
Active Sonar Waveform

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JASON was tasked by the ONR to study the recent spate of whale-beaching events which have been linked to sonar exercises. The initial goal of the study was to use the current level of understanding of these events to recommend modifications of the sonar waveform as a mitigation strategy. As we learned about the subject, however, it became clear to us that this is at present an impossible task; we just do not know enough about the damage mechanism and the chain of causation for an engineering solution to the problem

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1 EXECUTIVE SUMMARY

JASON was tasked by the ONR to investigate the reported incidents of marine mammal beachings in apparent response to mid-frequency (2-6 kHz) active sonar. To this end, we received several briefings organized by Bob Gisiner of the ONR'S marine mammal program. We also arranged on our own to hear from several other scientists regarding specific aspects of this issue; these aspects included the population biology of beaked whales (including possible genetic methods to investigate this biology), beaked whale physiology, current sonar system limitations, and possible interpretations of the available pathology data from the beachings. We would like to state at the outset that the evidence of sonar causation is, in our opinion, completely convincing and that therefore there is a serious issue of how best to avoid/minimize future beaching events.

Although the original hope was that our study could identify a relatively simple modification of the sonar waveforms in current use that would mitigate this problem, we concluded that the current state of knowledge was insufficient to support such a hoped-for "quick fix". Instead, we reviewed all the evidence with an eye towards deciding upon possible scenarios underlying the beachings; we thereafter used these scenarios to suggest needed research emphases and also short-term mitigation strategies. The specific possibilities investigated are:

- a. Beaked whales were close enough to the sonars, possibly because of their deep-diving lifestyle as adapted to local bathymetry, to have suffered "expected" damage, based on damage thresholds established for other marine organisms.
- b. Beaked whales have specialized anatomy, possibly due to their deep diving, which render them especially sensitive to acoustic waves.

c. Beaked whales are especially skittish, and the loud, reverberant acoustic fields caused uncontrolled attempts to escape.

Our sense is that the strongest case can, at the moment, be made for scenario c., but that this may change as more research is done on this problem.

For each scenario, one can identify key scientific areas of uncertainty and hence decide upon the most relevant research tasks. For example, the currently favored scenario necessitates direct behavioral studies of beaked whales as well as population studies so as to identify regions where peacetime operations should be curtailed. Also, various theories as to the source of the hemorrhaging seen in the pathology studies need to be tested. On the other hand, investigating sonar waveform changes are probably not a priority. This list would change if we adopt another scenario and in fact, we propose investigating all these possibilities in parallel. A discussion of what the resultant research program looks like is given in the report.

In addition, various mitigation strategies can be adopted even in the absence of a complete understanding. For example, it is clear in retrospect that operating in a narrow strait (and in fact up the slope in the strait), thereby leaving limited "escape" paths for marine mammals, is not a safe choice. Similarly, one can imagine the development of whale-detecting sonar waveforms and "whale-herding" techniques which could reduce the probability of induced beaching. A list of these is given in the report.

Finally, some of us felt that as serious as these beachings are, they do not represent a global problem for marine mammals. There are other aspects of human activity, namely the production of increasing levels of low frequency ocean noise via shipping and oil exploration, which may have a much wider impact and hence deserve ONR attention. In this regard, we include an addendum on how one might be able to achieve reasonable levels of quieting for large merchant ships.

2 INTRODUCTION

JASON was tasked by the ONR to study the recent spate of whale-beaching events which have been linked to sonar exercises. The initial goal of the study was to use the current level of understanding of these events to recommend modifications of the sonar waveform as a mitigation strategy. As we learned about the subject, however, it became clear to us that this is at present an impossible task; we just do not know enough about the damage mechanism and the chain of causation for an engineering solution to the problem.

Instead, we stepped back and looked more generally at sonar-induced whale beaching and tried to make sense of the complex data, conflicting scenarios and systematic uncertainties which have plagued this discussion. Our fundamental assumptions are that 1) the strong kinematic connections between sonar exercises and otherwise highly unusual beaching events provides almost irrefutable evidence that there is a real problem here, 2) that better understanding of the mechanisms at work will enable a serious risk-assessment to be done in conjunction with future sonar use and will enable a serious discussion among differing parties as to the trade-off between military readiness and marine mammal protection and that 3) the US Navy, through the ONR, must take the lead in formulating the appropriate suite of research approaches to accomplish the previous point. We are mindful of the fact that there will always be a segment of the population who will distrust any findings associated with ONR funding and who will refuse to balance conflicting national needs and desires, opting instead for an absolutist approach. One can only hope that the majority of the community would appreciate working towards a scientific consensus followed by a rational discussion of policy options.

The outline of this report is as follows. First, we review the basic phenomenology of several of the more well-studied events, most notably the Bahamas event of March, 2000 and the more recent Canary Islands incident. This allows us to compile a list of known facts and a list of unknown but needed information. Afterwards, we focus on the evidence for and against three possible scenarios: the expected damage scenario, the ultrasensitive whale scenario, and the skittish whale scenario. As we will see, our best guess at the moment is that the last possibility is the most likely one, but this is only a guess at present. Afterwards, we discuss prioritized research strategies to reduce the current uncertainties and mitigation tactics for the interim period. At the end, we include an addendum on the more general issue of how human activities are leading to oceanic noise pollution and how there is no concerted effort to understand how this might adversely affect marine life nor on how one might mitigate some of this. Several of us felt that the ONR should take a more pro-active role in marine biosphere protection, not wait for crises to develop before sponsoring necessary research.

Finally, we would like to thank all our briefers for helping us understand the facts of this problem. We had one day of talks put together by Bob Gisiner at the ONR; we also talked with D. Ketten regarding autopsy findings and whale hearing in general, J. Barlow regarding beached whale population surveys, J. Hildebrand and collaborators regarding beached whale physiology and modeling thereof and D. Houser regarding mechanisms of physiological damage.

3 RECENT BEACHING EVENTS

The backdrop of the JASON study is a set of recent beaching events which have resulted in the appreciation by all concerned that sonar systems in fleet use are truly causing a problem. The two main events, at least as far as the availability of useful data is concerned, occurred March 15-16, 2000 in the Bahamas (Figure 1) and September 24, 2002 in the Canary Islands. Reactions to these events continue to reverberate in the scientific and general community, the latest round of which was connected to the very recent publication in Nature [1] that claimed evidence for gas bubbles in autopsied animals from the Canary Islands. One should keep in mind that earlier incidents certainly did occur (for example, off the coast of Greece in may 1996), and a useful historical summary has been compiled by A. D'Amico [2].

What makes these strandings so convincingly sonar-related is the close spatiotemporal proximity of known mid-frequency sonar use and these highly atypical beaching events. Whale beachings have been noted for a very long time, but the species specificity seen here is new. Specifically, a high percentage of the affected animals are beaked whales (especially two species: *Ziphius cavirostris* and *Mesoplodon densirostris*) a relatively unstudied class of marine mammals [3](see Figure 2). Some of the main sources of uncertainties concern the population distribution of these whales and their unusual physiology.

We need not repeat here all the details of these events; they are covered quite adequately in the Bahamas beaching event interim report [4] and the local government website [5] devoted to the Canary Island incident. It is worth noting that the culprit appears to be mid-frequency (kHz range) operational sonar systems, not the LFA system (- hundred of HZ), the very low frequency systems used for ATOC research (tens of HZ) or the extremely localized high

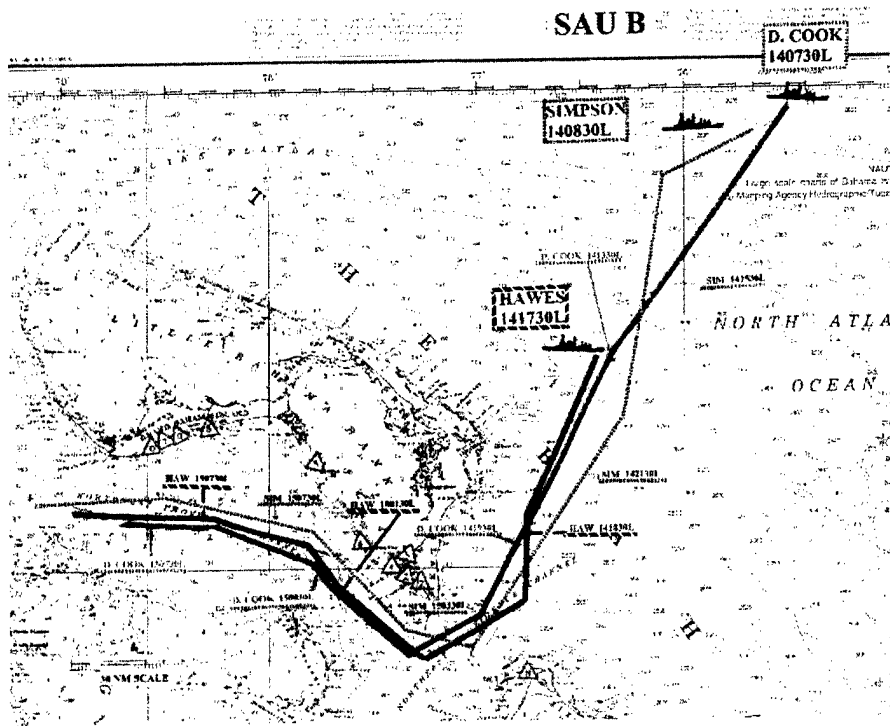
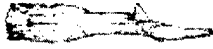
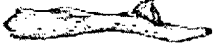
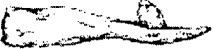


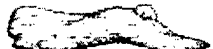








Figure 1: Tracks of the ships taking part in the Bahamas sonar exercise. Note that as the ships transit (from left to right), fleeing marine mammals would be driven from deep water into shallow regions near the islands. Beached whales are indicated by triangles.

frequency devices (20 kHz). This is not surprising, given estimates for the range of frequencies that are effectively detected by the beaked whale auditory system (see Figure 3). Given the variety of different beaching events, it is hard to argue that there is some very special confluence of acoustic events that uniquely trigger beaked whale beachings; instead the trauma, whatever its cause, seems to be a robust consequence of mid-frequency ensonification.

Let us first focus on what we know about beaked whales. These are medium-sized whales (2-12m long, around beluga whale size). Most observations of these whales have found them along the continental shelf, but limited open ocean surveys have found them as well. Their very low broaching profile and the limited time they spend at the surface have conspired to make

BEAKED WHALE REFERENCE GUIDE
Genus: *MESOPLODON*

<p><i>Mesoplodon bidens</i> Sowerby's beaked whale</p>  <p>North Atlantic Ocean</p>	<p><i>Mesoplodon bowdoini</i> Andrews' beaked whale</p>  <p>cold temperate southern hemisphere waters</p>
<p><i>Mesoplodon carlhubbsi</i> Hubbs' beaked whale</p>  <p>North Pacific Ocean</p>	<p><i>Mesoplodon densirostris</i> densebeaked whale</p>  <p>widespread, warm temperate & tropical waters</p>
<p><i>Mesoplodon europaeus</i> Gervais' beaked whale</p>  <p>Atlantic Ocean warm temperate & subtropical waters</p>	<p><i>Mesoplodon ginkgodens</i> ginkgo-toothed beaked whale</p>  <p>Indian & Pacific Oceans warm temperate & tropical waters</p>
<p><i>Mesoplodon grayi</i> Gray's beaked whale</p>  <p>cold temperate southern hemisphere waters</p>	<p><i>Mesoplodon hectori</i> Hector's beaked whale</p>  <p>cold temperate southern hemisphere waters</p>
<p><i>Mesoplodon layardii</i> straptooth whale</p>  <p>cold temperate southern hemisphere waters</p>	<p><i>Mesoplodon mirus</i> Truc's beaked whale</p>  <p>temperate North Atlantic & temperate southern Indo-Pacific</p>
<p><i>Mesoplodon peruvianus</i> lesser beaked whale</p>  <p>eastern Tropical Pacific (esp. Peru) & western South Pacific</p>	<p><i>Mesoplodon stejnegeri</i> Stejneger's beaked whale</p>  <p>cold temperate & subarctic North Pacific</p>

BEAKED WHALE REFERENCE GUIDE

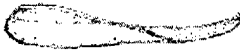


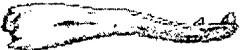
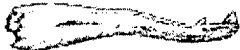
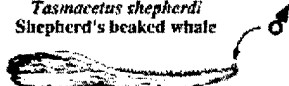

<p>Genus: <i>INDOPACETUS</i></p> <p><i>Indopacetus pacificus</i> Longman's beaked whale</p>  <p>Tropical Indo-Pacific Ocean</p>	
<p>Genus: <i>HYPEROODON</i></p> <p><i>Hyperoodon ampullatus</i> northern bottlenose whale</p>  <p>North Atlantic Ocean</p>	<p><i>Hyperoodon planifrons</i> southern bottlenose whale</p>  <p>cold southern hemisphere waters</p>
<p>Genus: <i>BERARDIUS</i></p> <p><i>Berardius arnuxii</i> ♂ Arnoux's beaked whale</p>  <p>cold southern hemisphere waters</p>	<p><i>Berardius bairdii</i> ♂ Baird's beaked whale</p>  <p>North Pacific Ocean</p>
<p>Genus: <i>TASMACETUS</i></p> <p><i>Tasmacetus shepherdi</i> Shepherd's beaked whale</p>  <p>cold temperate southern hemisphere waters, esp. New Zealand</p>	
<p>Genus: <i>ZIPHIUS</i></p> <p><i>Ziphius cavirostris</i> Cuvier's beaked whale</p>  <p>worldwide, in tropical, subtropical & temperate waters</p>	

Figure 1.1
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Figure 2: Beaked whale reference guide.

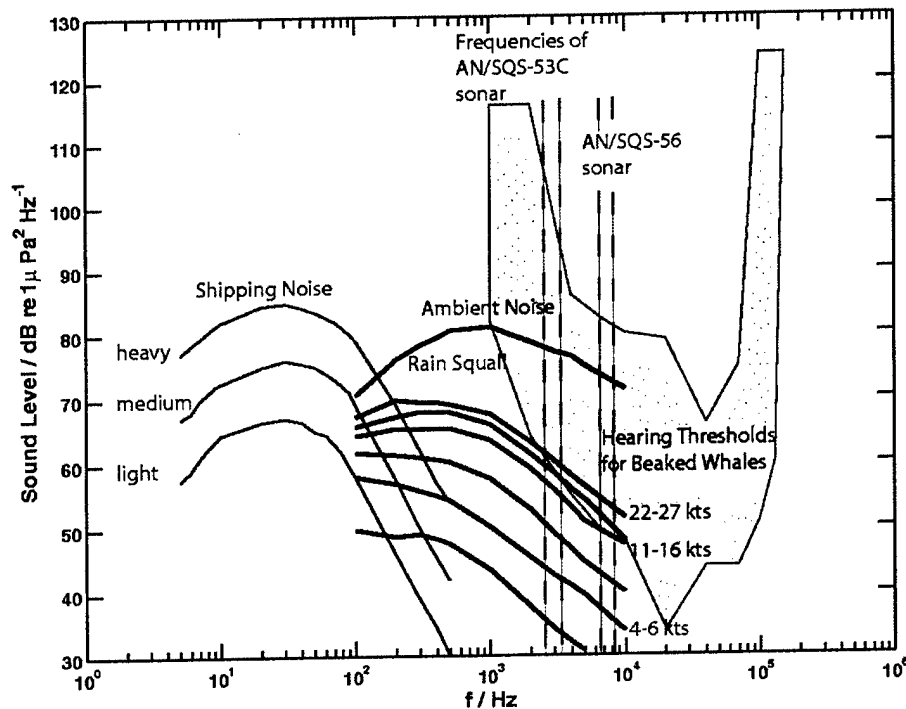


Figure 3: Hypothesized frequency dependence of beaked whale hearing threshold, as compared to typical sound levels in the ocean. Note that the sonar operating frequencies fall right within the sensitive band.

them resistant to easy surveying. A rough guess at the density is 10 per 1000 sq. km; this gives on the order of 100 in the Bahamas region, a number that is consistent with independent estimates by K. Balcomb.

Analysis of their feeding patterns [6] suggests that beaked whales are very deep divers. It has been estimated that they spend 80% or so of their time at depths. This would of course imply significant evolutionary adaptations in the gas-handling systems so as to avoid decompression sickness under normal behavioral regimens. They have a typical marine mammal auditory system (specialized jaw fats, a melon etc.) which strongly implies that they engage in echolocation, perhaps to detect prey. It has to date proven difficult to directly verify this reasonable hypothesis, with only one (unsubstantiated) claim of a recorded beaked whale signal [7]. It has also not proven possible

to date to tag these animals to directly detect the aforementioned diving behavior.

Autopsies performed on several of the beached animals reveal various types of pathologies [4,5]. There is general agreement that these pathologies are not merely a result of the beaching event per se, but represent direct evidence of some kind of trauma caused either directly or indirectly by the acoustic signal. These analyses are made difficult by our lack of experience with captive animals, of which none exist. One extremely critical issue is whether the aforementioned trauma, whatever its mechanistic origin, is serious enough to compromise the integrity of the organism; in other words, do we expect that significant numbers of whales not seen on the beach were nonetheless severely damaged and possibly wound up sinking to the bottom. We will return to this issue later.

To proceed, we have found it convenient to organize our thoughts under different scenarios. The first scenario, that the whales were in fact directly damaged by the acoustic field, can be assessed by knowledge of the source strength, propagation characteristics and existing information regarding damage thresholds. It also can be compared to the expected pathology results for acoustic trauma. We now turn to this first possibility.

4 THE UNLUCKY NAVY

One possibility is that the acoustic characteristics of the local environment together with the loudness of the source and long time period of ensoni-fication led to the exposure of beaked whales to directly damaging pressure fluctuation levels. To get started, we need a guess as to the threshold for such damage. The US Navy currently uses the notion of a temporary threshold shift (TTS) as a safety measure for underwater sound exposure (see Figure 4). In this protocol [8,9], sound levels of various kinds (impulsive, short tones

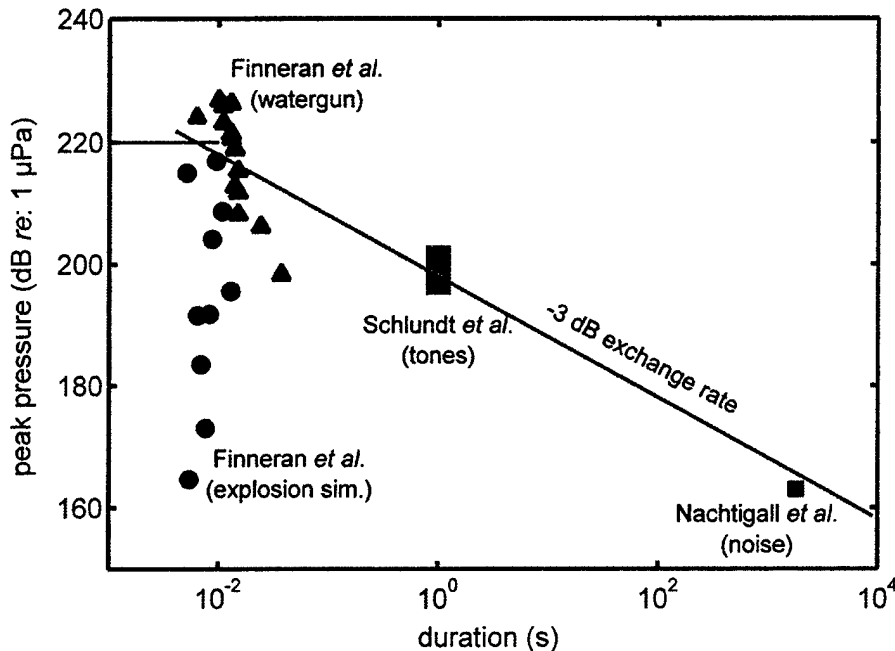


Figure 4: Temporary threshold shifts for a variety of sound types. For tones lasting for about a second, the level reported in ref. [9] is roughly 200 dB

- similar to mid-frequency sonars, broad-based noise) were presented to the marine mammal (in almost all cases, dolphins are used) and shifts in hearing threshold are determined. Note that this is a not-very-stringent lower limit on any damage threshold; TTS is a behavioral response that does not result

in any lasting damage. Data to date suggests that this level is roughly 200 dB, suggesting a damage threshold of perhaps 210 dB or so.

Given a source level of 235dB for the AN/SQS53 sonar (slightly higher for the AN/SQS56), it is easy to see that the animals would have to be very close to the source to see direct-damage levels. For spherical spreading, we are talking of at most 100 meters or so. This idea can be formalized a bit better by the concept introduced in the Bahamas stranding report of ping-seconds at a particular pressure level as a function of spatial position. The number of ping-seconds is roughly the total amount of time during the beaching incident in which a particular location was above the pre-set threshold. Figures 5a and 5b (at 160dB and 180dB respectively) showing ping-seconds for near-surface depths, show that the area coverage is minimal at levels far below 200 dB. Folding this in with the estimates of 100 beaked whales in the entire vicinity and the fact that the highest peaks are always near the surface in this ducted propagation environment, whereas the whales spend a significant proportion of time at depth, makes it extremely unlikely that 10-20 whales could have seen supra-threshold levels.

This analysis is consistent with the pathology findings. While there is clear evidence of bleeding various sorts (see Figure 6), experts tell us that the damage is not what would have been expected for direct acoustic trauma. The above is true for both the Bahamas event and the Canary Islands one. Finally, there is one other piece of circumstantial evidence against this scenario. In the Greek stranding event (see Figure 7), the first ping was reported at 5:25 and the first beaching at 9:30, roughly 25 km away. It seems to us unlikely that an animal that has received a severely traumatic blow would then be able to swim 4 hr @ 6 kts average, in order to satisfy the kinematics constraints. It is much more plausible that the whale started out much closer to its final beaching location, and hence could not have been exposed to levels greater than 200 dB. A similar conclusion can be reached for a recent

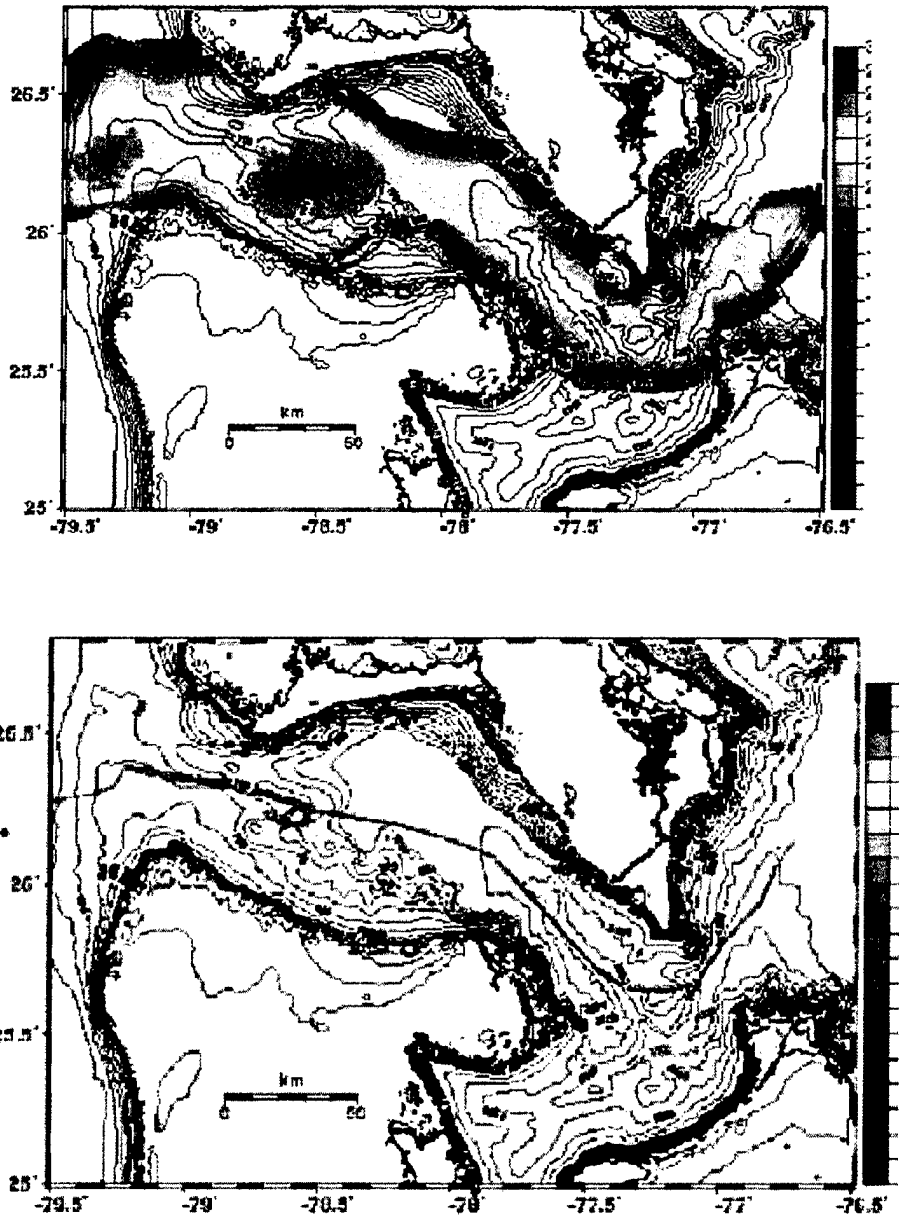


Figure 5: Ping-second representation of the sound level durations versus position in the Bahamas channel. The color code indicates the amount of time that a given spot was exposed to a sound level above a certain fixed threshold. For (a), the threshold is 160dB; for (b) 180 dB - taken from [4].



Figure 6: Evidence of bleeding into but apparently not directly in the ears of one of the beached animals - from [4].

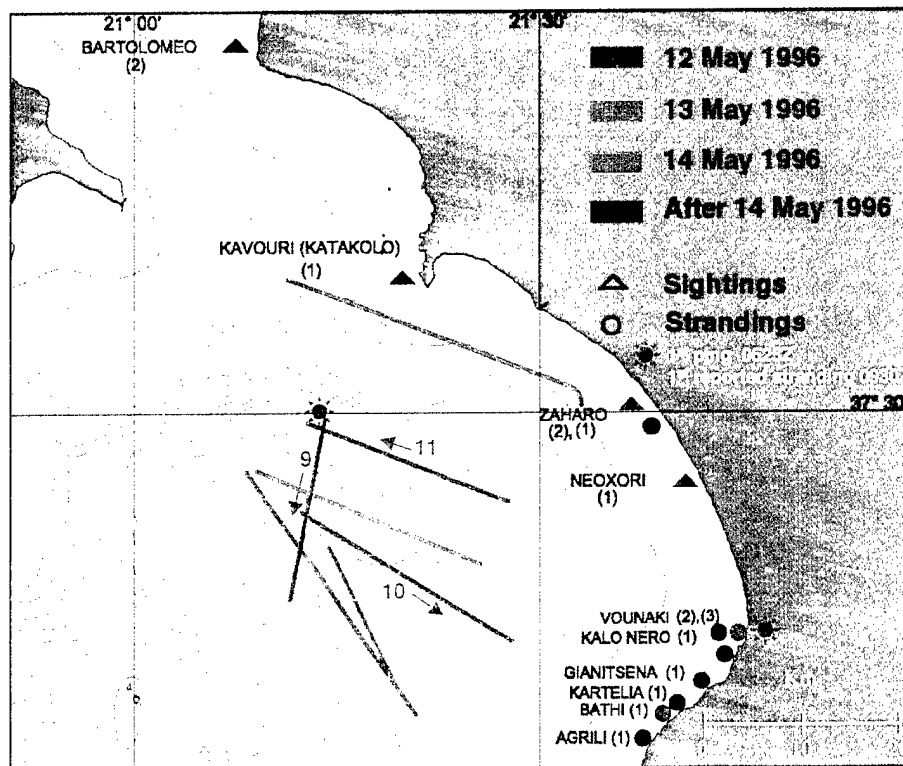


Figure 7: Reconstruction of a stranding event off the coast of Greece in 1996.

(fall 2002) beaching of two whales in the Gulf of California, if one assumes a causal connection to a seismic surveying ship roughly 100 km away.

One issue worth noting is the possibility of detecting the whales via the ship's sonar. If indeed whales must be within several hundred meters of the sonar to be injured, it seemed to us likely that their echos could have been detected. An analysis of this is presented in the Appendix. Upon further investigation, it seems that there is a problem with the sonar design if it is used for this purpose. Sonars have a blanking range, corresponding to turning off the receiver during the transmit phase. Given the extreme proximity of the marine mammal target, their echo would have most likely been blanked out. This could be remedied by having at least some pings be of extremely short duration. If this cannot be accomplished by the existing system, one might consider deploying a specific "whale-finding" sensor. We re-visit this issue at the end when we discuss short-term mitigation strategies.

All told, there is little evidence in support of this scenario. The only way it makes sense is if beaked whales (of a variety of species) travel together in large pods, if somehow they were so restricted by the bathymetry as to be directly in the path of the ships during the training event and if direct trauma showed up only in a subtle manner during autopsies. To be absolutely sure, however, one would need more detailed information regarding beaked whale habitats and possibly a careful retrospective analysis of how often sonars are deployed near coastlines and beachings are not observed. Also, it would obviously be helpful if measurements like TTS could be made directly on the relevant species, not inferred based on dolphin findings.

5 THE ULTRASENSITIVE WHALE

One of the problems of the damage scenario is the lack of species specificity. Since this is such an important part of the information at hand, it needs to be directly addressed. The second hypothesized scenario postulates that beaked whales are especially sensitive to pressure levels, suffering damage due either to some direct interaction with the acoustic field (perhaps because of some resonance) or perhaps indirectly via an acoustically-induced modification of their natural behavior.

To get a handle on this possibility, we reversed the logic of the previous section and calculated the level at which these as yet undetermined acoustic effects would have had to be operative so as to be consistent with simple kinematic and population assumptions. This calculation is presented in the Appendix and results in the need for finding sensitivity at roughly the 170 db level. As far as we have determined, there are only two hypotheses as to the source of this ultrasensitivity; an acoustic resonance associated with some beaked-whale specific anatomical structure or an acoustic-mediated growth in nitrogen bubbles in supersaturated blood.

A meeting was held under the auspices of the National Marine Fisheries Service [11] to evaluate the possible role of acoustic resonance in the Bahamas beaching event. The basic idea is that these are indeed specialized structures, known as the pterygoid sinuses (see Figure 8) which remain air-filled at depth. Given their initial size and the expected shrinkage under pressure, it seems superficially possible to find a depth at which there would be a resonant response. This idea was promulgated by several websites created by the environmentalist community. But further investigation reveals that this approach is hard to fathom. Standard assumptions regarding air bubbles suggest that $f_{res} \propto \sqrt{P_0}/R$ and volume $\sim R^3 \propto 1/P_0$. This gives a resonant frequency depth dependence of $f_{res} \propto d^{5/6}$ and in fact predicts kHz

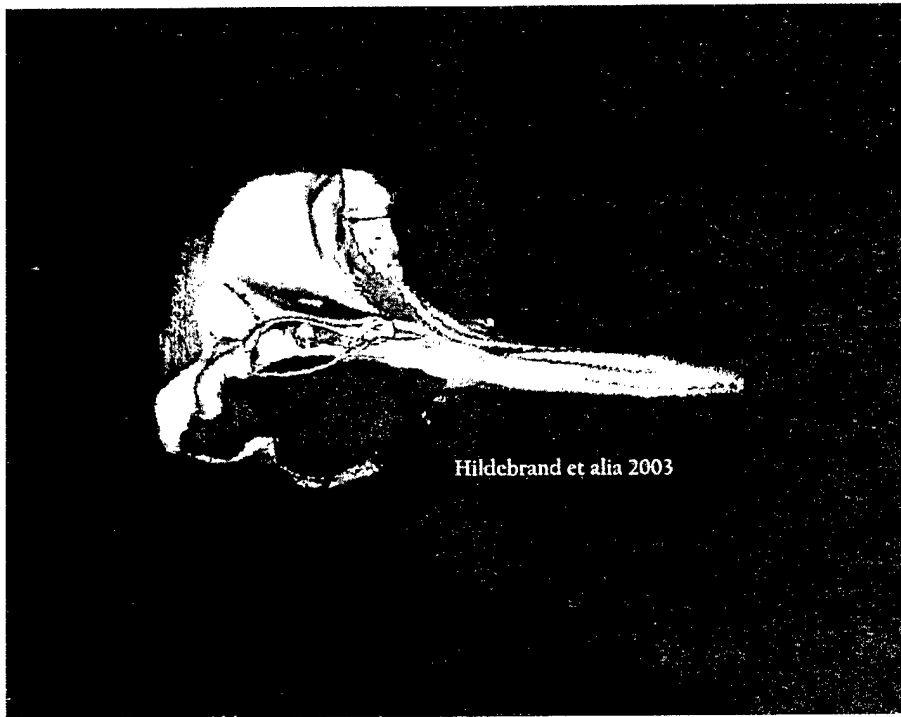


Figure 8: Tomographic reconstruction of the head of a Ziphius beaked whale specimen. The bottom structures are the specialized sinuses (from J Hildebrand and T. Cranford)

range resonances at 1 km depths. But the sound mostly propagates in the surface duct and almost never reaches significant amplitudes (160-170 db) at this depth. There is also the Q-value problem. A reasonable guess for Q is perhaps 5 or less, given data on, for example, human diver lung resonances at 40HZ and similar findings for dolphins [12]. At this value, the actual tissue displacement would only be amplified by a small factor from the basic air displacement in the excitation field and would presumably cause no damage. On the other hand, a large Q would mean that resonance would be extremely rare kinematically and we would be back to the problem with the previous scenario.

Of course the above arguments are merely heuristic and it pays to do a more serious calculation. We support the effort of J. Hildebrand and T.

Cranford to use tomographical reconstruction of beaked whale anatomy to construct a finite-element acoustical response model. This model should be useful for a variety of purposes (such as understanding the type of signals that can be transmitted by beaked whales) even if, as we suspect, the resonance idea falters.

A much more interesting set of ideas revolve around the role of acoustics in somehow setting off decompression disease associated with nitrogen bubble growth. Experiments on dolphins have shown [13] that lung collapse takes place at a depth of 70m; the method whereby they are protected from decompression hazards of shallow dives is unknown. Roughly, the problem is the growth of air bubbles due to the nitrogen supersaturation; the above results for dolphins gives a nitrogen pressure of 3atm whereas for seals it was 2-5 atm.

The equivalent results for beaked whales are, of course, unknown. Houser et al. [14] have claimed that slow deep diving whales would accumulate nitrogen to a greater extent than shallow diving marine mammals, but this as yet is highly speculative. If these measurements/speculations are correct, it rules out possible adaptive strategies such as using body fat as a nitrogen buffer.

This degree of supersaturation requires that there be some active method for preventing air bubble growth. The fact that humans vary greatly in the susceptibility to decompression disease means that there are physiological strategies for preventing bubble growth and that these could therefore be evolutionarily selected in deep-diving mammals. What would be needed is some way of trapping nascent nuclei followed by stabilization by some sort of impermeable shell.

How might interaction with an acoustic field affect this issue? One idea that we think is not relevant is the rectified diffusion concept. Crum and Mao [15] have pointed out that a bubble near its marginal stability

point can be sensitive to comparatively modest levels of sound. This is not surprising, because the equilibrium is unstable. Hence, a small degree of rectified diffusion (the idea that more gas will diffuse in when the bubble has expanded than will diffuse out when the bubble has contracted, in a typical oscillation cycle induced by the pressure field) can drive the bubble into a regime of rapid growth. In the presence of significant supersaturation (say 200%), Crum and Mao found that there would be rapid growth even without acoustic stimulation and that sound fields would have little effect until the very high level of 210 dB.

Of course it is possible that the sound field disrupts the needed suppression mechanism. It is hard to see how low levels of sound could disrupt a film robust enough to prevent free growth (or to prevent dissolving of small subcritical bubbles, if the containment strategy is to trap gas in very small nongrowing bubbles). There is nonetheless some evidence that this does occur, but the data are from rats and at much higher frequencies [16]. The upshot of all this is that we have not found a fully coherent story as to how this could work, but our degree of knowledge is so limited as to prevent us from concluding that it would be impossible.

The decompression disease scenario gained popularity when a recent paper claimed that beached whales from the Canary Islands incident showed evidence of fat emboli being widespread in vital organs. They hypothesized that these resulted from the expansion of pre-existing gas nuclei in nitrogen super-saturated tissues, i.e. normal decompression disease. To counter the argument that marine mammals do not suffer from decompression disease, they also showed that there is a small but non-zero percentage of beached marine mammals (not necessarily related in any way to sonar) which do have visible gas bubbles in their tissues (see Figure 9). We are not competent to offer an independent scientific assessment of these controversial claims.

The decompression disease idea does not necessarily require that the

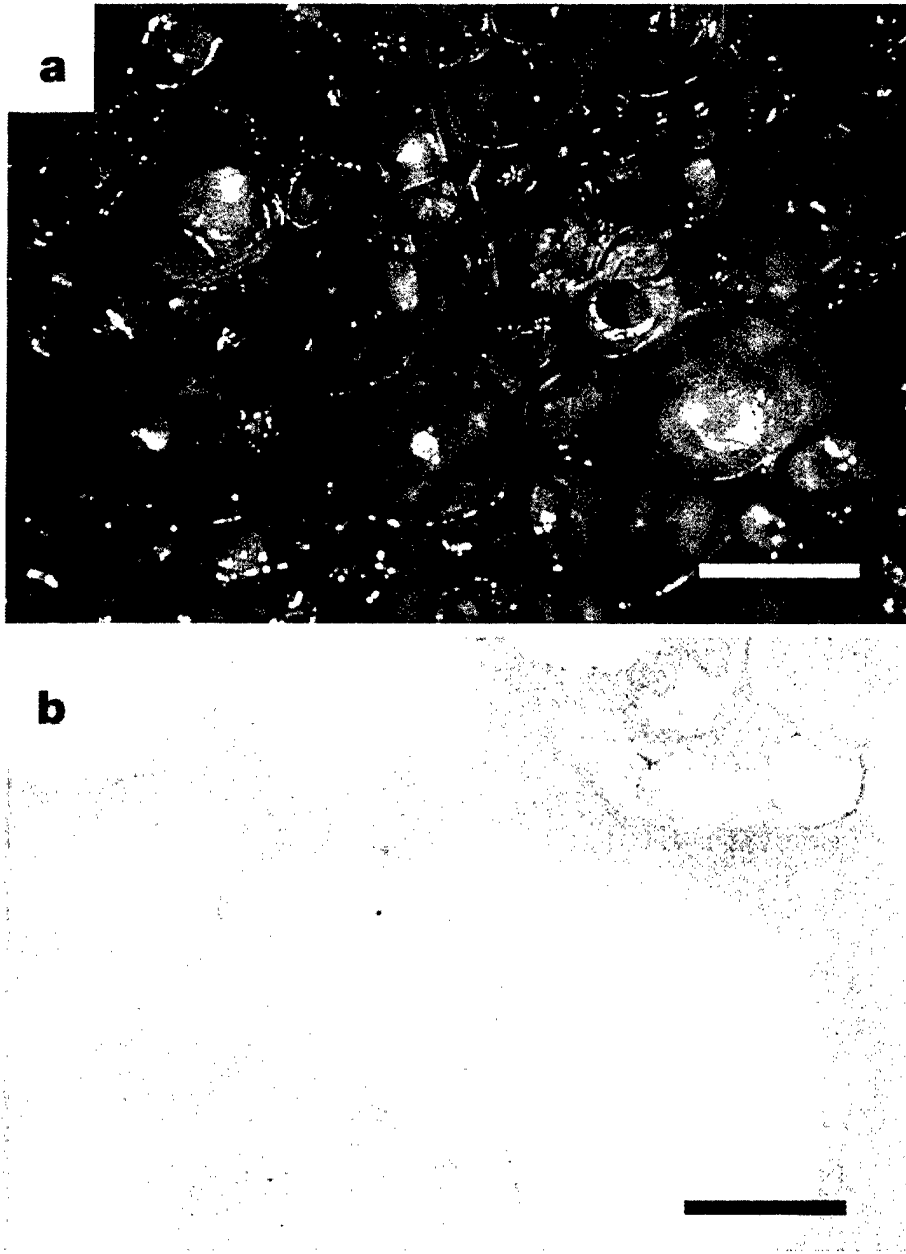


Figure 9: Gas-filled cavities in the liver of a stranded dolphin. a) surface of the liver, showing lesions. b) micrographs showing gas-bubble-induced cavities. Scale bar is 750 μm - from [1].

acoustic field be directly responsible for bubble growth. An alternate possibility is that the normal diving rhythm of the whales was disturbed by the sonar and this somehow led to rapid decompression (for example), thereby causing the disease. Given that we don't know the normal diving pattern, this idea is at the moment untestable.

The most critical prediction of the ultrasensitive whale scenario is that by the time the whales hit the beach, they have suffered extensive trauma. This means that there may have been many other whales that suffered extensive trauma that for one reason or another were never detected and that the measured effects in terms of numbers of animals may be a severe underestimate. Thus, one sees claims that almost all the beaked whales (approx. 100, according to our rough estimate) in the Bahamas area were eliminated, not just the fifteen or so that were beached. This could be disproven if we had been prescient enough to know the population structure prior to the sonar event and could now go back and re-measure.

In summary, the ultrasensitive whale approach is a compelling story in search of mechanistic support. It is supported by some scientists' interpretation of the pathology data and by some of the known specializations of beaked whale physiology and behavior. If true, it would have the most serious implications for future use of these (as well as other) sonar systems.

6 THE SKITTISH WHALE

The last scenario postulates a psychological, as opposed to physiological, response as being the primary effect of the ensonification. Basically, the whales panic as a result of the deployed sonar - possibly because it reminds them of their natural prey, the killer whale - and try to escape. Of course the loudness of the sound and the speed of the boats prevents them from outrunning the signal, given their very sensitive detection in the kHz range; even at depth they would be able to hear the signal for many km's. Given the local geometry (especially in the Bahamas where they were being driven up a narrow channel), many of them wind up hitting the beach.

This approach can be supported in part by several pieces of anecdotal evidence. We heard that some of the whales were sufficiently agitated to wind up a significant distance inland, in one case in a mangrove swamp. More seriously, a study of ship-whale collisions in the Mediterranean Sea found a conspicuous absence of beaked whales [17]. Of course this might just represent the effects of population size and percentage of time near the surface, but it also might be an indication that these whales are extremely averse to sound. This might also be consistent with the rarity of their own sound emissions, and with the additional anecdotal information that the addition of low intensity pingers to fishing nets totally eliminated any beaked-whale bycatch.

In this regard, information regarding human diver response to LFA frequency sonars is interesting. No direct damage was detected on humans exposed to modest sound levels, say 160 dB. However, the SURTASS website [18] documents that several divers exhibited "severe aversion" at 148 dB, leading to the operational threshold being set at 145 dB.

Of course the most significant problem with this scenario is the presence of pathological features in the beached whales that seemed to have occurred

prior to the actual beaching; these include some degree of bleeding and some damage to internal organs. One needs to find an explanation for this damage even if it turns out that the primary effect was psychological. One interesting direction emerges from the fact that cetaceans are missing various clotting factors [4], presumably as an adaptation to diving; if the same is true for beaked whales, it might suggest that they bleed easily and slight hemorrhaging is to be expected. In fact, JASON was told that there are humans with similarly deficient clotting factors, and these people hemorrhage easily under psychological stress, usually without serious permanent damage.

The primary prediction of this scenario is that the beaching is the real problem. That is, sonar tests done in open waters might cause the animal to panic, but they would then escape the sound with only minor damage. Similarly, beaked whale refloated after beaching should have just as much chance to survive as would a beaked whale beached due to any other circumstance.

7 RECOMMENDATIONS

Based on our analysis as explained above, we can make a series of recommendations, both for needed research and for short-term mitigation strategies. The research suggestions will not in any way be surprising or controversial, but we feel it is worth collecting them together. The mitigation strategy will require a recognition that the beaching problem is sufficiently important so as to necessitate changes in what would otherwise be considered optimal.

7.1 Research

As we have seen throughout, full assessments of the likelihoods of various scenarios is impossible given the current lack of knowledge regarding beaked whales. The research needed to remedy this situation relates to population biology, to whale physiology and to whale behavior (both under normal conditions and under ensonification).

Direct surveying of beaked whales is necessary but will probably prove insufficient for establishing their overall population structure. One of the ideas that seems worth considering is to use modern genetic techniques to form simple population site estimates. Some specific details as to one of the methods by which this can be carried out is discussed in a later part of this section. We should mention in this regard the recent completion [19] of a molecular phylogenetics study of beaked whales, which should be viewed as a useful start in this direction.

Our knowledge of beaked-whale physiology is extremely primitive. Thus, multiple and parallel efforts to study beaked whales deserve full support. We have already mentioned the idea of reconstructing the whale head as far as its acoustical properties are concerned. Also worthy of note is the continuing but as yet unsuccessful efforts to tag these whales to obtain some in situ

data. Ideally, one would like to redo the tissue supersaturation measurements on beaked whales (that were done initially on dolphins and seals) and one would like to analyze the clotting properties of their blood. Perhaps more effort should be made to find conditions under which one of these animals could live in captivity.

We are very much in favor of an idea we heard about called the "Stranded Whale Action Team" (SWAT). The concept is that at least some of the stranded animals are alive and can be refloated from the beach. If a properly-equipped team can reach these whales, they could perform some direct acoustic measurements, could attach a tag and possibly even a more sophisticated device to monitor nitrogen levels in the blood. Assuming a successful refloating, the tag would tell us whether the whale survives or not - as already discovered, this is one of the crucial unresolved issues. Of course, the logistics of having teams in place to affect such a rapid course of action are difficult; maybe someone on board one of the ships in a potentially "dangerous" sonar exercise could be trained to accomplish these tasks.

7.2 Mitigation

There is no hoped-for magic harpoon - we just do not understand the mechanisms well enough to predict whether or not simple changes in the sonar characteristics would help solve the problem (or make it worse). Nonetheless, it is clear in retrospect that the particular way the sonar exercises were carried out in the Bahamas was not optimal from the whale-safe perspective. Given the clear danger that adverse publicity can have on naval operating leeway (not to mention the fuzzier issue of trying not to unnecessarily damage the biosphere), it seems obvious to us that certain changes should be made. Specifically we suggest:

- a. Turning on the sonar systems adiabatically, such that nearby marine

mammals can escape and not be exposed to a full blast of sound.

- b. Occasionally, operate the sonar with short blanking times to check for nearby echoes that may signify marine mammals.
- c. Whenever possible, do exercises when transiting away from coastlines, while going downslope, and with there being escape routes for marine mammals. Perhaps it makes sense to do a whale-damage probability assessment before planning an exercise and thereby avoid any obviously problematic locations and plans.
- d. Explore the idea of whale-herding prior to exercises. That is, sweep the area with low-powered sonars aimed so as to drive any whales within hearing distance away from the exercise location. It will of course be claimed that this induces an air of artificiality to the training exercises, as one would never in practice do this in a real combat situation. The only response to this is the obvious rejoinder that one cannot optimize for two distinct factors (being whale-safe and conducting useful training) without some compromises in both directions.
- e. Explore the idea of using more complex waveforms which retain Doppler sensitivity but have a lower peak power (chirps or M-sequences, perhaps). Our intuition is that peak power might matter more than overall integrated energy, but this is merely an educated guess.

7.3 Estimating Whale Populations

As described elsewhere in this report, population density (whales per square kilometer) is an important input for estimating the lethal range of sonars from the observed numbers of beached whales. Unfortunately *Ziphius cavirostris*, the species that strands most often in association with sonars, is difficult to tally by direct count, as the animals spend most of their time at

depth and well away from shore. Estimates for this species range from 1-10 per 1000 sq. km, but there is great uncertainty regarding these numbers and especially the habitat distribution.

It is possible, however, to estimate the size of a breeding population from the genetic sequences of a small number of individuals, even a single individual. Genetic methods may not reveal local concentrations in population density, such as might be due to variations in food supply and climate, and they are not sensitive to rapid changes in population such as might have been caused by human activities (though probably not by sonar use alone). Nevertheless, genetic population estimates could be useful as a check on more direct censuses. Genetic measures could be useful in other ways as well. By measuring the consanguinity among whales stranding in a given incident, one might discover the number of pods involved. This might reveal whether the local whale population was uniformly affected, or whether a single unlucky pod found itself too close to the track of a sonar-bearing ship.

The basic idea underlying genetic estimates of population size is that the level of diversity between two individuals, or between the two copies of the genome in a single individual, results from competition between mutation (which increases diversity) and genetic drift (which reduces it). The rate of drift varies inversely as the population size, while mutation is independent of it. The elementary mathematics of these processes are described in the monograph by Crow and Kimura [20]; our discussion follows the notation of [21].

7.3.1 Genetic drift

(U) Consider first the effect of drift alone, without mutation. Suppose that the t^{th} generation of the population has $N(t)$ individuals, who mate at random to produce $N(t+1)$ progeny. Let $n_a(t)$ be the number of copies of a given allele a in the t^{th} generation. Here "allele" may represent one

of several versions of a gene that is expressed in the phenotype (*e.g.* blood type). On the other hand, if genetic sequence is available, better statistics can be obtained by working with nucleotides occurring at specific sites on the sequence. In the latter case, there are only four possible alleles per site: $a \in \{A, C, T, G\}$. Or one may work with oligotides consisting of (say) 20 consecutive sites, in which case the number of possible alleles would be 4^{20} . In the general case, let this number be $K \geq 2$. The abundance of allele a is $x_a(t) = n_a(t)/2N(t)$, where the factor of 2 occurs in the denominator because there are two copies of the site in each individual of a diploid species.

(U) A crucial assumption is that the alleles are selectively neutral, that is, that the choice of allele does not affect the fitness of the organism. There are statistical tests for neutrality, though we will not discuss them. It may be possible to determine directly whether a given locus belongs to the “junk” DNA that neither codes for proteins nor controls the expression of genes that do. Junk DNA is selectively neutral.

(U) With these assumptions, the probability of $n_a(t+1) \equiv n'_a$ copies of the allele in the next generation is simply binomial:

$$\text{Prob}[n'_a] = \binom{2N'_a}{n'_a} (x_a)^{n'_a} (1-x_a)^{2N'_a-n'_a}.$$

For brevity, primed symbols distinguish quantities in the $(t+1)^{\text{st}}$ generation from those in the t^{th} . From standard results for binomial trials, one knows that the expectation and variance of n'_a are $2N'_a x_a$ and $2N'_a x_a(1-x_a)$, respectively, and the corresponding moments of x'_a are therefore

$$E[x'_a] = x_a, \quad \text{var}[x'_a] = \frac{x_a(1-x_a)}{2N'}.$$
 (7-1)

It is useful to consider the quantity

$$H'_a \equiv E[x'_a(1-x'_a)],$$
 (7-2)

which one may call “ a -heterozygosity” because it can be interpreted as the probability that a randomly chosen individual in the $(t+1)^{\text{st}}$ generation has

exactly one copy of allele a . Equations (7-1) imply that

$$H'_a = H_a - \frac{H_a}{2N'},$$

which is very well approximated by the differential equation

$$\frac{dH_a}{dt} = -\frac{H_a}{2N} \quad (7-3)$$

unless the population is very small. Hence H_a decays exponentially on a timescale of $2N$ generations. Most discussions define heterozygosity more symmetrically as

$$H \equiv 1 - \sum_a x_a^2 = 2 \sum_{a < b} x_a x_b = \sum_a H_a, \quad (7-4)$$

which obeys the same differential equation (7-3).

(U) In this model of genetic drift, diversity decreases monotonically. The eventual result after many generations is that every individual has two copies of the allele ($x_a \rightarrow 1$), or else the allele goes extinct ($x_a \rightarrow 0$). Furthermore, as one can see from equation (7-3), if the population fluctuates in size, then the rate of drift is dominated by the times at which it is smallest. Somewhat more precisely, the effective population size is the harmonic mean over generations:

$$\langle N \rangle_h = \left[\frac{1}{T} \sum_{t=1}^T N(t)^{-1} \right]^{-1}$$

7.3.2 Statistical equilibrium

(U) Mutation tends to promote diversity and heterozygosity. Let μ be the probability per generation that allele a mutates to some other allele. For simplicity, it is assumed that any allele mutates to any other with equal probability $\mu/(K-1)$, although in fact this is not true for single bases. Then the probability of getting an a in a single "trial" (*i.e.* in one particular zygote) is

$$p'_a = x_a(1 - \mu) + (1 - x_a)\frac{\mu}{K - 1}, \quad (7-5)$$

where x_a is the frequency at that site in the previous generation. The first term on the right is the product of the independent probabilities that a is reproduced and does not mutate; the second prescribes that a different allele is reproduced but mutates into an a . (Of course reproduction and mutation may occur in either order or may be simultaneous). Reproduction of the whole generation $t + 1$ can still be viewed as a series of binomial trials, so that the expectation and variance for the the number of a s in the new generation are $2N'p'_a$ and $2N'p'_a(1 - p'_a)$, and the corresponding frequencies are

$$E(x'_a) = p'_a, \quad E(x'^2_a) = (p'_a)^2 + \frac{p'_a(1 - p'_a)}{2N'}.$$

Since $\sum_a p'_a = 1$, it follows that

$$E\left(1 - \sum_a x'^2_a\right) = \left(1 - \frac{1}{2N'}\right) \left(1 - \sum_a p'^2_a\right).$$

This expression leads immediately to eq. (7-3) if $\mu = 0$. Otherwise, using eq. (7-5) and the fact that $\sum_a x'_a = 1$, one finds after a little algebra that

$$\sum_a p'^2_a = \frac{2\mu}{K-1} + \left(1 - \frac{2\mu K}{K-1}\right) \sum_a x^2_a + O(\mu^2).$$

The terms quadratic in μ can be neglected if $\mu \ll 1$, but the linear ones cannot. Substituting the last equation into the one before it and expressing the remaining sums in terms of H [eq. (7-4)] yields

$$H(t+1) - H(t) \approx 2\mu - \left(\frac{1}{2N'} + \frac{2\mu K}{K-1}\right) H, \quad (7-6)$$

which can of course also be approximated by a differential equation. We have discarded terms of order μN^{-1} as well as those of order μ^2 .

(U) In equilibrium at a fixed population size N ,

$$H = \frac{4\mu N}{1 + 4\mu N(1 - 1/K)^{-1}}. \quad (7-7)$$

The combination $4\mu N$ is so important that it is commonly designated by a special symbol, π . Sometimes π is used for a quantity estimated from

genetic data that would be equivalent to $4\mu N$ in this model, apart from fluctuations, but might in reality depart from it because of complications such as fluctuating population size. Estimates of π can be formed by comparing corresponding sequences from different individuals, or even by comparing the two homologous sequences in a single individual.

(U) Directly from eq. (7-6), one sees that the exponential timescale (in generations) on which equilibrium is approached is

$$\tau_{\text{eq}} = \left(\frac{1}{2N} + \frac{2\mu K}{K-1} \right)^{-1}. \quad (7-8)$$

This can be very long: for a typical mammalian mutation rate $\mu = 10^{-8}$ (per base pair per generation), τ_{eq} is likely to be dominated by population size. If the human population were to remain constant at its current size ($N \approx 6 \times 10^9$), then $\tau_{\text{eq}} \approx 7 \times 10^7$ generations, or 1.4×10^8 years! Clearly it is unreasonable to expect equilibrium in humans. Indeed, a recent study of diversity in higher primates based on a sequence (Xq13.3) of 10^4 base pairs quotes an effective population size of 35,000 for chimpanzees (*Pan troglodytes*) but only 10,000 for humans [22]. Even the former number is likely to be an underestimate: estimates of chimpanzee populations by census, though uncertain, generally range from 100,000 – 200,000 [23]. The number quoted for humans probably corresponds less to the actual population at any particular time in the past than to the age of the species. For suppose that *H. sapiens sapiens* arose by critical (and selectively favored) mutations in a very small group. Then the initial homozygosity $H(0) \approx 0$, and if the population expanded much more rapidly than $1/t_{\text{eq}}(N)$ then $H(t) \approx 2\mu t$ after t generations, whence the effective population size computed by assuming the equilibrium (7-7) would be $N_{\text{eff}} = t/2$. This is consistent with the data of ref. [22] if the species is about 2×10^4 generations old, in rough agreement with the paleontological record.

The aforementioned simple discussion does not, of course, try to take into account the real challenges of trying to use limited data with uncertain

mutation models and make robust estimates nonetheless. Luckily, there is a growing literature in this area [24-27] and we are optimistic that one will be able to make progress along this direction.

8 ADDENDUM

Discussions of human impacts on whales have dealt almost exclusively with isolated events during which a herd was exposed to severe acoustic radiation. Yet from the point of view of the general health and survival of the population these events are minor a consideration. Here we speculate on what could be done to reduce the ambient noise between 30 and 200 Hz which is largely the result of global shipping and which has increased from 15 to 20 dB over the last few decades.

1. The total mortality of suspected military-related strandings in the last 40 years is fewer than 300 animals; all involved two genera of beaked whales; all involved mid-range tactical sonar.
2. There are many other factors affecting the well-being of the marine mammal populations and other marine life. We mention changes in ocean circulation (global warming), bycatch, collisions with ships and rising acoustic noise levels.
3. Ocean noise above 200 Hz is generally dominated by wind and wave noise, rain noise and other weather-related phenomena. Below 200 Hz it is dominated by shipping noise. Attenuation of low frequencies is low, and the background noise is a cumulative effect of distant shipping. This noise has increased by 15 to 20 dB in the last fifty years (see Figure 10), the result of increased shipping transport. There has been no corresponding increase in the southern hemisphere, as expected. In some ocean basins (Gulf of Mexico, for example) some of the low frequency noise enhancement is associated with drilling and exploration.
4. It is generally accepted that the increased noise level is a significant liability to marine mammals which depend on sound for their existence: for feeding, communicating and navigating. We will assume that the

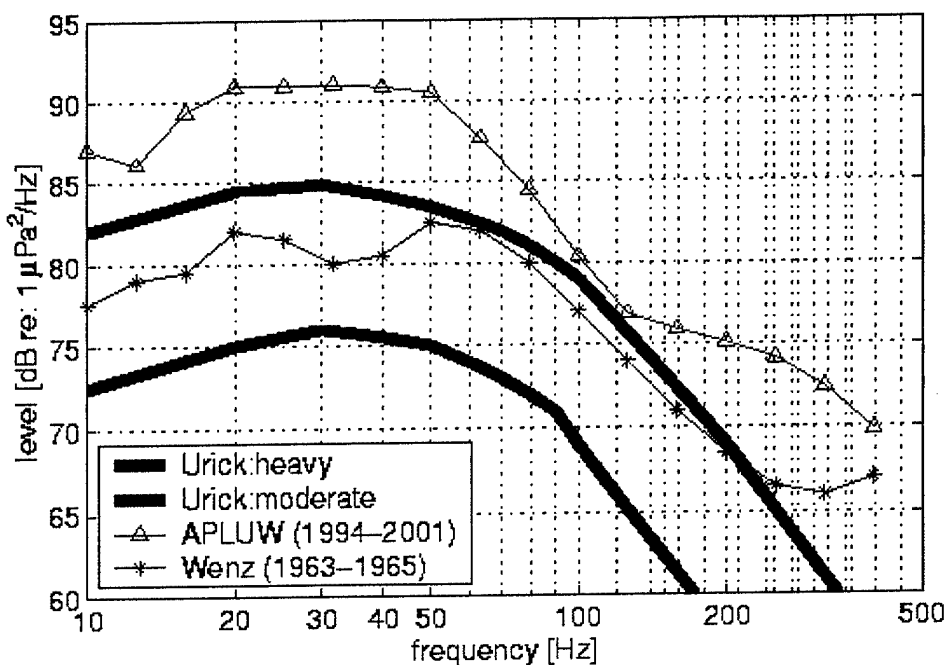


Figure 10: Changing ocean noise.

effect on the general well being of the species far outweighs the effect of occasional events leading to catastrophic strandings. This is generally accepted in the community, but we are not aware of any quantitative studies.

5. It is in the Navy's self-interest to operate its fleet at low noise levels. This is absolutely crucial for the submarine fleet and here we have seen a reduction in self-generated noise by many orders of magnitude for all navies. It can be argued that it is in the Navy's strategic interest to lower the general noise level and thus enhance our ASW capabilities. It is important also for surface ships to escape detection by enemy vessels. But it is desirable for other reasons as well. High levels of self-noise are associated with oscillations of hull and machinery that can lead to early fatigue problems. Increased noise levels in the crews quarters lead to human fatigue problems.

6. The dominant noise generation is by the formation and collapsing of cavities formed at the propeller blades. Cavities form when the negative pressure (suction) exceeds the ambient pressure; surface ships are then particularly vulnerable. The acoustic radiation is broadband and most of it goes into high frequencies which are quickly damped. The low-frequency ambient noise here of principal concern is associated with the inhomogeneity in the pressure field and the flow field; propeller blades in their upwards position are at a lesser pressure than in their downward position, and the vessel-induced flow field varies with elevation.
7. Efforts to reduce cavity noise go back to the early fifties in a program called PRAIRIE/MASKER. Here, air bubbles replace water vapor bubbles from propeller blades, thus suppressing low frequency emissions. These and other ideas could be revisited.“
8. The Navy has initiated certain defensive measures to guard against the occasional events of catastrophic beachings. This initiative should be in parallel with a study of the technical means required to lower the man-made ocean global noise level. Rather than being on the defensive for occasional destruction of marine life, this would be a constructive move toward enhancement of the marine life, and of greater import to the general well-being of life in the ocean.

A APPENDIX

A.1 Whale-safe Sonar

We have estimated that hemorrhaging and similar severe mechanical damage require extremely high received levels, probably in excess of 200 dB. Based on experiments with other cetaceans, even the much less severe phenomenon of temporary threshold shifts would have required 180-190 dB. If direct damage was the cause of the Bahama strandings, then the whales must have come within a few hundred meters of the sonar. Let us assume for arguments sake that they were within the surface duct, where the sound would have been loudest. To make this quantitative, we use the sonar equation in the form

$$\text{SPL} = \text{SL} + \text{DI}_T - \text{TL}, \quad (\text{A-1})$$

in which the notation conforms as much as possible to that of Urick [10], so that SPL is the sound pressure level received by the whale (re $1\mu\text{Pa}$), SL is the source level (re $1\mu\text{Pa}$ @ 1 m), DI_T is the directivity index of the transmitted beam, and TL the transmission loss. Given the depth $h = 200$ meters and critical angle $\theta_c = 3.7^\circ$ of the surface duct, transmission loss should be dominated by spherical spreading at ranges $\leq h/\theta_c \approx 3$ km, so that $TL = 20 \log R$, where R is the range in meters. According to the Joint Interim Report on the Bahamas strandings [4], the AN/SQS-53C sonar was used with $SL = 235$ dB. Ensonification was omnidirectional in azimuth and had a beamwidth of $\pm 15^\circ$ in vertical angle, so that $\text{DI}_T = 10 \log(\sec 75^\circ) \approx 6$ dB. This leads to

$$\log R = \frac{241 - RL}{20}.$$

Thus in order to have experienced $RL \geq 200\text{dB}$, the whales should have been closer than 110 meters, and to have experienced $RL \geq 180\text{dB}$, they should have been within 1.1 km.

At such short ranges, the whales might have been detectable by the sonar. The echo returned to the sonar from the whale is $EL = SPL + TS + DI_R - TL$, where TS is the target strength of the whale, and DI_R is the directivity index on reception. We can eliminate the transmission loss from this expression using eq. (A-1),

$$EL = 2 * SPL - SL - DI_T + DI_R \quad (A-2)$$

The rather peculiar appearance of this form of the sonar equation, in which the echo level decreases as the source level increases, results from holding the sound pressure level at the whale constant.

The target strength of the whale is rather uncertain. The geometric area of an adult male *Ziphius cavirostris* is about 7.5 m^2 at broadside if we model it as a neutrally buoyant cylinder of length $L = 6.4 \text{ m}$ and mass $M = 7000 \text{ kg}$. But the acoustic impedance $Z = \rho v_s$ is not very different from that of water itself. At normal incidence to a planar interface between two infinite half spaces of acoustic impedances Z_1 & Z_2 , the amplitudes of incident and reflected waves are related by

$$\delta p_R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right) \delta p_I$$

The sound speed in whale blubber is about 10% less than that of water, and the density is less by a similar factor. We therefore shall estimate the parenthesized factor involving the acoustic impedances to be 0.1. This enters the target strength as the square, so our estimate for the effective cross section is of order $10^{-2}A$, whence $TS \approx -11 \text{ dB re m}^2$. Air spaces in the lungs and sinuses may in fact dominate the target strength, but their volume is uncertain and varies with depth, so we neglect their contribution.

The directivity index on reception is also uncertain since we lack details of the AN/SQS-53C sonar. We shall simply assume that the horizontal and vertical beamwidths in reception are comparable to the vertical beamwidth in transmission, *viz.* 30° , so that $DI_R \approx 17 \text{ dB}$.

In order to be detectable, the echo must be sufficiently far above ambient noise. From Urick, the spectral level of the noise is about 60 dB at 3 kHz (the operating frequency of the sonar) for a typical wind speed of 12 knots. This refers to a one-Hertz bandwidth. We are told that the actual bandwidth of the sonar can be up to 100 Hz, depending upon its mode of operation. Thus we take $NL = 80$ dB for the noise integrated over the band. Putting it all together, we have

$$EL - NL = 85 + 2(SPL - 200) + (TS + 11) \text{ dB.} \quad (\text{A-3})$$

For reference, the most uncertain parameters have been retained but scaled to their nominal values.

The expression (A-3) suggests that whales close enough to have suffered direct mechanical damage should easily be detectable with this sonar, even if the actual threshold for damage is as low as 180 rather than 200 dB.

Some caveats are in order. First, at the range corresponding to $SPL = 200$ dB, 110 meters, whales would have been within the blanking range of the sonar since the transmitted pulses lasted 0.5 sec or longer. At the available bandwidth of 100 Hz, however, the pulses could have been reduced to 10^{-2} sec in principle, in which case the blanking range would have been only 7.5 m. Second, we have taken no account of reverberation from the bottom, which could overwhelm the echo from the whale if its distance were greater than the water depth. This difficulty also exists for detecting submarines, however, so we assume that the sonar can overcome it by a combination of vertical aperture and doppler processing. In any case, the two problems are complementary in the sense that the first arises only at small ranges—probably less than the water depth—while the second applies only at longer range.

The above considerations suggest the following modifications to sonar operation during training exercises.

- The sonar data should be recorded and saved for later analysis, including searches for whale echoes. This step in itself will not mitigate the damage to cetaceans, but it will help to narrow the range of hypotheses as to the causes of that damage.
- Before operating the sonar at standard power levels, operate at a reduced peak power with very short pulses (say 10 milliseconds) and search for echoes consistent with nearby whales. The arithmetic above suggests that most whales close enough to be physically damaged when the sonar operates at full power should easily be detected at a sonar power 20 dB lower.

A.2 Damage Threshold Estimate

In the Bahamas stranding acoustic propagation was described by a surface duct of depth h approximately 200 m. We will assume that all power trapped within this duct is uniformly distributed (in the vertical direction) within it and that the whales spend all their time in the duct. We neglect attenuation losses and assume cylindrical spreading (valid at distances $\gg h \sec \theta_1 \sim 3$ km, where θ_1 is defined below); it is not necessary to assume that the beam is azimuthally symmetric, and in general beams are strongly collimated azimuthally. Then for a transmitted power P_{tr} and acceptance fraction f into the duct the intensity at a range r is

$$I_{received} = \frac{f P_{tr}}{2\pi r h}.$$

Expressing P_{tr} and $I_{received}$ in customary dB form:

$$\begin{aligned}
 P_{tr} &= \frac{4\pi(1\text{m})^2(1\mu\text{Pa})^2}{\rho c_s} 10^{P/10} \\
 I &= 10 \log \frac{I_{received}}{(1\mu\text{Pa})^2/\rho c_s} \\
 &= 10 \log \frac{f P_{tr} \rho c_s}{2\pi r h (1\mu\text{Pa})^2} \\
 &= 10 \log \left(\frac{2f}{r h} 10^{P/10} \right) \\
 &= P + 10 \log \frac{2f}{r h} \tag{A-4}
 \end{aligned}$$

where r and h are now their numerical values in units of meters.

In an isothermal mixed layer (which ignores the small adiabatic increase of temperature with depth) at 20°C the sound speed (m/sec) is

$$c_s \approx 1540 + 1.58 \times 10^{-6} p,$$

where the pressure (in Pa) $p = 1.00 \times 10^4 h$. For an isotropic source f is found from

$$f = \cos \theta_1,$$

where θ_1 is the angle of incidence of the last ray (from a surface source) trapped within the duct. Snell's law then gives

$$\cos \theta_1 = \sqrt{1 - \sin^2 \theta_1} = \sqrt{1 - c_1^2/c_2^2},$$

where

$$\frac{c_1}{c_2} \approx 1 - 1.03 \times 10^{-5} h,$$

so that

$$f \approx \sqrt{2 \times 1.03 \times 10^{-5} h}.$$

If the source is beamed in the horizontal plane with an (azimuthally averaged) antenna gain G then

$$f \approx G \sqrt{2 \times 1.03 \times 10^{-5} h}.$$

In the Bahamas stranding incident the radiated power is described as being confined between angles $\pm 15^\circ$ of the horizontal. If the angular distribution is constant within this range and zero outside it, then

$$G = \sec 75^\circ = 3.86.$$

Substituting the expression for f yields

$$I = P + 10 \log \frac{2G\sqrt{2 \times 1.03 \times 10^{-5}h}}{rh}.$$

We first consider a point source of sound. If all whales (of the relevant species, Cuvier's beaked whales) within a lethal radius r_ℓ strand, the mean density (m^{-2}) of whales in the surface duct is n , and the number stranded is N , then $r_\ell = \sqrt{N/\pi n}$ and the lethal intensity is given by

$$I_\ell = P + 5 \log \frac{8\pi G^2 n \times 1.03 \times 10^{-5}}{hN}.$$

Substituting $N = 10$, $n = 10^{-8}$, $G = 3.86$, $h = 200$ yields $r_\ell = 18$ km (consistent with our assumptions) and

$$I_\ell = P - 69 \text{ dB}.$$

For $P = 235$ dB we find $I_\ell = 166$ dB.

In the Bahamas stranding the ships were moving (much faster than the whales, which may be considered stationary), and traversed a path of length $L = vt$ during the incident. Then $r_\ell = N/(nL) = 4.2$ km (marginally consistent with our assumptions) and the lethal intensity is

$$I_\ell = P + 10 \log \frac{2GnL}{N} \sqrt{\frac{2 \times 1.03 \times 10^{-5}}{h}}.$$

Substituting $L = 240$ km, with the other parameters the same as before, yields

$$I_\ell = P - 62 \text{ dB}.$$

For $P = 235$ dB we find $I_\ell = 173$ dB

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