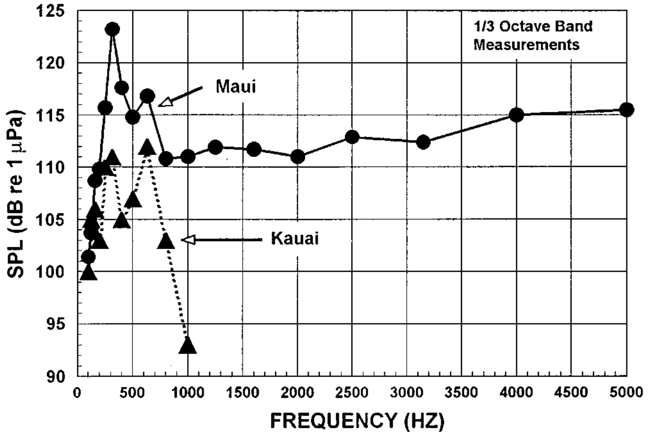

Fig. 1. The averaged 1/3 octave band spectrum of sound aurally identified as humpback whale chorusing sounds measured approximately 1.5 miles from shore in W. Maui during the peak in the humpback whale season (from Au and Green [14]), and off Kauai in 1998.

It is important to understand that chorusing sounds in Hawaiian waters during the humpback whale winter season seem to be continuous and always present. Helweg and Herman [17] conducted remote recordings off Kauai for 5 min every 2 h around the clock for the 1988 season. They reported that humpback whale singing occurred throughout the 24-h period during seasonal residency. Au *et al.* [13] remotely monitored the chorusing sounds of humpback whales for 4 min every 30 min throughout a 24-h period. Remote monitoring of humpback whale choruses took place for almost the entire 1998 humpback whale season with a package that was deployed on the bottom approximately $\frac{1}{2}$ miles off shore in West Maui. They found that these whales sang continuously with a maximum in the sound pressure level corresponding closely with the maximum whale count from aerial survey work of Mobley *et al.* [15].

E. Detection Threshold

Finally in the sonar equation, F&M used a detection threshold (DT), of -14 dB obtained by Cato [7] for human subjects. However, Cato's result was specified as being the broad band signal to noise ratio applied to the band between 55 Hz and 15 kHz. Using the broadband noise data of Cato, the noise level in a 100-Hz band between 400–500 Hz will cause the detection threshold to be 16 dB greater than the detection threshold used by F&M. Thus the value of DT from Cato's result for a bandwidth of 100 Hz should be $+2$ dB rather than -14 dB. The overall effect of a higher but more accurate DT value is that a propagation loss of 16 dB less can be tolerated for the transmission loss term in the sonar equation. We understand that detection threshold values depend on both the response bias and detection sensitivity of subjects (Urick [2]), factors not considered by Cato [7]. However, Cato's DT value is the only one available in the literature.

F. Estimating Echolocation Detection Range

In order to estimate detection ranges, F&M first assumed a one-way transmission loss of 58 dB and calculated the signal excess at 400 Hz

TABLE I
ESTIMATED TARGET DETECTION RANGES

Term in the Sonar Equation	F&M Values (dB) for 400 Hz	F&M Values(dB) for 2 kHz	Realistic Values (dB) for 400 Hz	Realistic Values (dB) for 2 kHz
SL	182	182	174	174
TS	6	6	0	0
NL	84	87	111-123	94 -104
DI	0	5	0	5
DT	-14	-14	2	2
TL	58	58	58	58
SE	2	4	**-55 to –67**	**-33 to-43**
Det range	4 – 6 km	4 – 6 km	**0**	**0**

and at 2 kHz. Given in Table I are the values for the different variables in the sonar equation used by F&M and the values that we have argued to be more appropriate, along with estimated detection ranges. Our calculations using more realistic values for the variables in the sonar equation resulted in signal excess of -53 to -65 dB at 400 Hz and -31 to -41 dB at 2 kHz, which means that if a singing whale is subjected to a one-way transmission loss of 58 dB, any echoes from another whale would be completely buried in noise. We can go further and calculate the detection ranges at 400 and 2 kHz that would result in a signal excess of 0 dB. From the values in Table I, a 0-dB signal excess will be obtained at 400 Hz if the transmission loss was 24.5–30.5 dB. Using (2), this translates to a detection range of 25 to 55 m, far from the 4–6 km obtained by F&M. At 2 kHz, the signal excess of 0 dB will be obtained if the one way transmission loss is between 36.5–41.5 dB, depending on the noise level. These one way transmission losses translate to 123–235 m, once again, far from 4–6 km.

Makris and Cato [8] and Makris *et al.* [18] considered a similar problem as F&M by examining the feasibility of detecting non singing whales by using the echoes produced when songs reflected off other whales. Their interest was in acoustic tracking of whales and their calculations were basically the same as in F&M but with a somewhat more rigorous approach. Their results clearly showed that humpback whale songs might be effective as a sonar signal if the receiver was a towed array but would be ineffective if the singer was the receiver.

III. USE OF THE GREEN FUNCTION

F&M argued that the song "signal" from a whale at range x_d will be different from the echo from a target at $x_d/2$ by considering the equation

$$G(f, x_s, x_t)^2 = G(f, x_d, x_s) \qquad (3)$$

where G is the Green's function for the propagation geometry, the Green's function on the left is for an echo from a target at x_t, and on the right for a direct wave from a distant source at x_d. Since this equation has no solution (x_t, x_d) valid in any finite band of frequencies, echoes from a target will not be the same as the direct signal from another whale. This conclusion is rather self evident if we assume that the propagation paths for an echo and a direct signal are different. Unfortunately, F&M concluded "Thus, to an experienced listener such as a humpback whale, echoes can always be distinguished from the songs of distant singers." This statement is **totally speculative** and amounts to technical hand waving without any supportive data but only a reliance on the "superb" hearing capabilities of humpback whales. We have little to no knowledge of how well baleen whales can hear and their auditory system may in fact not be "superb."

More importantly, the Green's function is applicable to a specific environment and propagation situation in which the depths of the transmitter and receiver, along with the bottom depth and type and propagation range are known. Humpback whales are typically on the move almost continuously and so would encounter continually changing environments and, therefore, the Green's function for both a one-way or two-way travel must be continually changing. Within Hawaii alone, singers may be in deep or shallow water, over mud, coral, sand, or basalt, and may experience a variety of propagation conditions depending on bathymetry, wind and wave action. Furthermore, there are many "breeding grounds" in which singing is reported not only dispersed within the Hawaiian Islands, but also in other locations in the North Pacific, North Atlantic, South Pacific, South Atlantic, and Indian Oceans (Helweg *et al.* [19], Helweg *et al.* [20], Payne [21]). Singing also is observed along presumed migration routes in the open ocean (Clapham and Matilla [24], Norris *et al.* [25]). The bathymetry, bottom types, and propagation conditions in each of these sites may vary substantially. How a singer could distinguish an echo from direct signals from several other singers is beyond our comprehension.

IV. CHARACTERISTIC OF HUMPBACK WHALE SONGS

F&M drew heavily upon unpublished descriptive analysis of humpback song by Mercado [22]. However, we believe they tailored their evidence, retaining components that support their sonar model, discarding those that did not fit. For example, the song sample provided in F&M's paper [1 , Fig. 2] illustrates F&M's arguments, but is not at all reflective of the full range of sound types in a typical song sequence. For example, a sample phrase recorded in Tongan waters shown in Fig. 2 of our paper, contains four song units, each with very different spectral and temporal qualities. Five other phrases were observed that year, some containing less diversity and others more. This example illustrate the possible over- or mis-interpretation of sound function based on limited sampling.

F&M stated that "song is a regular sequence of sound separated by silent intervals of roughly similar duration." Song is a regular sequence of sounds, but the sound units may vary from milliseconds to tens of seconds in duration, and the silent intervals also vary substantially [5], [6], [18]–[20]. F&M's paper [1, Fig. 3] in no way illustrates that a "notable feature of song is its monotony." Payne's [21] reference to the humpback whale song monotony lies in repetition of song theme sequences over the course of hours. F&M's paper [1 , Fig. 3] provides only a snapshot of repetitions within a theme. Moreover, the song unit sequence presented in F&M's paper [1 Fig. 3] does not appear to be typical, but rather appears to be an example of atypical or "aberrant" song sometimes observed in winter waters (Payne [21]). Description of "ratcheting" is inaccurate. When ratchet-like sounds are observed,

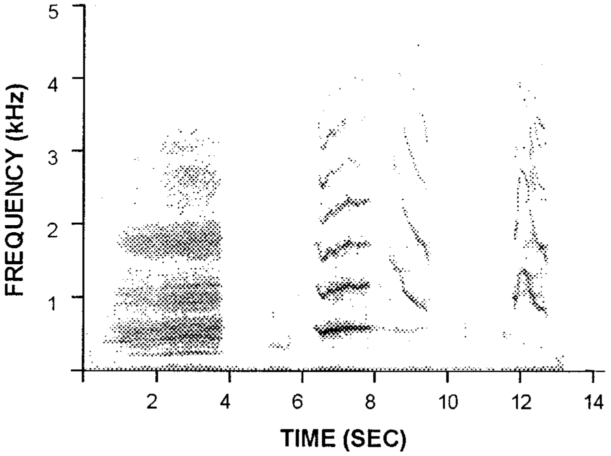

Fig. 2. Spectrogram of a song phrase from Tonga recorded in 1996. Note the diversity in the four song units (Courtesy of the South Pacific Humpback Whale Project).

they tend to occur during surfacing. However, not all surfacings are accompanied by ratcheting, and not all singers rise to breathe at the same phrase location in their song (Payne [21], Helweg *et al.* [19], [20]). F&M then assert that spectral artifacts introduced by sliding spectrogram windows confounded earlier analysis of the acoustic structure of song. However, the details of such artifacts and their effects on marine mammal sounds have been clearly described by Watkins [23] in 1967, well before the first analysis of humpback whale songs. Early researchers would have been well aware of this publication. The important point is that the filter bandwidth or FFT resolution bin used in any analysis must be specified, since this is what determines the appearance of the sonagram. F&M fail to do this. Amplitude modulated sounds appear pulsed or as spectral lines depending on the filter bandwidth, but tonal sounds will always appear tonal. Inspection of whale song literature does not reveal any problems in the distinction between tonal and pulsed sounds as claimed by F&M.

V. Humpback Behavior

During the 1997 humpback whale season in Hawaii, Darling [37] spent 38 days specifically observing the behavior of singing humpback whales. Besides recording the sounds produced, he genetically and with photo ID sexed conspecifics who joined singers. From 82 encounters with singers, Darling was able to audio-record, photo-identify, monitor and document 42 incidents of interaction between singers and conspecifics. His account of the behavior of singers while and after cessation of singing do not support the sonar model of songs. In 32 instances the singer was joined by a lone adult. In five instances, the singer stopped singing and joined a group, either a cow-calf pair with escort or a larger competitive group. In five other instances, the singer stopped singing and joined a nearby group. Most of the joiners were adult male humpback whales. Darling also observed instances in which an escort swimming with a cow-calf pair was singing. The assertion of F&M that singers can localize females using their songs and simply join up with a female that may be several km away was never observed by Darling. The fact that singers are regularly joined by other adult males, usually resulting in the cessation of the song and brief interaction seem to strengthen the hypothesis that songs are used for a male–male communication or display function.

Other observations of humpback whale behavior in the waters of west Maui are consistent with the observations of Darling [37] and not at all consistent with a sonar function for songs. Field researchers have often observed pods of humpback whales containing female whales swim closer than 1 km pass singing whales without any observable response by the singers (personal communications from A. Craig and A. Pack). If a singer is using songs to localize female whales, one might expect the singer to swim toward the female whales as they swim past him. However, this is not the case. Although no quantitative data on the number of such encounters have been collected, these observations are nevertheless real and important in considering the sonar hypothesis.

F&M also appear to have accepted oversimplified depictions of "the singing whale" and "what humpback whales do" as accurate for all humpbacks in all regions. F&M state "females are often accompanied by a calf of that year or of a previous year and one or more male escorts." The assumption that escorts are male is generally but not always true (Clapham and Matilla [24]). In addition, group structure changes as a function of time of day and day of year (Helweg and Herman [17]). For example in Hawaiian waters, adults (male and female) generally are alone in the morning, and pod size increases over the day. Another objectionable statement by F&M is "singing within a group of competing escorts has never been observed." This is not true; singing within a group of competing escorts has been observed (Frankel *et al.* [16], Tyack [26]). Importantly, agonistic behavior typical of lead escorts is highly energetic which may preclude singing. Thus, assuming that the singer has somehow "echolocated" a female and then "doesn't have to use its sonar" while competing is an unsupported assertion.

F&M provided a "typical interaction" in [1 , Fig. 4] of their paper stating that "a solitary whale sings for about 40 min, is silent for ten minutes, then sings again for about 40 min." This describes that behavior they have illustrated in [1 , Fig. 4], but does not describe typical time structure of singing, which usually continues without pause for many hours (Payne [21]). F&M then conclude their behavioral scenario by stating that "on the breeding grounds . . . the role of singing has been unclear, as males do not sing when they are with females and females generally ignore or avoid singers." They also pose the question "but then why do males hardly ever sing to nearby females?" Again, this portrays a limited concept of social interaction. They have stated correctly that songs can propagate over dozens of kilometers. Thus, males may sing to females, although perhaps not within a body length or so. Although females do not ordinarily approach and affiliate with *singers*, they do occasionally approach singers (Medrano *et al.*[27], Darling [37]). F&M have no evidence that females ignore or avoid singers whose *songs* they are hearing. Finally, F&M stated that "escorts almost never sing," when in fact, it is not uncommon at all to find singing escorts (Darling [37]). Two of the authors of this paper have in fact observed at different times, an escort singing. Three out of three other humpback whale researchers we have interviewed also have observed escort singing. We believe that the presence of singing escorts seriously compromises and even nullifies the sonar model of F&M. If a male humpback whale uses its song as a sonar to locate females, then why would a male escorting a female need to be singing at all?

VI. Evolutionary Aspect

If one were to believe the scenario described by F&M, one might be inclined to accept their sonar model of humpback whale song. However, their behavioral and acoustical scenario is oversimplified and at times simply wrong, resulting in little evolutionary parsimony. For example, they assert "song is of fixed structure." This is wrong. Song structure is plastic, changing at variable rate within each singing season (Payne and Payne [6], Payne [21]). Moreover, song changes completely within about five years, such that songs recorded in the same location about five years apart will not have any song units in common (Payne and Payne [6]). Humpback whales have been in existence as a species for at least 20 million years (Ketten [27]). If song is a mechanism for males to find females, and singers who fail to successfully echolocate females fail to mate, then a strong evolutionary constraint would be placed on plasticity in sonar signal structure. Furthermore, if song were used for sonar, one would expect that the process of natural selection would result in convergence to an optimal signal. Although the sonar waveforms used by bats and dolphins are diverse, the waveforms used by each species tend to be relatively stereotypical and may indeed be used to identify the species (Au [28], Busnel and Fish [29], Nachtigall and Moore [30] Thomas *et al.* [31]). Therefore, it seems F&M's basic sonar model is inaccurate—evolution will favor a stable signal if mating success depends on successful echo detection and interpretation.

F&M continue to speculate, stating "Immature males may learn to echolocate by affiliating with mature or immature male singers." Once again, this is not a plausible evolutionary scenario. What specifically is the immature male learning from another mature or immature male? Moreover, there is no evidence of pedagogy in humpback whales, in particular in male humpback whales, not to mention any other non-human species (Boyd and Richerson [32], Galef [33]). More importantly, because song is plastic and changes between seasons, shouldn't we consider every singer to be continuously "learning to echolocate"? Then, taking this argument to its logical end, how could a male that uses a continuously inefficient sonar system out compete (in both proximal and evolutionary terms) a male that uses a reliable stereotypical sonar system? Based on the scenario described in [1, p.9], our understanding is that F&M are developing a model in which male humpback whales produce complex signals then use energy detection of "female echoes" with sets of matched filters. However, propagation and signal detection conditions can change from hour to hour as a function of location and relative position of the source and target, oceanographic conditions, plus songs change over the course of months. How do they propose that singers maintain efficient matched filters in such variable conditions? Furthermore, Au and Pawloski [38] have shown that the bottlenose dolphin, which has been shown to have an excellent sonar system, does not perform any processing that would be equivalent to match filtering. They conducted a target detection experiment in which the response bias of an echolocating dolphin was manipulated so that target detection performance as a function of the animal false alarm rate could be measured. Au and Pawloski [38] found that the dolphin required approximately 7.4 dB higher signal-to-noise ratio than an ideal receiver to achieve a particular performance level. By comparison, it would seem far fetched to think that humpback whales would be processing signals as a ideal receiver.

VII. F&M PROPOSED EXPERIMENT

F&M have proposed to test of their sonar hypothesis by having a vessel record a singer and transmit the song to a second vessel, a short distance away, that would broadcast the song back to the singer. F&M predicted that if humpback song is used as active sonar, the singer will approach the source of the simulated echo. If the whale does not respond, then the echolocation hypothesis is disproved. Despite the logistical and technical difficulties of such an experiment, its basic theoretical premise is flawed since we do not yet fully understand the function of song. However, much attention has been spent on its apparent functional similarity to bird song. The bird literature offers alternative, more parsimonious explanations for the results of this proposed experiment. Similar experiments have been conducted, collectively referred to as 'interactive playback' experiments, where the experimenter alters the playback signal in response to the subject's behavior, to better probe the system. The body of work has been summarized in Kroodsma and Miller [34] and Bradbury and Vehrencamp [35]. One of many song manipulations examined has been song-type matching, that is, when a challenging bird switches its S song type (analogous to theme in humpback song). The experiment proposed by F&M amounts to a song-matching playback. The general conclusion from all of the bird literature is that such song-type matching is a tactic used to direct an otherwise omni-directional signal at a specific receiver. It is always used in an aggressive manner. Nielsen and Vehrencamp [36] concluded that song-type matching is the most aggressive signal before the animals close with each other and prepare for physical battle. This suggests that there is the possibility that the 'approach' response predicted by F&M could actually indicate an agonistic encounter between males. This interpretation can be challenged as well, but demonstrates that the proposed experiment is flawed. Perhaps an improved design would be to have the 'playback' vessel stationed 500 m away, and use a factorial design, where the two factors are whale identity and simulated distance. Whale identity would be either the realtime playback of the singer, or playback of another singer recently recorded. This would have to be an interactive playback so that the theme transitions would be matched in the presentation of recorded whale song. The second factor would be simulated distance. By comparing unaltered song, and song that has been filtered, time-shifted, and reduced in amplitude to simulate propagation effects. In this way, one could determine if singers respond only to loud stimuli, or to weak presentation of their own song, as would be predicted by the echolocation hypothesis.

VIII. CONCLUSIONS

We believe that we have presented a sound case to refute the humpback whale sonar hypothesis of F&M. Our arguments have been centered on application of the sonar equation, humpback whale acoustics and humpback whale behavior. We also argue that the Green's function argument of F&M is not realistic and requires the unjustifiable assumption that a humpback whale would be able to tell the difference between a song emitted by other whales from echoes off other whales. Finally, it is important to understand that considerable field observations over many sessions should be under taken before constructing such a bold hypothesis as the one suggested by F&M. Armchair theorizing with limited observations of the animal's behaviors is inappropriate and inadvisable. We believe that F&M decoupled the characteristics of humpback whale songs and acoustic propagation conditions from the knowledge of humpback whale typical behavioral patterns obtained from long-term, multi-season observations. F&M chose some isolated behavioral patterns as a basis of a theory or hypothesis which does not correspond to typical humpback whale behavioral patterns.

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Errata

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Since publication of the paper[1] , the author has discovered a number of misprints and errors in the analytical results. The following is a list of corrections.

1) In (1a), (1c), (1e), (2a), (2b) , (2c), (2e), and Fig. 1 including the caption, delete the subscript stars (*) on the various symbols, and also in the text, pp. 264, 265.
2) In the italic text, p.268, approximately half-way down the first column, “hierarch” should be “hierarchy”. In the third line above Section V, “highest” should be “higher order”. In the last line of the first column, p.282, delete the last five “f”s. In the second column text one line below (A19), add “from” after “determined”.
3) In (28), $\langle dN_1^{(k)^*}\rangle$ etc., should be $\langle dN^2\rangle = \langle dN_1\rangle \int \delta(dN_2 - \delta N_1)dN_2 = \langle dN_1\rangle$. In (37b), and (39b) replace $L^{(k)}$ by $\mathcal{L}^{(k)}$ and add subscript ℓ to $\mathbf{Z}^{(k)}$ in the exponent of the integrand. In (50a), $\exp[\mathrm{irEcos}(\psi - \phi)]$ is customarily wriiten as $\exp[-\mathrm{irEcos}(\psi - \phi)]$, with $+ir$ in the transform pair (not indicated with (50a). In (58c), replace l_0 by $\mathcal{I}_0$ in the first equation. Similarly, in (61), $l > l_0$ becomes $\mathcal{I} > \mathcal{I}_0$. In (63), in $P_1(X \geq X_0|S_{in})_{\langle R\rangle_r}$, replace X, X_0 by $\mathcal{I}, \mathcal{I}_0$.
4) A factor $\sqrt{1+\beta}$ was inadvertently omitted in the numerators of (64a) and (64b) and (66a)–(66c), for w_1.
5) In (64a) replace 2 by $\sqrt{2}$ in K_β. In (66a) delete the $\sqrt{2}$ in K_β.
6) *Normalization:* Although any reasonable intensity normalization will serve, $\overline{\psi}$, rather than $\overline{\psi}_c$ is preferable in (64a)–(67b) and for $\mathcal{E}, \mathcal{E}_0, l, l_0$,cf. (57).
7) $(\beta+1)^{\frac{\beta+1}{2}}$ should be replaced by $(\beta+1)^{\frac{\beta+2}{2}}$ in (64c).

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