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The Decibel Report:
Acoustic Sound Measurement, Modeling, and the Effects of Sonar on Marine Mammals

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PREFACE

This effort was performed under the auspices of the Offices of the Deputy Chief of Naval Operations, Fleet Readiness and Logistics (N4, Vice Admiral M. K. Loose) and the Assistant Secretary of the Navy, Installations and Environmental (ASN I&E, B. J. Penn). Joint funding was provided by the (1) U.S. Fleet Forces Command (N02/04ICG: Margaret Harrell, SES (N04) and Mark Honecker, SES (N02) under N4657909WR001NR; (2) Naval Undersea Warfare Center (NUWC) Division, Newport, RI, Office of the Technical Director (Paul Lefebvre, SES) under N6660405PG20051; and (3) NUWC Division Newport Sensors and Sonar Systems Department (David Grande, Department Head) under NWCF 615V960.

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14. ABSTRACT

This report is an authoritative and comprehensive explanation of sound-level quantities, metrics, and sonar models; its purpose is to provide best available science to acoustics and marine biology subject matter experts, sonar and environmental planners, and policy decision-makers so they can be better informed of the terminology, usage, and practices undertaken for modeling underwater sound energy effects pertinent to U.S. Naval sonar operations and the marine habitat.

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LIST OF ABBREVIATIONS AND ACRONYMS

µPa	Micropascal
1 µPa	Standard reference pressure for underwater sound
20 µPa	Standard reference pressure for in-air sound
ANSI (S1.1)	American National Standard Institute (Acoustic Terminology)
ASA	Acoustical Society of America
ASN I&E	Assistant Secretary of the Navy, Installations and Environmental
ASW	Antisubmarine warfare
ß/	Natural system of logarithmic decay (or gain)
BRS	Behavioral Response Studies
CASS/GRAB	Comprehensive Acoustic System Simulation/Gaussian Ray Acoustic Bundle
CCU	Consultive Committee for Units
CGPM	General Conference on Weights and Measures
CIPM	International Committee for Weights and Measures
CNO	Chief of Naval Operations
dB	Decibel
DCNO	Deputy Chief of Naval Operations
DEF	Definition
DOC	Department of Commerce
DOD	Department of the Defense
DOE	Department of Energy
DON	Department of the Navy
ESA	Endangered Species Act
I	Intensity (acoustic)
ICG	Integrated Coordinating Group
JOST	Joint Subcommittee on Ocean Science and Technology

LIST OF ABBREVIATIONS AND ACRONYMS (Cont'd)

LMRC	Living Marine Mammal Research Center
L_N	Ambient and/or platform noise level
L_p	Power level
L_R	Reverberation level
L_{REC}	Reeeive level
L_S	Source level
M3R	Marine Mammal Mitigation and Response
MEEI	Massaehusetts Eye and Ear Infirmary
MIT	Massaehusetts Institute of Technology
MMP	Marine Mammal Program
MMPA	Marine Mammal Proteetion Aet of 1972
MSC	Mile of standard eable
N_{AG}	Array gain
NAS	National Aeademy of Seienee
N_{DI}	Direetivity index
N_{FM}	Figure of merit
NMFS	National Marine Fisheries Service
NOAA	National Oeeanie and Atmospherie Administration
Np	Neper
NRC	National Researeh Counеil
N_{RD}	Reeognition differential
N_{SE}	Signal exeess
N_{TS}	Target strength
NITS	Noise-indueed threshold shift
NURC	National Undersea Researeh Center (NOAA)
NUWC	Naval Undersea Warfare Center
N_W	Propagation (or transmission) loss
OPNAV	Offiee of Naval Operations
ONR	Offiee of Naval Researeh
Pa	Paseal
P_D	Detection probability
p_{ref}	Sound pressure reference quantity
PTS	Permanent threshold shift
R	Ratio of power or other proportional quantities
RDT&E	Research, development, test, and evaluation
rms	Root mean square
$S(t)$	Oseillating signal
SBR	Signal-to-baekground ratio
SEL	Sound energy level
SES	Senior Executive Serviee
SI	International Standards
SLMROG	Sonar and Living Marine Resources Oversight Group

LIST OF ABBREVIATIONS AND ACRONYMS (Cont'd)

SME	Subject matter expert
SPAWAR	Space and Naval Warfare Center
SPL	Sound pressure level
SU	Sensation unit
TS	Threshold shift
TTS	Temporary threshold shift
TU	Transmission unit
USC	United States Code
USFFC	U.S. Fleet Forces Command
WHOI	Woods Hole Oceanographic Institution
ρc	Acoustic or characteristic impedance

THE DECIBEL REPORT: ACOUSTIC SOUND MEASUREMENT, MODELING, AND THE EFFECTS OF SONAR ON MARINE MAMMALS

1. INTRODUCTION

1.1 PURPOSE

Application of best available seienee is a phrase that has beeome very familiar to working professionals in aetive sonar and marine seienee eommunities, yet, in some areas, there remains a general lack of eommunieation among subject matter experts (SMEs) (for example, underwater acousticians, marine biologists, mathcmaticians, physicists) because of the various ways the SMEs have interpreted the science. Speeifieally, a large part of the eonfusion stems from diffieulties that the professionals have had in either understanding or explaining sound-level quantities ealled deeibels and the underwater acoustic prediction models to whieh deeibels are applied.

This report is an authoritative and eomprehensive explanation of sound-level quantitics, metries, and sonar models; its purpose is to provide best available seienee to aeousties and marine biology SMEs, sonar and environmental planners, and policy decision-makers so they ean be better informed of the terminology, usage, and practiees undertaken for modeling underwater sound energy effeets pertinent to U.S. Naval sonar operations and the marine habitat.

1.2 BACKGROUND

The collection and interpretation of scientific information about sonar and the marine habitat requires the best talents from the scienee eommunity in a number of diseiplines—for example, underwater aeousties, marine biology, mathematies, physics, computer seience, oceanography, system engineering, signal processing, and operations researeh. Beeause of the scientific ehallenges in determining the effects of anthropogenie sound on marine life, and marine mammals in partieular, it is ineumbent upon the U.S. Navy and eommunity leadership within these disciplines to work collectively in a way that both national security interests and ocean environmental resourees are eontinually safeguarded.

In the spring of 2007, the Chief of Naval Operations (CNO) direeted the establishment of a sonar Integrated Coordinating Group (ICG),* "to synchronize and integrate OPNAV and Fleet activities related to sonar environmental eompliance in support of the Navy's Title 10 duties."[1] The ICG under its parent command, Commander, U.S. Fleet Forees Command (USFFC) in Norfolk, VA, is required, among other responsibilities, to evaluate seientifie researeh pertaining to aetive sonar use and its impaet on the marine environment.[1] The underlying strategy for seientifie evaluation has been to aequire and apply the best available seience that is obtainable only through community-wide solicitation and mutually cooperative efforts.[2]

* The authors of this report are current members or alumni of the ICG.

1.3 SCOPE

In addition to the introduction, this report contains nine numbered sections and an appendix. Section 2 explores the concept of optimal sonar use, environmental compliance, and best available science. Section 3 is a detailed technical discussion of the decibel—the fundamental unit that is used to describe sound energy in water and yet has for a long time been misunderstood by even some of the most knowledgeable practitioners and laypersons alike. The basic sonar equations are described in section 4. Variants of these equations are used for acoustic performance modeling and range prediction. Section 5 provides a discussion of metrics and various models used for obtaining estimates of sonar impacts on marine mammals based on the best-available scientific practices. This section addresses the impact of ambient noise on responses to sound energy in the marine environment and also explains the distinction between loudness and intensity. Section 6 describes how one might begin to consider converting sound energy levels in air to equivalent levels in water and vice versa. Section 7 provides a glimpse of some of the ongoing scientific research that will enable improved environmental assessments and impact estimates for current and next-generation anthropogenic sound energy sources. Section 8 summarizes the main concepts described in the report, and section 9 is a list of references. Section 10 enumerates the people and organizations whose contributions, assistance, guidance, and support have made this report possible.

2. SONAR USE, ENVIRONMENTAL COMPLIANCE, AND BEST AVAILABLE SCIENCE

Optimal Naval sonar use, environmental planning, regulatory decisions, and policy-making are interrelated activities involving a number of U.S. government agencies such as the Department of the Navy (DON), Department of Commerce (DOC), Department of Energy (DOE), and other interagencies at federal, state, and local levels. Each government agency has its own specific responsibilities, yet each must be able to work collectively and cooperatively with other government agencies to meet legal requirements of federal, state, and local policies and statutes.

In the case of the U.S. Navy, the Navy must maintain a war-ready status of its deployed forces and, if called upon, optimally deploy its sonar to ensure that national security interests are upheld in accordance with U.S. Code, Title 10 stipulations. At the same time, the Navy must comply with environmental regulations and statutes such as the Marine Mammal Protection Act of 1972 (MMPA) to safeguard the well-being of the marine habitat. The vested stakeholders are manifold, not the least of which is the American taxpayer.

The government agencies involved (for example, DON, DOC, DOE) must base policy decisions on the information provided to them; in the case of sonar use and the marine habitat, this information is predicated on obtaining and using the best available science. It is crucially important, therefore, that scientific information pertaining to anthropogenic sound energy and its effect on the marine habitat be articulated in a common language that is understood by all vested government officials and the leadership within the various scientific communities.

2.1 CASE STUDY: BAHAMAS NORTHWEST PASSAGE STRANDING EVENT, MARCH 2000

In March 2000, a mass stranding cluster of 16 cetaceans occurred in the Northwest Passage of the Bahamas within a 36-hour period over three islands (Grand Bahamas, Abaco, and North Eleuthra). The event coincided with U.S. Navy active sonar operations in the area. Of 16 marine mammals stranded, there were 6 deaths. The remaining 10, whose fates were undetermined, were either pushed off the beach and/or escaped to deeper water. The six animals that died were beaked whales, five Cuvier and one Blainville's beaked whale. A direct association was made between the stranding event and sonar operations.[3]

D. Ketten notes from the event that the cause of the deaths was the physical consequences of the stranding, including hyperthermia, suffocation, and blood loss from external wounds caused by coral cuts and shark attacks; moreover, the circumstances in which the animals rapidly returned to sea with no evidence of re-stranding are consistent with nonpermanent trauma. Ketten, therefore, concluded that the cause of the auditory trauma per se was not the cause of death in these animals, but it may have been an important contributing factor.[4]

It was determined that the stranding likely resulted from a confluence of factors, unique to the particular circumstances of this event. D. Cato points out the difficulties in quantifying marine animal behavioral responses and the necessity for much more research and data collection.[5] Since the 2000 stranding event, the U.S. Navy, as an act of stewardship, has put into worldwide practice a series of mitigation measures when it activates its sonar during training operations. Through substantial investment of its own research funding, the U.S. Navy continually monitors, updates, and implements the best available science to properly balance its legal responsibility to defend national security interests and its environmental stewardship to comply with environmental statutes and regulations. For example, since the Bahamas 2000 event, evidence has emerged that demonstrates that certain beaked whales in particular environments avoid loud sounds from ships and sonar signals, but return to their natural habitat after the signal emissions terminate or leave the environment.[6] A. D'Amico and a team of researchers have been tracking beaked whale behavior and migrations worldwide to improve the necessary data collections and best available scientific data.[7, 8]

2.2 CHALLENGES IN ACQUIRING AND ACTING ON THE BEST AVAILABLE SCIENCE

The collection and interpretation of scientific information on sonar and the marine habitat requires the best talents from the science community in a number of disciplines—underwater acoustics, marine biology, mathematics, physics, computer science, oceanography, system engineering, signal processing, and operations research, to name only some. The complexity of this task cannot be underestimated: it was a difficult challenge for scientific leadership from the various disciplines to come to agreeable terms with measurement quantities, units, and physical models to which the quantities and units are applied. For example, since the mid-1990s there have been a number of reports on worldwide marine mammal stranding events with operational sonars in proximity, yet the scientific evidence documenting such events is still very lacking.[8]

The difficulties associated with gaining consensus from the scientific community in the availability and interpretation of scientific data have encumbered the ability of sonar and environmental planners and policy makers to obtain the best available science. For nearly two decades, confusion has remained over the interpretation and use of the term "decibel," the basic unit of sound energy, and the physics underlying anthropogenic sound energy transmission in the ocean and its effect on marine life. The problem addressing the need for standardization of units was first introduced by William Carey[9] in 1995 and reintroduced almost a decade later in a series of publications.[10, 11, 12, 13] This report is an extension of these past efforts: it addresses some of the challenges that still remain and reestablishes some of the proposed metrics and modeling standards recommended for modeling sonar effects on marine life.

2.3 RECOMMENDED READING FOR PRACTITIONERS OF THE DECIBEL AND THOSE MODELING SONAR EFFECTS ON MARINE LIFE

Ideally, the continued joint effort of the sonar and marine environmental communities to better appreciate and model the physics of marine mammal behavior and its response to anthropogenic sound energy will result in an established unified set of standards and procedures including well-defined physical quantities, units of measure, performance metrics, input parameters, and paradigms that can be shared and clearly understood by all vested stakeholders. Only in this manner can performance results generated by these model(s) provide solutions that are uniform, consistent, technically accurate, and understood by all interested parties.

The best way to become familiarized with the decibel is through hands-on experience. There are many texts and articles to choose from to assist in learning more about the decibel and modeling sound energy effects on marine species. In an effort to promote community-wide standard practice, the authors have selected 10 reference sources as essential reading material for the serious-minded professional engaged in studying the effects of sonar on marine life. Four sources reflect interests from the marine biology community; six originate from the underwater acoustics and physics communities.

2.3.1 Suggested Reading from the Marine Biology Community

- Richardson, W. J., C. R. Greene, C. I. Malone, and F. H. Thompson, *Marine Mammals and Noise*, Academic Press, 1995.
- National Research Council (NRC) of the National Academics, "Ocean Noise and Marine Mammals," The National Academic Press, Washington DC, 2003.
- Southall, B. L., et al., "Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations," *Aquatic Mammals*, vol. 33, 4 November 2007.
- Southall, B. L., et al., "Addressing the Effects of Human-Generated Sound on Marine Life: An Integrated Research Plan for U.S. Federal Agencies," Report of the Joint Subcommittee on Ocean Science & Technology (JSOST), 13 January 2009.

2.3.2 Suggested Reading from the Underwater Acoustics/Engineering and Physics Communities

- Kinsler, L. E., A. R. Frey, A. B. Coppens, and J. V. Sanders, *Fundamental of Acoustics*, Third Edition, John Wiley & Sons, Inc., 1982.
- Urick, R. J., *Principles of Underwater Sound*, Third Edition, McGraw-Hill, Inc., 1983.

- Carey, W., "Special Issue Peer-Reviewed Technical Communication: Sound Sources and Levels in the Ocean," *IEEE Journal of Oceanic Engineering*, 2006.

- Hodges, R. P., *Underwater Acoustics: Analysis, Design and Performance of Sonar*, First Edition, John Wiley & Sons, Inc., June 2010.

- Carey, W. M., and Richard B. Evans, *Ocean Ambient Noise: Measurement and Theory*, First Edition, Springer-Verlag Publisher (publication date pending).

- Bell, Thaddeus G., *Probing the Ocean for Submarines*, Second Edition (publication date pending).

The reader is cautioned to exercise judgment in the interpretation of materials. For example, the latter reference source, which exposes the reader to the many technological challenges faced by the Navy and scientific leadership in order to successfully field an extremely complex technology, was written by Thaddeus Bell—a world-renowned authority on sonar design, performance analysis, and sonar performance predictions, to name a few of his many accomplishments.

There are, however, reference materials on underwater acoustics available to the public that are technically inaccurate. In fact, even some knowledgeable scientists in the field have been prone to large errors,[14] a trend that seems to have permeated to present day. A large number of freelance articles on acoustics and the decibel can be found on the Worldwide Web. While some of these are deemed to be useful and informative,[15] others contain technical inaccuracies that can be highly misleading to the neophyte. As stakeholders from the vested scientific communities strive toward uniformity and standardization, over time these impediments to obtaining the best available science will be recognized and removed from these Web sites and corresponding literature. Only then will the "true" science be able to be understood and shared by all.

3. THE DECIBEL: DEFINITIONS, ORIGINS, PHYSICAL, AND REFERENCE QUANTITIES

Section 3 is a detailed technical discussion of the decibel—the fundamental unit that is used to describe sound energy and intensity in water and yet has been long misunderstood by even some of the most knowledgeable practitioners and laypersons alike.

3.1 DEFINITIONS

This section provides four definitions of the decibel, three of which are considered current, common practice definitions that are accessible to a wide audience and one that is the preferred definition for community-wide standard practice. The authors of this report reviewed the three common practical definitions for technical accuracy and completeness and then compared them to the preferred standard definition for community-wide use. A justification for the recommended standard is also provided.

3.1.1 Common Practice Definitions and Common Misuses

Before the origins and evolution of the decibel are examined, it is useful to review some current definitions that are accessible to both the lay public and scientific communities to compare likenesses, disparate interpretations, and technical inaccuracies. For brevity, only three definitions from seemingly reputable reference sources were arbitrarily selected: (1) *Webster's New World College Dictionary*,[16] (2) Wikipedia, a popular Web-based encyclopedia that can be accessed at the following Web site address: http://en.wikipedia.org/wiki/Decibel,[17] and; (3) *A Glossary of Ocean Science and Undersea Technology Terms*.[18]

1. Definition 1 (DEF 1) (Webster) – decibel (*Acoustics*) A numerical expression of the relative loudness of a sound: the difference in decibels between two sounds is ten times the common logarithm of the ratio of their power levels.[16]

2. Definition 2 (DEF 2) (Wikipedia) – "The decibel (dB) is a logarithmic unit of measurement that expresses the magnitude of a physical quantity (usually power or intensity) relative to a specified or implied *reference level*. A decibel is one tenth of a Bel, a seldom-used unit."[17] (Wikipedia goes on to say. . . "The definitions of the decibel and Bel use base-10 logarithms."[17])

3. Definition 3 (DEF 3) (National Academy of Science (NAS)) – "decibel. The decibel is one tenth of a Bel. Thus, the decibel is a unit of level when the base of the logarithm is the tenth root of ten and the quantities concerned are proportional to power."[18]

In DEF 1, the second part of the sentence (after the colon) is explicit; however, the first part contains an error relative to the loudness of sound. Loudness is a term often used, if only colloquially, to be synonymous with the power or intensity of a signal (that is, the physical

quantities to which sound levels are most referred); however, loudness and power, just as loudness and intensity, are not always interchangeable, particularly when comparisons are made between different animal species (see subsection 5.4). The authors, therefore, rejected DEF 1.*

DEF 2 makes a valiant attempt at defining decibel, yet it leaves out the most important detail, either directly or indirectly, which is the specified unit value (there is only one) based on a ratio of two powers equaling $10^{0.1}$. By mention of the use of base 10 logarithms, there may be a hint of the use of a unit power ratio, yet such a limited definition is incomplete and provides no logical and concise way to make such an interpretation. Had DEF 2 specified 10 times the common logarithm of the ratio of power levels as was done in DEF 1, that is to say, had it included a multiplicative factor of 10 preceding the logarithmic expression, an inferred unit power level could be interpreted in the definition. The authors, therefore, rejected DEF 2. The basis for rejection is articulated in subsection 3.2.

DEF 3 is a more concise and technically accurate definition than are DEF 1 and DEF 2. Although a number of intermediate steps have been omitted from DEF 3, these steps are implicit and are articulated in subsection 3.2. DEF 3 also includes Bel in its definition, which is not essential to the definition of decibel and may understandably cause confusion among some readers (see subsection 3.2). Nonetheless, DEF 3 includes the necessary ingredients, and the authors find this definition minimally acceptable.

3.1.2 Standard Definition of the Decibel for Recommended Use

The definition of decibel that is recommended for community-wide practice and considered to be the most technically accurate and complete definition by the authors is Definition 4 (DEF 4) (note the conspicuous absence of Bel in this definition):

DEF 4 (American National Standard Acoustic Terminology S1.1 (ANSI S1.1[19]) – "decibel, unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power. Unit symbol, dB. NOTE - Examples of quantities that qualify are power (in any form), sound pressure squared, particle velocity squared, sound intensity, sound-energy density, and voltage squared. Thus the decibel is a unit of sound-pressure-squared level; it is common practice, however, to shorten this to sound pressure level, when no ambiguity results from doing so."[19]

Except for the inclusion of the Bel in DEF 3, DEF 3 is very close to the authors' preferred definition, DEF 4.

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* It is understandable how the confusion between loudness and intensity may have developed, as most electronics sound equipment is designed to be optimized to the sensitivity of the human ear. Turning up the volume dial on a stereophonic sound system increases the loudness as well as the level of intensity. A falling redwood, however, leaves a mark of increased sound intensity level that can be measured by a nearby sound level recorder even if left unattended by a human observer. Such a sound is void of loudness to the far-away observer, yet the measured intensity level still remains. Loudness is dependent on the hearing sensitivity in conjunction with proximity to the sound source. Intensity level is independent of hearing sensitivity.

The authors acknowledge in the last sentence of DEF 4 that shortened definitions are and will likely remain in common practice; however, while ambiguities still remain between scientific communities (for example, sonar and marine environmentalists), complete rather than shortened definitions are still warranted. To avoid any ambiguity, stakeholders in sonar and marine environment communities should strive to use complete definitions in standard practice; moreover, for the case of transient impulsive sources, W. Carey astutely points out:

> "These transient sounds are of interest because it is common practice to use either peak or peak-to-peak pressures in the determination of source levels. This practice is not correct as peak pressure ratios are not proportional to power ratios and the decibel should not be used."[12]

It is equally inappropriate to substitute peak pressure levels for root-mean-square (rms) pressure levels in environmental models as is often observed because the reference intensity levels upon which the sonar computations are modeled are dependent on pressure-squared quantities and not peak quantities. The engineer or scientist who executes the environmental model should appropriately label her/his results in terms that are clearly understood in order to avoid ambiguities and misinterpretation.

3.2 TRACING THE DECIBEL TO ITS ORIGINS

3.2.1 Mile of Standard Cable (MSC)

The decibel was defined in 1924; however, for more than 20 years prior to it being named, the term "mile of standard cable" (MSC) had been used in its place. MSC was a unit of power ratio used for determining the transmission loss in electrical power lines used by the British. MSC was defined as the ratio of powers of an 800-Hz signal at the two ends of a loop of cable 1 mile in length.[20]

In the United States, a line of cable of 19-gauge open wire having a resistance of 88 ohms and a capacity of 0.054 microfarad per loop mile, similar to that used by the British, was representative of the standard for the MSC. MSC corresponds to the ratio r of two amounts of sound or electrical power across a cable length of 1 mile.[21] As longer length circuits are measured over N miles of cable, received power R_N will be reduced in accordance with an exponential function of the ratio corresponding to 1 mile:

$$R_N = r^N. \tag{1}$$

The length of cable N in miles is a logarithmic function of the power ratio R_N, and R_N is the ratio of powers measured at the end points of the cable of length N. To see this clearly, one simply takes the logarithm (to the base r) of both sides of equation (1):

$$N = \log_r R_N. \tag{2}$$

To compute the logarithm to a general base, x, that is to say, computing the logarithm to an arbitrary secondary base x, given the logarithm to a primary pre-specified base, a (for example, $a = r$, as in equation (2)), an equivalence relation for the transformation of bases was made by R. Hartley.[22] Hartley articulated that, in describing a new system of logarithmic units, two such systems can be interrelated, one as a primary unit and the other as a secondary unit, by a simple translation of bases between each system. The "unit logarithm" for either system can be expressed as $\log_a(a)$ where a is some arbitrary base. When a is taken as the ratio of two powers (for example, $a = R_N = 1\text{MSC}$), $\log_a(a)$ is the power-ratio numerical equivalent of expressing a unit meter (or yard) bar length equal to 1 or a unit kilogram mass equal to 1. Although the unit quantity of a appears dimensionless, it carries along with it the dimension of power in watts or another proportional quantity. Furthermore, the logarithm of an arbitrary number R_N given by $\log_a(R_N)$ divided by the unit logarithm always yields $\log_a(R_N)$ (see equation (3)). To obtain a secondary unit for a system of logarithms to a new base, one chooses an arbitrary number x and computes $\log_a(x)$ as the secondary unit. The secondary unit will have magnitude:

$$\frac{\log_a(x)}{\log_a(a)} = \log_a(x). \tag{3}$$

If one were to express the number R_N, where R_N is a ratio of two numbers, in terms of $\log_a(R_N)$ and the secondary unit $\log_a(x)$, one obtains:

$$\frac{\log_a(R_N)}{\log_a(x)} = \log_x(R_N) = N, \tag{4}$$

where N is the number of secondary units described completely by the seeondary base x. Note that the seeondary unit, thusly expressed, is independent of the primary base a and depends only on x.

If one eonsiders the numerieal constant $10^{0.1}$ equal to the ratio $a = r$ of two powers (for example, equation (2)) and chooses $x = 10$ as the (preferred) secondary base over the primary base r, equation (4) can be reeast in the following form:

$$N = \log_{(10^{0.1})}(R_N) = 10\log_{10} R_N. \tag{5}$$

The ratio of two powers corresponding to a unit difference of $10^{0.1}$, has been in use for many years; however its identity as a fundamental quantity has been obscured by the transformation of logarithm to the base $10^{0.1}$ to ten times the logarithm to the base 10. Working in base 10 logarithmic units appears on the surface to be more mathematically tractable; yet, fundamentally, the decibel is a measurable quantity of logarithmic decay (or gain) to the base $10^{0.1}$ just as the "neper" is a recognized measureable quantity in the scientific literature of logarithmic decay (or gain) to the base e where $e = 2.718$. Measurable unit quantities of logarithmic decay (or gain) are analogous to unit-length quantities (as a meter or yard bar length) or unit-mass quantities (as a kilogram cubic mass) equal to 1.

3.2.2 Transmission Unit (TU), Successor to the MSC

In 1924, the MSC was replaced by the generic term transmission unit (TU). Both the MSC and its successor TU were defined as unit measures (that is, measures defined in such a way that a single unit of such a measure has a numerical value equal to one). The ratio was based on power measurements between the endpoints in a mile of standard telephone cable. It is noteworthy that sound power changes just detectable by the human ear are close to those corresponding to a mile of standard cable. This near equivalent smallest increment in sound hearing detectable by a normal listener was designated "sensation unit" (SU) by H. Fletcher of Bell System.[23, 24]

The minimum perceptible difference between two sound levels occurs when they have a power ratio of approximately 3:2. As will be described in the following section, within the nominal hearing frequency range for humans, a 1-decibel change represents a power ratio of $10^{0.1} = 1.259$ or approximately 5:4. A 2-decibel change represents a ratio of $10^{0.2} = 1.585$ or approximately 3:2. For normal hearing, the least detectable sound falls within the range of approximately 1 to 2 decibels.[25]

The TU was a unit of measure for expressing the power efficiency (that is, the transmission loss) in telephone communications circuits.[21, 26, 27] The power efficiency was initially defined by the ratio of the sound power output to the sound power input between two points in a line of telephone cable. The TU was considered to be a practical measure for determining power loss in the line. Over time, the definition of a power ratio was modified and expanded to include ratios involving other measurement values, such as the ratio taken at a single point in the line where both measures of the signal power and noise power could be obtained, or the ratio of a single measurement divided by a known reference quantity.

The latter definition of a power ratio became essential in order to interpret the meaning of decibel in quantifiable and absolute physical units, the lack of which drew heavy criticism from opponents of the TU when it was first proposed.[28, 29, 30]

The abbreviation dB for the term decibel originated in 1924 and was the replacement, in name only, for a unit of measure that had been called the transmission unit (abbreviated TU).

3.2.3 Decibel (dB), Successor to the TU

Because the decibel (dB) became the replacement for the TU in name only, it is important to understand the origins of the TU. The TU was introduced in 1923 in the Bell System as a "practical measuring stick" for determining power loss in telephone lines. Accordingly, the TU was defined so that two amounts of power differ by "one transmission unit" when they are in the ratio of $10^{0.1}$. More precisely, the TU is equal to 10 times the common logarithm (base 10) of the ratio between two powers, and when the two powers are in the ratio $10^{0.1}$, this standard measure had the numerical equivalent of 1 TU. Hence,

$$10 \cdot \log_{10} 10^{0.1} = 1[\mathrm{TU}]. \tag{6}$$

The brackets on the right side of equation (6) and those equations that follow are shorthand for "in physical unit quantities of." For example, in equation (6), the unit quantity is transmission unit with the implicit physical quantity of power. It is important to note that a multiplier of 10 precedes the logarithm to make the entire expression on the left side equate to 1.

It is further noted that any two amounts of power will differ by N units when they are in the ratio $10^{(N/10)}$.[31] For example,

$$10 \cdot \log_{10} 10^{(N/10)} = N[\mathrm{TU}]. \tag{7}$$

Equation (7) can be generalized to include any ratio of powers, $P_1/P_2 = 10^{(N/10)}$ for $N = 1$ or any value of N:

$$\frac{\log_{10}(P_1/P_2)}{\log_{10}(10^{0.1})} = N[\mathrm{TU}]. \tag{8}$$

Alternatively, an abbreviated form of equation (8) can be written as

$$10 \cdot \log_{10}(P_1/P_2) = N[\mathrm{TU}], \tag{9}$$

where, TU is the transmission unit, N is a number indicating the number of (TU) units, P_1 is the power at measurement point 1, and P_2 is the power at measurement point 2.

As the TU gained usage, power measured at point P_2 could also be collocated with power measured at point P_1 or alternatively power measured at point P_2 could be a reference quantity. Equation (9) states that the number of TUs corresponding to the ratio of any two powers is ten times the common logarithm of that ratio.

According to W.H. Martin of Bell Systems,[31] members of the Bell System participated in invited discussions with the International Advisory Committee on Long Distance Telephony in Europe to recommend standards for use by the European communications industry. U.S. representatives suggested that the fundamental unit be defined to be equal in magnitude to that of "ten transmission units"—the equivalent of a power ratio equaling $10^{1.0}$—and that this fundamental unit be called the Bel (or bel) after the company's namesake, Alexander Graham

Bell. For practical reasons, the usage of "Bel" was replaced by the "decibel" based on the power ratio of $10^{0.1}$ since higher resolution measurement accuracies were achievable using the smaller of the two units. The intent of the prefix deci- was to give the connotation of one-tenth of a relation. The decibel was defined as the logarithmic form of the power ratio having the value of $10^{0.1}$; it is the (base 10) exponent in the power ratio that explicitly defines this one-tenth relation. The logarithmic form has been inserted in the decibel formula, as a matter of numerical convenience only, and although the one-tenth relation is intrinsic to describing differences between the decibel and the Bel, it is expressly the exponent in power ratios (and not the logarithmic operation) that is essential to the relation.

As the decibel evolved and gained familiarity, its use became widely practiced in other fields of engineering. The unit quantity for which the decibel was first defined, electrical power (that is, watts), became commonly substituted for other physical quantities, such as intensity, pressure, voltage and current, most commonly used in underwater acoustics applications. Acoustic intensity and pressure are mechanical quantities, and voltage and current are electrical quantities. Underwater sound devices called hydrophones that receive sound energy and transducers that transmit and/or receive sound energy, due to their special molecular properties, can convert electrical energy into mechanical energy and vice versa.

Many modern-day engineers and scientists use the decibel according to its definition (that is, 10 times the common $\log_{10}$ of a power ratio) without questioning its origin. As previously noted, the Bel was originally defined based on a power ratio of $10^{1.0}$, which upon application of a base 10 logarithmic operation equates to 10 TU; whereas, the decibel, based on a power ratio of $10^{0.1}$, equates to 1 TU. Perhaps a more precise statement for defining the relation between the Bel and decibel is best stated in terms of their predecessor, the TU. A revised statement expressing the relation might read as follows: Because a Bel equals 10 TUs and a decibel (dB) equals 1 TU, a decibel is one-tenth of a Bel. From the definition of TU (equations (6) through (9)), one can obtain a formal connection between the decibel and the Bel. For a ratio of powers $P_1/P_2 = 10^{0.1}$, the defining primary unit quantity for a decibel, and from equations (8) and (9), it follows that

$$\frac{\log_{10}(P_1/P_2)}{\log_{10}(10^{0.1})} = 10 \cdot \log_{10}(10^{0.1}) = 1[\mathrm{TU}] = 1[\mathrm{dB}]. \tag{10}$$

More generally, for any ratio of powers $P_1/P_2 = 10^{(N/10)}$,

$$\frac{\log_{10}(P_1/P_2)}{\log_{10}(10^{0.1})} = 10 \cdot \log_{10}(10^{N/10}) = N[\mathrm{dB}]. \tag{11}$$

For a ratio of powers $P_1/P_2 = 10^{1.0}$, the defining primary unit quantity for a Bel is

$$\frac{\log_{10}(P_1/P_2)}{\log_{10}(10^{1.0})} = \frac{\log_{10} 10^{1.0}}{\log_{10}(10^{1.0})} = 1[\mathrm{Bel}]. \tag{12}$$

More generally, for any ratio of powers $P_1/P_2 = 10^N$:

$$\frac{\log_{10}(P_1/P_2)}{\log_{10}(10^{1.0})} = \log_{10}(10^N) = N[\text{Bels}]. \tag{13}$$

From the original definition of a Bel (that is, 1 Bel = 10 TU = 10 dB):

$$\log_{10}(10^N) = N(\text{Bels}) = N \cdot 10[\text{dB}]. \tag{14}$$

Setting $N = 1$ in equation (14):

$$\log_{10}(10^{1.0}) = 1[\text{Bel}] = 10[\text{dB}]. \tag{15}$$

Alternatively,

$$1[\text{dB}] = 0.1[\text{Bel}]. \tag{16}$$

The Bel represents a power ratio of 10:1, which is generally too large for most practical calculations. Hence, the subunit decibel, commonly referred to as "one-tenth of a Bel," as described by equations (15) and (16), was the accepted convention beginning from the quarter- to mid-twentieth century as the preferred unit in acoustics and engineering.[21, 27, 29] Equation (15) means that 10 decibels (as defined by an equivalent number of TUs) equals 1 Bel; it follows from equation (16) that 1 decibel equals one-tenth of a Bel.

It may seem that the explanation of the Bel and decibel is complete. Before that determination can be made, one must further probe the original definition of the TU. In a seminal paper on the decibel, J. W. Horton wrote:

> "The fundamental relations have been further confused by describing the decibel as one-tenth of a Bel when the truth is that its value is the tenth root of the value of a Bel." [Horton, 1954]."[14]

It is the relation between exponent values in corresponding power ratios, namely 0.1 for the decibel and 1.0 for the Bel that determines the one-tenth relation between the two quantities. As Horton astutely recognized,[14] both the Bel and decibel are defined in accordance with their respective power ratios, and these power ratios differ by a factor of one-tenth root, rather than the respective exponents in the ratios, which differ by one-tenth. The distinction is very subtle, yet it begs the question: Should the decibel be defined according to its prespecified power ratio of $10^{0.1}$ or some other variable such as the exponent in the power ratio, or logarithm of a ratio, or something else?

The power ratio must be the determining factor. One has only to re-examine the left-hand side of equations (6) through (9), which give the mathematical formulae for the TU. Note the denominator term of equation (8) includes the "practical measuring stick" for TU (and decibel equivalent), namely the power ratio given as $10^{0.1}$. In order to see this more clearly, additional options will be explored.

To make thc expression for the deeibel equate to a unity measure, a multiplieative faetor of 10 preeedes the logarithm in the definition. Notiee that, in the definition of the dccibcl (equation (10)), the balance between the multiplicative faetor of 10 preeeding the logarithm and the exponent of one-tenth following the logarithm brings the total expression to a value of unity. For the Bel, equation (13), only the logarithm of the ratio is required to obtain a "unity" valuc beeause it is based on a power ratio of 10^{1}. In the deeibel definition, the multiplieative faetor of 10 preeeding the logarithm preserves the one-tenth relation of power ratios for which the *TU* was originally defined. Consider a situation where the TU might have been otherwise defined. For example, let TU be defined by a one-twelfth relation between exponents in respeetive power ratios. A multiplieative factor of 10 would no longer suffice for describing a unity measure. A new expression would be required. By using the physical construet of equation (10) and replaeing the power ratio $10^{1/10}$ by $10^{1/12}$, one obtains:

$$\frac{\log_{10}(P_1/P_2)}{\log_{10}\left(10^{1/12}\right)} = N\left[\text{duo - deeibels}\right]. \tag{17}$$

$$12\cdot\log_{10}(P_1/P_2) = N\left[\text{duo - deeibels}\right]. \tag{18}$$

Based on a one-twelfth relation, a new multiplieative faetor, 12, must be used for redefining TU, and this new unit of measure would neeessarily replaee the term deeibel with a new term for eonnoting the revised one-twelfth relation, sueh as the duo-deeibel.

The determining faetor in these definitions is indeed the power ratio. Perhaps Horton[14] is emphasizing the point when he states that the value of thc decibcl is the tenth root of the value of the Bel. The power ratio $10^{0.1}$ for the ease of the deeibel, $10^{1.0}$ for the ease of the Bel, or $10^{1/12}$ for the ease of thc duo-deeibel in the present context is akin to a "measuring stiek" representing a unit quantity with the number 1 attaehed to it by applying to those ratios a logarithmie transformation of $\log_a(a)$, where a is both the base of the logarithm and the speeifie power ratio defining the unit quantity. (Also see equations (3) through (5).) Analogously, the unit measure for a bar length of 1 meter or yard is the number 1 when presented on a eommon linear seale that measures distanee in meters or yards. The numerator term (for example, equations (11) through (13) and (17)) ineludes a power ratio quantity that is divided by a unity measure (the denominator term) in whieh the total expression equals the sum of individual unity measures. In other words, the power ratio $10^{0.1}$ expressed in deeibels, $10^{1.0}$ expressed in Bels, or $10^{1/12}$ expressed in duo-deeibels, is the numerieal equivalent of 1 in eaeh of their respeetive units, just as a bar length of 1 meter or yard expresses a unit measure of length 1. Logarithmie operations are introdueed into the deeibel equation for mathematieal eonvenienee. Removing the logarithmic operation from equation (11) and substituting the power ratio by a length quantity L yields

$$\frac{L}{\text{unit length in meters or yards}} = N\left[\text{meters or yards}\right]. \tag{19}$$

Unit length is here defined as 1, the equivalent of a bar length of 1 meter or yard. L is an arbitrary distanee quantity (1, 2, 3, 4.5, or any other number), and N is the sum total of unit

lengths (including fractional lengths) in meters or yards comprising L, and equaling N [meters or yards]. In this simple example, like other examples in which the physical quantities L have values based on a linear measurement scale of base 10, the answer is simply $L = N$. Using this type of linear scale to define a measurement quantity seems like a trivial exercise, since any numerical quantity divided by one yields the same numerical quantity, whether the quantity be expressed as a length quantity (for example, meter, yard, nautical mile) or other physical quantity such as mass (for example, gram, pound, ton). Yet the physical construct that determines the value of a quantity is the same as that for decibels, except for equation (19), which avoids using logarithmic operations and power ratios in the description of a physical quantity (contrary to their use in equations (10) and (11) that define decibels)—the apparent source of the confusion in the use of decibels.

Although it may seem sometimes paradoxical, a logarithmic scale is used in describing decibels as a matter of mathematical simplicity and engineering convenience. There are a number of physical phenomena in nature including sound energy transmission and reception that appeal to the human senses logarithmically and are best understood when expressed on a logarithmic scale as opposed to a linear scale. For example, acoustic power is measurable over a range of values for sound sources as weak as 10^{-12} watts, the least detectable sound to the human ear, to values as high as 10^{2} watts that approach the human threshold of pain. By introducing the common logarithm (to the base ten) and the $10^{0.1}$ power relation as the unit measure for the TU and decibel, the linear scale, spanning a range of 10^{14} incremental acoustic power units, can be reduced on a logarithmic scale covering a much smaller range of units from 0 dB (the lowest of values) to approximately 140 dB, the highest of values in terms of their decibel equivalents. For most engineering work, application of the logarithmic decibel has been deemed much more practicable than attempting to keep track of all the incremental linear counterparts.

Horton's definition of the decibel[14] creates even more troublesome ground to cover. Because the denominator term (equation (10)) represents measurable quantities to which decibel values are attached, they must necessarily be associated with an absolute quantity. Some acousticians would argue that decibels are dimensionless quantities because the ratio of like quantities cancels out in the numerator and denominator. Yet this argument is no more correct than if to assert choosing a unit measure of 1 yard as the denominator quantity (equation (19)) in order to ascertain the number of bar lengths of 1 yard represented by a length quantity in the numerator term. The corresponding ratio would be dimensionless and other than units specified in yards. Experience, however, shows that this assertion is not so, and the same could also be said of decibel calculations.

Most practitioners would say that decibels are dimensionless quantities, and over time the scientific community has accepted this notion; however, decibels are measurable physical quantities whose units should always be specified within the context of their proper usage. If and when the authorities on international standards were to adopt a new unit of logarithmic decay (see subsection 3.5) as a unit quantity, then scientists would need to rethink the concept of dimensionless quantity, as such a quantity would hold equal stature to a length quantity (for example, 1 meter) or any other known physical quantity.

3.3 TYPICAL PHYSICAL QUANTITIES AND RATIOS OF QUANTITIES ASSOCIATED WITH LOGARITHMIC UNITS

Logarithmic quantities most often used in underwater acoustic applications are the logarithm of the ratio of two quantities of the same kind—two powers, two intensities, two voltages, two currents, or two sound pressures. Logarithmic quantities particularly dealt with are transmission path quantities, signal levels, frequency intervals, and decision content. For transmission path quantities and levels, one must deal with two sets of quantities (field quantities and power quantities), the ratios for which correspond to the logarithmic quantities.

Field quantity is a quantity such as voltage, current, sound pressure, electric field strength, velocity, and charge density, the square of which in linear systems is proportional to power. Power quantity is power or a quantity directly proportional to power, for example, energy density, acoustic intensity, and luminous intensity.[32]

3.4 MOST COMMON LOGARITHMIC UNITS: NEPER, BEL, AND DECIBEL

The most frequently used units for logarithmic quantities are the neper, Bel, and its submultiple, the decibel. The neper and the Bel are expressed as the logarithm of the ratio of the absolute values of two field quantities or of two power quantities. The use of the neper is typically restricted to theoretical calculations where this unit is most convenient. The Bel and decibel are logarithmic reference quantities, which, for a ratio of two power quantities correspond to ratios of 10 and $10^{0.1}$, respectively, and for a ratio of two field quantities correspond to ratios $10^{0.5}$ and $10^{.05}$, respectively. The neper is the logarithmic reference quantity, which, for a ratio of two field quantities, corresponds to the ratio e and, for a ratio of two power quantities, corresponds to a ratio e^2. The following relations in equations (20) and (21) hold between neper, Bel, and decibel.[32]

$$1\,[\text{Bel}] = 10\,[\text{decibels}] = 0.5\log_e(10)\,[\text{nepers}] = 1.151\,[\text{nepers}]. \tag{20}$$

Alternatively,

$$1\,[\text{neper}] = 2\log_{10}(e)\,[\text{Bel}] = 0.8686\,[\text{Bel}] = 8.686\,[\text{dB}]. \tag{21}$$

Although the neper, Bel, and decibel have been widely used in standard practice, the neper was formally proposed by the International Committee for Weights and Measures (CIPM) in 2001 as the primary International Standards (SI) unit for defining logarithmic decay (or gain).[33] The recommendation was made to members of the 21st General Conference on Weights and Measures (CGPM) but was never adopted. The proposers emphasized that, even if this new view were accepted, it in no way was meant to imply that the use of the Bel and decibel, for technical applications in acoustics and signal transmission or decay, should give way to the use of the neper. The following section elucidates on the use of power ratio quantities for expressing the logarithmic relation between two such quantities and the debate between the use of the neper versus decibel as a preferred unit for expressing such quantities.

3.5 DECIBEL VERSUS NEPER CONTROVERSY

In 1955, Hartley[22] noted a number of reasons for using a unit of logarithm: (1) for computational convenience, particularly when the logarithm is applied to base-ten units; (2) for theoretical and science-based calculations such as in describing wave motion or differential equations, where logarithms to the base e (that is, neper, symbol Np) are preferred and (3), for relating to some specific physical quantity, such as decay of power in a telephone transmission cable (subsection 3.2.2 described how the logarithmic TU has been applied to this usage).

In order to better understand and appreciate the origins and evolution of the decibel as a logarithmic unit and its usage over the past century, it is important to trace its early history. In doing so, one must revisit the decibel's main competitor, the neper. Logarithmic units to the base e (where e = 2.718. . .) are called nepers (the symbol for which is Np), named after its founder, John Neper, a 16th century Scottish mathematician. In 1924, around the time the decibel was first being proposed as a measure of power loss in telephone lines, a quantity of logarithmic decay, namely, the neper, had already been well-established in Europe. The standard was based on what was then called the "natural or ß*l* system" based on an attenuation or damping parameter b, associated with cable lines given by $b = 1.151 \log_{10}(P_1/P_2)$. The symbol ß represents a damping constant and the symbol l is a length parameter.

The ß*l* system was favored at the International Telephone Conference in Paris in 1910 and had been adopted exclusively on the European continent.[28] There was much debate at the time of the introduction of the TU—particularly from the German scientific community—between the two competing systems, the TU and ß*l*.[29] Like the decibel, which performs the same functions, the neper came into use in the middle 1920s, replacing the MSC. The decibel, however, became popular in Britain and America and is based on log to the base ten; the neper was used in continental Europe and the base of its logarithm was e. One neper approximately equals 8.686 decibels. (see equations (20) and (21) for relations.)

Breisig suggested one of the reasons for the early resistance to the TU was that the conversion requirement would entail a "great loss of ready working experience [particularly to those without high theoretical training]."[29] A second reason was the financial loss in scrapping old apparatus, and a third was based on the advice of the Conference at Paris in 1910 that a good system had already been introduced from the beginning.[30] In Berlin in 1923, Breisig proposed a compromise that the attenuation exponent 0.1 be called one deci and that transmission equivalents be expressed in decis, but his proposal was rejected by the majority of European telephone administrations.[30] Had Breisig's suggestion been accepted, the decibel as it is now known, might have been called by the prefix deci without the consonant bel attached to it.

The debate over choosing one unit as the preferred international standard was never completely resolved, but a compromise was made when the two units, neper and Bel (and subunit decibel), were deemed acceptable for worldwide practice by the European International Advisory Committee to European administrations on long distance telephone.[31] As already mentioned, the Bel was named after Alexander Graham Bell, founder of the Bell Systems. The Bel and decibel were largely used on the North American continent; the neper remained in use in Europe. From time to time, the debate between choosing either the decibel or neper as the

preferred international standard has resurfaced. At the present time, however, recommendations for one standard logarithmic unit as a primary (or coherent) unit quantity have been tabled by the prevailing scientific authorities.

As recent as 2001, I. Mills, along with two other eminent scientists, made a strong case that the neper be considered as the primary unit of logarithmic decay (or gain).[33] The 21st CGPM convened in 2001 to consider a resolution proposed by the CIPM (from the Consultive Committee for Units (CCU) in matters concerning international standards) that the neper should be considered as the primary unit for defining logarithmic decay (or gain). The recommendation, however, was not (nor has it since been) adopted by the CGPM.

It is somewhat ironic that the neper was again brought to the forefront more than 75 years after it was first proposed as a standard quantity for power decay in transmission lines by Breisig.[28] The Bel and decibel have shared a similar fate of not being recognized formally as an SI unit; however, the neper, Bel, and decibel are acknowledged by the CGPM, as units outside the SI, as being recognized and accepted for worldwide practice on an informal, if not formal, pragmatic basis.

In order to appreciate why the debate between decibel and neper continues long after the concept of the neper was proposed, the remainder of this section provides salient information, such as the underpinnings of logarithmic decay and the relevance of these two units.

A typical application of logarithmic decay of an oscillating signal, whose amplitude decays exponentially over distance (for example, through a communications line) is given by

$$S(l) = S_0 \cdot e^{-ßl}, \tag{22}$$

where $S(l)$ is the oscillating signal, ß is a damping coefficient and l is a length or distance parameter (which could be substituted by t, a time parameter). From equation (22), one obtains

$$D = \ln(S(l)/S_0) = -ßl \ [\mathrm{Np}], \tag{23}$$

where D is the logarithmic decay and ln is the symbol for $\log_e$, the natural logarithm (to the base e). D is expressed in equation (23) in units of nepers (Np). Note that, for an amplitude ratio of $S(l)/S_0 = 1/e$ (or e), there is a logarithmic loss (or gain) of –1 Np (or + 1 Np). Recall that, in subsection 3.2.1, it was shown that the unit logarithm for an arbitrary system is expressed as $\log_a a$, where a is the ratio of powers and logarithmic base of the system in question.[22] Because the power P is proportional to the square of the amplitude, given that $P(l) = P_0$ when $S(l) = S_0$, one obtains

$$P(l)/P_0 = (S(l)/S_0)^2. \tag{24}$$

With the help of equation (4), which allows for the conversion of power units expressed in logarithms to the base e^2 to equivalent units expressed in logarithms to the base e, the power level L_p as a logarithmic decay to the base e is given by

$$L_P = (1/2)\ln(P(l)/P_0) = \ln(S(l)/S_0)\ [\mathrm{Np}]. \tag{25}$$

This research is interested in power levels and the relations between nepers, Bels, and decibels. First, an equivalency relation among the three unit quantities must be obtained. From equations (13), (14), and (25), one can start with the following generalized form given any ratio of two powers:

$$L_P = (1/2)\ln(P(l)/P_0)\ [\mathrm{Np}]. \tag{26}$$

$$L_P = \log_{10}(P(l)/P_0)\ [\mathrm{Bel}]. \tag{27}$$

$$L_P = 10\log_{10}(P(l)/P_0)\ [\mathrm{dB}]. \tag{28}$$

By substitution of the numerical value of 10 for the power ratio $P(l)/P_0$ in these formulae, the following relation is obtained:

$$L_P = (1/2)\ln\ (10)[\mathrm{Np}] = 1.151\ [\mathrm{Np}] = 1\ [\mathrm{Bel}] = 10\ [\mathrm{dB}]. \tag{29}$$

Note that equation (29) is consistent with equations (20) and (21).[32] The obvious question is: if there is a mathematical equivalency among the three unit quantities, how does one determine which unit quantity should be considered the primary unit and the remaining units considered secondary? A follow-up question is: Does it even matter?

If one were to consider the neper as the primary unit and the Bel and decibel as secondary units, according to Hartley's description of interrelated systems of logarithmic units,[22] the secondary unit expressed as logarithm to base 10 quantity in the present context is related to the primary unit expressed as a logarithm to the base e quantity by transformation of logarithmic bases via equation (4). In this manner, units of Bel and decibel have each been derived as a secondary (that is noncoherent) unit to the primary (coherent) neper unit; however, because the primary unit was arbitrarily chosen in the first place, there is nothing prohibitive (at least from a purely mathematical perspective) from defining the Bel (and its submultiple, the decibel) as the primary unit for logarithmic power decay and making the neper a secondary unit.

One observes from equations (26) through (29) that the two systems are quite interchangeable. Breisig argued there is little scientific gain, if any, to be had by switching from the older "ß*l*" system, already in widespread use by Europeans for over a decade, to the newly proposed TU (and eventual dB) system, especially since equipment and records had been established earlier using the older system.[30]

There is a looser, if not scientific, argument that an irrational-number-based system (that is, e = 2.718...) is less practical in the ß*l* system than is a decimal-based system. Thus, over the

long run, calculations would become easier to follow along with measurement data—a claim that some might arguably reject, given the current confusion that persists with decibel usage today.

Lushen[34] argued that the claim that the ß1 system is irrationally based and less practical is completely false because the attenuation or damping factor b (or ß1) expressed in decimal notation (that is, TU) is $b = 1.151 \log_{10}(P_1/P_2)$; moreover, the damping coefficient ß can be physically related to the resistance of the line conductor R, inductance L, and capacitance C by the expression $\beta = R \cdot (C/L)^{0.5}$ while the number of TUs is obtained from the expression $N = 8.686 \cdot \left(R(C/L)^{0.5}\right)$. According to Luschen, the transcendental number that crops up in TU calculations negates all arguments that the ß1 system is less tractable, particularly since the two systems are deemed to be interchangeable, accounting for round-off errors. Luschen also argues that, because the natural ß1 system is scientifically based, the natural-based units would be more suitable for standard use.[34]

From a scientific perspective, Mills, Taylor, and Thor made the case for choosing the neper as the preferred unit for describing logarithmic decay in power because its description as a logarithmic quantity met with all the scientific guidance and criteria for acceptance according to SI standard units.[33] Their recommendation to adopt the neper (rather than the Bel or decibel) was meant in no way to deprecate the use of the decibel or Bel, nor was it meant to imply replacement of the decibel and Bel in acoustics and signal transmission applications that have been commonly accepted into standard practice for many decades.

Arguments were made by opponents of the TU system that there were no substantive advantages to changing from the old to the new system, even though there were claims by some, mostly on the American side, that a decimal-based system would be easier to follow than a system based on an irrational number (for example, e = 2.718...). Thus, it was no real surprise that, during the international conference that took place in Europe in 1924 to discuss telephone industry standards, the European International Advisory Committee adopted both recommended units. It is an interesting fact that, to this day, although it has been considered a number of times, the decibel has never been formally recognized as an official standard measure by the SI authorities. Nonetheless, the Bel and its sub-multiple decibel have gained worldwide acceptance by practitioners in engineering and the sciences ever since its first adoption by Bell Systems more than 85 years ago.

3.6 JUSTIFICATION FOR USING A MEASUREMENT QUANTITY OF POWER IN COMPUTING TU AND DECIBEL

Because dissipation of power is what really matters in telephone systems—as in other systems involving energy transmission—Purves maintained that the practical unit of telephone transmission should be based on the idea of power loss.[35, 36] Purves noted that there is no practical difference whether the working unit of attenuation is based on voltage, current, or power. Purves stated:

> "The whole object of telephony is the transmission of acoustic tones. The first necessity is a device for collecting the sound energy wave of the voice, or the source, and the last necessity is a device for conveying the energy of similar sound waves to the ear, that is to say the first and last links in the chain of telephone design are the mouthpiece of the transmitter and the earpiece, or horn, of the receiver. The only measure of efficiency of the system is the ratio of the sound input power to the sound output power delivered by the ear-piece.[35, 36]

In all other parts of the electrical system, the associate power decrements make up the only true measure of transmission loss. Purves goes on to say:

> "The attenuation of power, therefore, remains the only thing which measures the work done by the initial energy in all parts of the system."[35, 36]

The analogy given by Purvis is also valid for acoustic systems today, although the terminology has changed somewhat. Attenuation losses in the modern sonar equation are special energy losses due to molecular interactions of the moving wavefront with the medium and heat absorption by the medium induced from such interactions (see section 4 for a broader discussion). It is interesting that most underwater acoustieians today will use the modern definition of attenuation as an absorption loss,[37, 38] yet there remain a number of professionals who will revert to the definition of attenuation as generalized energy losses from the earlier context.

As different parts of a telephone circuit have different effieiencies, the transmission efficiencies of various parts could be represented as indices taken as the ratios expressing changes in powers between the various points. The combined effect would be expressed as a product of a number of ratios. Such calculations were deemed cumbersome for engineering calculations; hence, the common logarithm (to the base 10) of these ratios was introduced so that the aggregate effect of individual ratios could be more easily computed from the sum of the individual parts.

Power is a measureable physical quantity, yet the dB and its predecessor, the TU, defined by 10 times the logarithm to the base 10 of the ratio of two powers, is typically interpreted as dimensionless; however, the attachment of the deeibel to a physical power quantity should not be obscured. Also, a ratio of the physical units is expressed as a division (or multiplication), and the logarithm of the ratio is expressed as a difference (or sum), mainly for ease in computation.

According to F. B. Jewett,[39] then Vice President of the American Telephone and Telegraph Co., the two powers (for example, equations (26) to (28)) need not be in electrical form: they could be the powers in airwaves or at points in any vibrating mechanical system. Jewett further maintained that it is not necessary that either or both powers be speech power, and it is not required that one power be derived from the other. The two powers may be both at the same point in the line and of different character such as speech power and noise power. Moreover, one of the powers may be at a point in one line, and the other at a point in a second line as in comparing crosstalk with speech power.[39] It is obvious that there are numerous variations to the theme of a ratio of powers for computing TUs or dBs. The following section shows why acoustical power plays such a major role; moreover, within this theme, there are sub-themes wherein power may also be substituted for voltage and current in a number of instances.

3.7 MODERN USAGE OF THE DECIBEL: PHYSICAL QUANTITIES AND STANDARD REFERENCE QUANTITIES

In modern usage, when absolute measurements—rather than just gains or losses in power level—are required, the denominator term in the ratio of quantities measured or estimated is often expressed as a referenee quantity. In this way, even though deeibels are eonsidered by many as dimensionless quantities, the absolute physieal quantity, upon whieh the deeibel level is based, is retained. For instanee, the standard referenee unit aeeepted by most underwater aeoustieians is 1 mieropascal (1 μPa); the most preferred standard referenee unit in air acoustics is 20 μPa. Uriek emphasizes that "the deeibel is a comparison of intensities or energy densities, rather than direetly of aeoustie pressures."[37] The expression dB re 1 μPa is an abbreviated form of "dB re the intensity of a plane wave of pressure equal to 1 μPa."* The nuanee is often overlooked. When work is done in a single medium, typieally the square of the pressure is used. This praetiee is permissible beeause intensity is proportional to pressure-squared, and, in computing power ratios, the eommon aeoustie impedanee drops out of the ealeulation. The intensity is inversely proportional to the aeoustie impedanee of the medium in whieh the aeoustie wavefront travels. Where more than one media is concerned (such as in air-to-water transmissions and viee versa), full intensity referenee quantities must be applied beeause aeoustic impedanees are known to greatly differ between propagation media. Note also that the mieropaseal is a unit of pressure (equal to foree per unit area) and intensity is proportional to the pressure-squared.

Intensities and pressures are typieally measured by performing an average of instantaneous levels over a finite time interval. Another type of measurement is the energy density, whieh is a measure of the sum of instantaneous levels over a finite time interval; for this type of measurement, the term sound energy level (SEL) has eome into praetiee. The SEL is based on the sound intensity level averaged over some time duration, typieally on the order of seeonds or less; therefore the referenee quantity for SEL is written dB relative to 1 μPa^2-see (see subseetion 5.2.1).

One observes from the modern definition of the deeibel, still generally defined as the old definition (see equation (11)), that the one-tenth power relation has been preserved by a multiplieative faetor equal to 10 preeeding the logarithm, in aeeordanee with the original definition of TU. Further, the most preferred standard physical referenee unit of sound energy is the aeoustic intensity I. Power P is equal to intensity times area as deseribed by equation (30):

$$P\ [\text{watts}] = I\ [\text{watts per square meter}] \times \text{Area}\ [\text{square meters}], \tag{30}$$

where the reference power is typically taken to be 10^{-12} W (1 picowatt).

Conversely, aeoustie intensity I is expressed in units of power per unit area or watts per square meter (W/m^2), given by the following:

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* The symbolic notation for reference quantities found in the scientific literature is widely varied. The most common notations for "decibel relative to 1 micropascal" are "dB//1 μPa" or "dB re 1 μPa." For decibel relative to 1 micropascal-squared notations most commonly used are "dB//1 μPa^2 or "dB re 1 μPa^2.

$$I\left[\mathrm{W/m^2}\right] = P[\mathrm{W}] / Area\left[\mathrm{m^2}\right], \tag{31}$$

where the reference intensity typically used is 10^{-12} W/m^2. Acoustic intensity, however, is rarely measured directly. Underwater microphones, called hydrophones, measure the pressure (amplitude) of a sound wave rather than its intensity. The intensity is related to acoustic pressure p by the following expression:

$$I = p^2/(\rho c). \tag{32}$$

The intensity of a sound wave is directly proportional to the square of its pressure and inversely proportional to the medium density and the speed of sound in the medium. The product of denominator terms, medium density times the sound speed in the medium (ρc), goes by a number of names: specific acoustic resistance, specific acoustic impedance, characteristic impedance, or just acoustic impedance. The acoustic impedance is a characteristic of the medium in which the sound propagates. In seawater, ρc approximately equals 1.5×10^5 g/(cm^2)(sec), and, in air, it approximately equals 42 g/(cm^2)(sec).[37] An approximate ratio of ρc for seawater-to-air used in nominal calculations is 3600. This number may vary slightly depending on temperature conditions. From equation (32), the ratio of intensities, seawater-to-air, given the same pressures, must therefore equal 0.000278, the inverse of the impedance ratio (that is, 1/3600).

The relative intensity, I_{REL} (dB), in decibels is calculated as the ratio of the estimated or measured absolute intensity I_{ABS} of a sound wave to a known prescribed reference intensity:

$$I(\mathrm{dB}) = 10\log_{10}(I_{\mathrm{ABS}}/I_{\mathrm{REF}}). \tag{33}$$

If the sound pressure being measured and the reference pressure are taken from the same medium (water, for example), then the acoustic impedance cancels out of equation (33) and the intensity in dB can be computed directly from the measured pressure:

$$I \sim p^2. \tag{34}$$

To be able to compare relative intensities given in dB to one another, a standard reference intensity or reference pressure should always be stated. It is, therefore, essential that sound levels expressed in decibels include the reference pressure. Scientists have agreed to use 1 µPa as the reference pressure for underwater sound. For air pressure, scientists most typically use 20 µPa as a standard value, which is about the least perceptible sound to the human ear. Pressures are described as an applied force over an area. To put these reference units in perspective, 1 µPa is equivalent to a pressure equal to one one-hundred-thousandth (10^{-5}) of 1 dyne-per-square-centimeter, also referred to as "1 microbar," which is one million times smaller than atmospheric pressure, where 1 atmosphere equals 14 pounds-per-square-inch. That is to say, the preferred reference pressure in water, 1 µPa, is one hundred billion times smaller (10^{-11}) than standard atmospheric pressure. Hence, measureable pressure quantities can be quite small indeed.

4. BASIC SONAR EQUATIONS

The detection, classification, and localization performance of a sonar system depends on many factors. Two major factors are the dynamic ocean environment and operator level of proficiency. For passive systems, target-radiated noise, receive apparatus, ambient noise, hydrodynamic flow noise and shipborne internal noise are other relevant factors. For active systems, transmit and receive apparatus, target echo reflectivity, ambient noise, hydrodynamic flow noise, shipborne internal noise, and reverberation interference are the other relevant factors.

The "L" terms expressed in decibels in the sonar equation (described in subsections 4.1.1 and 4.1.2) represent measured or estimated quantities with respect to some reference quantity in which 1 micropascal is most typically used for modern calculations. In earlier applications of the sonar equation, 1 microbar (that is, the equivalent of 1 dyne per square centimeter) was the preferred standard reference quantity; however, in practice, microbars as reference quantities are rarely, if ever, used anymore. To convert a given level refereneed in microbars to a level referenced in micropascals, one has simply to add 100 dB to that level.

A distinction between levels and quantities should be made here. Levels are described by decibels where a decibel is 10 times the logarithm of the ratio between two (physical) quantities. Quantities are physical units (for example, power, intensity, pressure) upon which decibel levels are computed.

The "N" terms in the sonar equation represent relative differences between two levels as either gains or losses. For example, N_w represents a difference between two levels at some specified range R and a reference distance R_0 of 1 meter (or 1 yard). The N_{DI} term represents the difference in levels between a directional beam and an omnidirectional beam, and the N_{RD} term represents a ratio of the signal level to the background interference level. In underwater acoustics terminology where decibel notation is most frequently used, a ratio (or division) of two physical quantities, where each quantity is expressed in absolute physical terms, is expressed as the difference between the two levels when converted to decibels (see section on decibels).

When logarithmic differences are calculated between two quantities q_1 and q_3, for example, where each quantity shares the same associated reference quantity q_2, and where q_2 is an absolute physical quantity, such as 1 μ Pa, the standard reference quantity most often used in underwater acoustics, the reference quantity is automatically divided out, but should never be forgotten. The N terms carry along the baggage of their L counterparts but leave behind any associated reference quantities. In a sense, as the sonar equation fills out temporally and spatially, the N terms seem to be just going along for the ride.

$$N(\text{dB}) = 10\log_{10}(q_1/q_2) - 10\log_{10}(q_3/q_2) = 10\log_{10}(q_1/q_3) \tag{35}$$

In equation (35), note the seeming disappearance of the reference quantity q_2. Although the q_2 subtracts out of the equation, its significance as a physical quantity remains.

4.1 ACTIVE SONAR EQUATION

In active sonar there are two fundamental performance limitations, one caused by the ambient background noise, and the other by reverberation. In general, one or the other will dominate, so that the two effects can be initially considered separately.

4.1.1 Noise-Limited Sonar Conditions

Under noise-limited conditions:

$$N_{SE} = L_S - 2N_W + N_{TS} - (L_N - N_{DI}) - N_{RD}. \tag{36}$$

$$N_W = 20\log(R/R_0) + \alpha R \quad \text{(Spherical Spreading Law)}, \tag{37}$$

$$N_W = 10\log(R/R_0) + \alpha R \quad \text{(Cylindrical Spreading Law)}, \tag{38}$$

where N_{SE} is the signal excess, L_S is the source level, N_W is the propagation loss (or transmission loss) where R and R_0 are as defined in section 4, N_{TS} is the target strength, L_N is the noise level, N_{DI} is the directivity index of the array (an approximation to the array gain), and N_{RD} is the recognition differential. N_W typically comprises two components, one a geometric (for example, spherical, cylindrical) spreading law wherein sound energy traveling outward from its source location covers an ever increasing area like the surface of an expanding balloon so as to diminish the intensity as the square-of-the range, with increasing range (spherical spreading law). In shallow-water environments with surface and bottom boundaries in proximity, sound energy traveling outward covers an area similar to the surface of an expanding balloon inside a circular hat box with expanding sidewalls so as to diminish the intensity as range to the first power, with increasing range (cylindrical spreading law). The second component is the absorption loss (with range-dependent coefficient α) due to molecular interaction of the moving sound wave and the medium. At higher and higher frequencies (that is, rapid oscillations of the water molecules), more and more sound energy is absorbed by ocean medium. The terms combined in equation (36) comprise the generic noise-limited sonar equation expressed in units called decibels (section 3). Although decibel units represent the ratio of power-like quantities and appear as dimensionless, all of the sonar equation parameters are traceable to physical quantities and should be so specified. Typically, they are expressed as the following physical quantities:

1. L_S : dB//1 μPa^2 / Hz@1 meter (or 1 yard*) – These symbols are read as source level in units of decibels relative to 1 micropascal squared, measured in (an equivalent) energy band 1 Hz wide and at a projected distance of 1 meter (or 1 yard) from the center of the acoustic source. Note micropascal squared represents a physical quantity of pressure-squared, which is proportional to the acoustic intensity of a moving plane wave in the undersea channel, and although the majority of measurements in underwater acoustics are collected in units of pressure

* An additive correction of 0.78 dB should be applied to sonar equation calculations when a reference distance of meters is being converted to a reference distance of yards (that is, 20log (39.37/36) = +0.78).

(or voltage), it is the acoustic intensity (watts/meter^2) that is the accepted standard reference quantity for underwater sound energy.

The directed source level is dependent on the radiated acoustic power and transmit directivity index:

$$N_{DI(T)} = 10\log(I_{DIR}/1_{OMNI}),$$

where I_{DIR} is the intensity level of a directional projector and I_{OMNI} is equivalent to the intensity level of an omnidirectional projector, resulting in the same total acoustic power.

The source level energy band 1 Hz-wide is associated with a central frequency component, also in units of Hz, which should be so specified. For source level energy bands exceeding 1 Hz in which the frequency spectrum within the band is relatively continuous and flat (for example, ≤ -6 dB per octave), the following conversion formula can be used to obtain an equivalent 1-Hz-wide spectrum level at the central frequency (that is, the geometric mean frequency (GMF)) of the extended band, where GMF $= \sqrt{F_1 F_2}$ and F_1 and F_2 are frequencies of the lower and upper band limits, respectively.

$$L_S\ (\text{in 1 - Hz band}) = [L_S(\text{in extended frequency band})] - [10\log_{10}(\text{extended bandwidth in Hz})].$$

2. N_W : dB – These symbols are read as propagation loss in units of decibels. Propagation loss is the loss in signal strength with increasing distance from the acoustic source located at a reference distance R_o of 1 meter (or 1 yard); therefore, propagation loss, when combined with signal strength, $L_S - N_W$, can be traced to the same physical quantities of L_S.

3. N_{TS} : dB – These symbols are read as target strength in units of decibels. Target strength provides a measure of the reflective gain or loss from an ensonified target of interest. The geometry is such that the target strength is calculated from a plane wave incident on a target and reflected back to a point 1-meter (or yard) from the target acoustic center. Target strength is a physical extension of the signal strength propagating through the undersea medium and reflecting back as an echo; therefore, when taken collectively with other sonar parameters (that is, $L_S - N_W + N_{TS}$, it can be traced to the same physical quantity of L_S.

4. L_N : dB//1 μPa^2 / Hz – These symbols are read as background noise level in units of decibels relative to 1 micropascal squared, measured in (an equivalent) energy band 1 Hz wide. With the exception of the 1-meter (or yard) reference quantity for L_S, the same rules apply to L_N for ascertaining the physical quantities associated with it. In noise-limited conditions, there are two types of background interference that must be considered: (1) ambient ocean noise that is frequency dependent and generally range independent and (2) the sonar host platform-generated self-noise that is frequency dependent, and, for moving platforms, is also platform speed, that is, hydrodynamic flow, dependent.

5. N_{DI} : dB – These symbols are read as receiving directivity index in units of decibels. The directivity index provides a measure of the gain in signal versus noise that is achieved through electronic summing of hydrophone elements into a sonar array. The elements are summed in a manner that forms a sonar beam in which directional noise is discriminated from omnidirectional noise using a single hydrophone element. The term "receiving directivity index" (N_{DI}) is typically associated with a theoretical value, and when actual measurements are collected at sea, the term "array gain" (N_{AG}) is frequently used in its place. Since N_{DI} is a physical extension of the total background interference, when combined with L_N (that is, $L_N - N_{DI}$), it can be traced to the same physical quantity of L_N.

6. N_{RD} : dB – These symbols are read as recognition differential in units of decibels. The recognition differential is the minimum signal-to-noise ratio at which the sonar system's signal processor, display apparatus, and operator are estimated to detect a target signal at a given range, with an associated 50 % detection range probability (that is, $P_D = 0.5$ and pre-specified likelihood, however small, of expected false alarms (for example, $P_{FA} = 0.0001$). Because N_{RD} is a statistical quantity, it of necessity makes the entire sonar equation and individual sonar parameters statistical in nature. Hence, in plain form, the sonar equation is a statistical predictive model for estimating sonar detection ranges, which is supported by the definition of signal excess, N_{SE} (explained in item 7). When $N_{SE} = 0$ dB, equation (36) can be rewritten to show that N_{RD} is dependent on all the other sonar parameters: $N_{RD} = L_S - 2N_W + N_{TS} - (L_N - N_{DI})$. The physical quantities associated with N_{RD} are those traced to sonar parameters L_S and L_N described above; they are also the same quantities associated with N_{SE} (see below for amplified discussion).

7. N_{SE} : dB – These symbols are read as signal excess in units of decibels. A signal excess (N_{SE}) of 0 dB equates to a detection probability of 50% ($P_D = 0.5$) and a pre-specified false alarm probability (for example, $P_{FA} = 0.0001$). Positive or negative values of N_{SE} equate to detection probabilities correspondingly higher or lower. N_{SE} represents the decibel equivalent of a ratio of physical quantities. In decibel notation, the numerator is represented by the total received signal level $L_S - 2NW + N_{TS}$ and the denominator by the total received noise level $L_N - N_{DI}$. Hence, the sonar equation is an expression of signal-to-noise ratio, and, on the face of it ratios of physical quantities, are sometimes interpreted as being dimensionless. However as was explained in subsection 3.8, all decibel units are traceable to respective physical quantities. In the case of N_{SE} and its sonar terms, the numerator component carries all the physical baggage incorporated in the L_S term (defined above) and the denominator component carries all the baggage of the L_N term (also defined above). Note that there is complete consistency in physical quantities of the signal and noise components; namely, they are both traceable to the same physical units of micropascal squared in a 1-Hz band (or some other equivalent band) and can be either implicitly or explicitly converted to physical quantities of acoustic intensity, the preferred reference quantity for most sonar calculations.

4.1.2 Reverberation-Limited Sonar Conditions

When active sonar is used, scattering occurs from small objects in the sea as well as from the bottom and surface. This scattering can be a major source of interference that occurs only with active sonar operations. Backscattered sound energy raises the level of sonar interference at the receiver. This scattering phenomenon is called reverberation; the level of interference is the reverberation level. Scattering within a volumetric patch of the ocean is called volume scattering. Scattering effects from the ocean surface are typically referred to as either "surface" or "boundary scattering." Scattering from the ocean bottom is also a type of boundary scattering, but is most commonly referred to as "bottom scattering."

In reverberation-limited conditions,

$$N_{SE} = L_S - 2N_W + N_{TS} - (L_R) - N_{RD}, \tag{39}$$

where other terms (with assumed spherical spreading) are defined as before, and

$$L_R = L_S - 40\log_{10} R + S_V + 10\log_{10} V \quad \text{(Volume Scattering Reverberation)}, \tag{40}$$

$$L_R = L_S - 40\log_{10} R + S_S + 10\log_{10} A \quad \text{(Bottom Scattering Reverberation)}, \tag{41}$$

R is the range to the volumetric or area reverberation patch, S_V *and* S_S are volume and surface scattering strengths, respectively, and V and A are volumetric and boundary area patches, respectively, which are complicated functions of frequency, pulse duration, range from emitter to patch, sound speed, and the transmit and receive beam patterns. The reverberation equations clearly show that, for any specified increase or decrease in an emitted source level (L_S), the reverberation level (L_R) will increase or decrease an equal amount; moreover, the two-way propagation loss term ($40\log_{10} R$) clearly shows that reverberation level is dependent on range or distance traveled from the source with the highest levels being closest to the source. Note that equations (40) and (41) demonstrate that the determining quantity in physical units is that traceable to the source level term L_S, as defined earlier, corrected for distance R, which is the propagation loss to and from the reverberation patch (that is, $L_S - 40\log_{10} R$). This reverberation level L_R is the background interference component analogous to the L_N of the previous section and has the equivalent units of $\mathrm{dB}//1\,\mu\mathrm{Pa}^2/\mathrm{Hz}$.

Note also that under reverberation-limited sonar conditions, in accordance with equations (42) and (43), an increase (or decrease) in source level L_S can only result in an equivalent increase (or decrease) in the corresponding reverberation level. In the noise-limited case for active sonar conditions and for passive sonar as well, an increase in source level improves the figure-of-merit, thereby enhancing detection range potential; the same cannot be said of all reverberation-limited situations. In fact, there are subtle tradeoffs where reduction in source level can actually be advantageous under certain conditions as was the case during recent parametric sonar testing and evaluations performed by the Naval Undersea Warfare Center (NUWC) Division, Newport, Rhode Island from 2001 – 2004.[40]

4.2 PASSIVE SONAR EQUATION

Passive sonar systems "listen" without transmitting. Although passive sonar systems are often employed in military settings, they are also used in scientific applications, for example, detecting presence or absence of animal life in various marine environments.

Unlike active sonar, only one-way propagation is involved in passive sonar. Because of the different types of sonars deployed and signal processing used, the recognition differential for a 50% probability-of-detection-range estimation will be different for each sonar—active and passive. The equation for determining the performance of a passive sonar is

$$N_{SE} = L_S - N_W - (L_N - N_{DI}) - N_{RD}, \tag{42}$$

where N_{SE} is the signal excess, L_S is the source level, N_W is the transmission loss, L_N is the noise level, N_{DI} is the directivity index of the array (an approximation to the array gain) and N_{RD} is the recognition differential. The figure of merit (N_{FM}) of a passive sonar is

$$N_{FM} = L_S - (L_N - N_{DI} - N_{RD}). \tag{43}$$

Notice that the passive figure-of-merit contains all of the terms in the passive sonar equation except for propagation loss. N_{FM} is a versatile function: (1) it is useful for determining the estimated 50% detection range for any propagation loss environment at an equivalent level of N_W and (2) it can also be applied to active sonar computations under noise-limited conditions (note, however, that the active N_{FM} requires the addition of a target strength term N_{TS}, and the two-way propagation requires a division by two of the computed N_{FM} to obtain an N_{FM} for a one-way propagation loss 50% detection range equivalency).

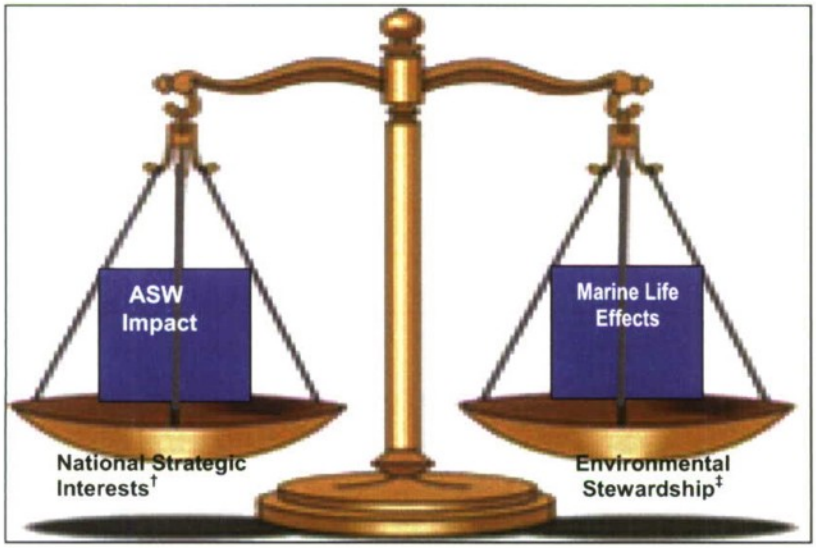
5. MODELING MARINE BEHAVIORAL EFFECTS

5.1 BALANCE OF REQUIREMENTS

Federal regulations governing activities that may affect the environment include U.S. Navy training and testing activities in the maritime environment. Therefore, the potential environmental impact of Navy training and testing must be quantitatively assessed. In an effort to comply with applicable environmental laws, the U.S. Navy in recent years has been modeling active sonar performance and the estimated behavioral effects of sonar on marine mammals.

The laws and regulations and their interrelationships with active sonar emissions in the marine environment are quite complex. For more than a decade, the Navy has struggled with a myriad of law suits emanating from nongovernment organizations aimed at curtailing active sonar use during military training operations. While defending against these law suits and complying with environmental laws, such as the MMPA, the Navy must also comply with Section 5062 of Title 10 of the US Code (USC), which legally mandates the Navy to defend and protect the Nation. Title 10 directs the CNO to organize, train, and equip all Naval forces for combat. The Navy must strike a balance to ensure U.S. national security interests are upheld and full compliance with environmental regulations and statutes is maintained (see figure 1).

Marine Mammal Mitigation Measures
(Navy must maintain Title 10 obligations and environmental compliance.*)



*Recent Supreme Court hearing (November 2008) rules in favor of decision that vacates a preliminary injunction imposing restrictions on the Navy's sonar training, and thereby, the scales are kept in balance.[41]
†Navy has national defense responsibility to determine mitigation impact on ASW performance.
‡ Navy has stewardship responsibility to collect scientific data on marine mammal behaviors and habituations.

Figure 1. Benefits and Risks Must Be Balanced

5.2 MODELING SONAR EFFECTS ON MARINE MAMMAL BEHAVIOR

The Navy continually collects, evaluates, and updates scientific data to ensure they are the best available and applies these data to physics-based modeling to not only assess antisubmarine warfare (ASW) performance capabilities, but also to estimate the potential impact of its active sonar training activities on marine mammals. The modeling of ASW performance has become a matured activity after many decades of experience, collective knowledge, and empirical verification and therefore will not be addressed here. Modeling the effects of active sonar on marine mammal behavior, however, has been a fairly recent undertaking—only within the last two decades. This section therefore focuses on the methodologies and practices undertaken by the Navy to model the behavioral effects of sonar on marine mammals.

5.2.1 Metrics Used For Estimating Physiological Effects

There are a number of metrics that are useful for measuring sonar effects on marine mammals. Some of the key metrics most commonly used are mentioned here. For a more elaborate discussion including pitfalls in their application and use, the reader is referred to Carey's "Sound Sources and Levels in the Ocean"[10] and Madsen's "Marine Mammals and Noise: Problems with Root-Mean-Square Pressure Levels for Transients."[42] Two of the most common measurement quantities are (1) the root-mean-squared energy referred to as the "sound pressure level" (SPL) and (2) the energy flux density sometimes referred to as the "sound energy level" (SEL).*

The rms of a plane wave in a time window from 0 to T is given by Madsen:[42]

$$p_{rms} = \left[1/T \int p^2(t)dt\right]^{0.5}, \tag{44}$$

where

$$\mathrm{SPL}_{\mathrm{rms}} = 10\log_{10}\frac{\left[1/T \int p^2(t)dt\right]}{(p_{\mathrm{REF}})^2} \quad [\mathrm{dB}//1\,\mu\mathrm{Pa}], \tag{45}$$

and where both integrals in equations (44) and (45) are evaluated from 0 to time T, usually in milliseconds. In equation (45), $(p_{\mathrm{REF}})^2$ is the reference pressure-squared, and the reference sound pressure is 1 micropascal ($1\,\mu\mathrm{Pa}$).[19]

The energy flux density or SEL is similar to the rms SPL but contains an extra term to account for the elapsed time integration of an elongated pulse. The energy flux density or SEL is given by

$$\mathrm{SEL} = 10\log_{10}\int p^2(t)dt = 10\log_{10}\left[1/T \int p^2(t)dt\right] + 10\log_{10}(T) \quad [\mathrm{dB}//1\,\mu\mathrm{Pa}^2\text{-sec}]. \tag{46}$$

* SEL is proportional to energy, and SPL is proportional to power. The relationship between power and energy is given by: power = energy/time.

Madsen cautions that, for rms calculations of certain transient pulses, calculations can vary by greater than 10 dB depending on the analysis time-window applied to the calculation.[42] Carey also points out some of the hazards in working with peak or peak-to-peak measures in attempting to perform model predictions.[12] (Clearly, there is fertile ground for further research and investigation in defining additional standard metrics.)

Computed SELs are used to construct permanent threshold shift (PTS) and temporary threshold shift (TTS) estimations, and SPLs are used to estimate non-TTS effects. A more detailed discussion on PTS, TTS and non-TTS is given in subsection 5.2.3, which described how these modeled parameters are used to model the behavioral effects on various categories of marine species.

5.2.2 Implementation of Sonar Equation Parameters for Modeling Sonar Effects on Marine Mammals

Modeling of the potential sonar effects on marine mammals has been and will continue to be required in order to maintain environmental compliance. This effort includes continual technical and data acquisition support to maintain continual updates to environmental analyses as required by the regulatory authorities. These analyses require some level of quantitative analysis and data output from an effects model execution to provide predictions of estimated levels of behavioral disturbance to marine mammals prior to Navy training exercises and testing. This quantitative assessment is required—particularly for the MMPA and the Endangered Species Act (ESA)—because of the regulatory agencies need to issue authorizations for a specified number of level of harassments. Figure 2 provides an overview of how modeling is generally employed to determine the potential effects of sonar on marine mammal behavior.

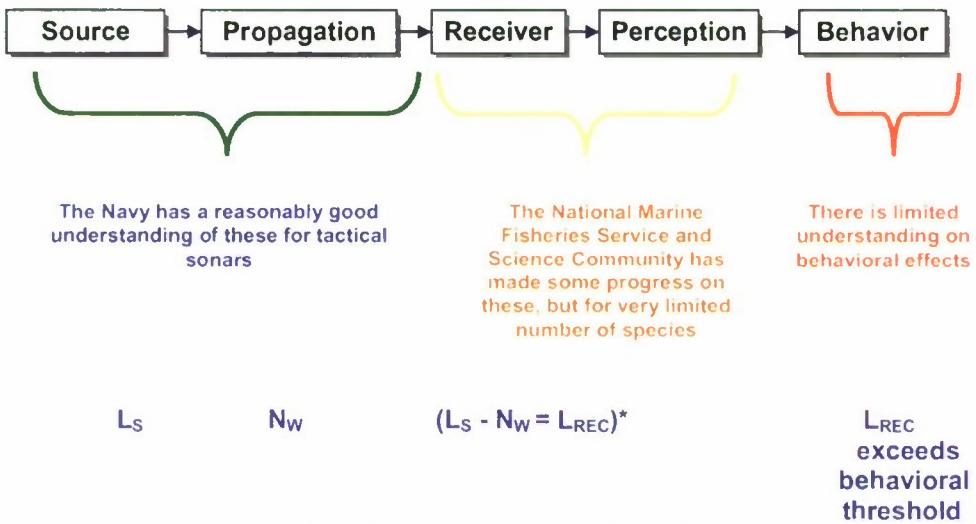


Figure 2. Model Paradigm To Determine Behavioral Effects Based on Best Available Science

As depicted in figure 2, there are a number of required steps for modeling behavioral effects. Modeling, by its very nature, provides only an estimate, and therefore must be predicated on the best available science and sound scientific practices. In the capacity to perform modeling and analysis predicated on best available science, there are areas of strength and weakness for best assessing behavioral effects. On the chart from left to right (figure 2), modeling the acoustic source and propagation through the ocean medium are areas of strength. In acoustic source technology, the design and implementation of fielded active sonars is mature and has been studied and modeled for several decades, as have the propagation characteristics of active sonar emissions through the underwater environment.

The next two categories, receiver and perception, are difficult undertakings to model. Unlike the ASW problem in which the receiver consists of the receiving sonar array, signal processor, and display and perception is the human interactive element to call out a detection, for behavioral effects modeling, one must postulate from the best available science how the marine mammal receives and perceives an active sonar emission. As one might expect, there is limited scientific data available to support modeling animal recognition differential and behavioral response. Lacking such data, one can attempt to model animal response based on the receive level L_{REC} at the face of the animal, where $L_{REC} = L_S - N_W$, and observe animal behavioral response from these types of measurements.

Currently there are three ongoing programs in the Navy to collect such measurements. The Marine Mammal Program (MMP) at the Space and Naval Warfare Center (SPAWAR), San Diego, CA conducts highly controlled, hearing-threshold-response experimental testing using animals in captivity. The second program is the Behavioral Response Studies (BRS), an ongoing research program primarily funded under the National Oceanic and Atmospheric Administration (NOAA), the Office of Naval Research (ONR), and the Office of the Deputy Chief of Naval Operations (DCNO). The program is supported by leading researchers from government, industry, and academia. Marine mammals are tagged (with noninvasive suction cups) in the wild, and their dive profiles, habituation, vocalizations, and acoustic response patterns are electronically recorded for later retrieval. The third program is the Marine Mammal Mitigation and Response (M3R) Program, also supported by the ONR and the DCNO, in which opportunistic detections of marine mammal vocalizations are recorded from bottom and moored sensors in Navy test sites in the Bahamas and off the coast of Southern California.

5.2.3 Regulatory Framework Upon Which Acoustic Models are Based

Pursuant to the MMPA, an applicant (in this case, the Navy) is required to estimate the number of animals that will be affected by their activities. This estimate lets the regulatory agency, the National Marine Fisheries Service (NMFS), determine what analysis must be performed to determine whether the activity will have a negligible impact on the species or stock and whether the activity warrants authorization. The Navy and NMFS have agreed to a paradigm for modeling marine mammal effects that considers the sound energy at the animal and the potential for either physiological or behavioral reactions. The following paragraphs describe how these categories are defined and applied to effects modeling.

Modeling is used by the Navy and regulatory agencies for estimating the potential impacts from Navy training activities on marine mammals. The goal of this modeling effort is to provide estimates of marine mammal exposures to anthropogenic sound to ascertain quantitative measures of behavioral disturbances to marine mammals. The desired effect of the modeling is to obtain, based on the best available science, quantitative estimates of physiological and behavioral harassment levels, for guiding regulatory decision-making.

For military readiness activities, MMPA Level A harassment includes any act that injures or has the significant potential to injure a marine mammal or marine mammal stock in the wild. Injury, as defined in Navy analyses and previous NMFS rulings, is the destruction or loss of biological tissue.

For military readiness activities, MMPA Level B harassment includes all actions that disturb or are likely to disturb a marine mammal or marine mammal stock in the wild through the disruption of natural behavioral patterns including, but not limited to, migration, surfacing, nursing, breeding, feeding, or sheltering to a point where such behavioral patterns are abandoned or significantly altered.

The most familiar effect of exposure to high intensity sound is hearing loss, meaning an increase in the hearing threshold. This phenomenon is called a noise-induced threshold shift (NITS), or simply a threshold shift (TS).[43] A TS may be either permanent, in which case it is called a permanent threshold shift (PTS), or temporary, in which case it is called a temporary threshold shift (TTS). The distinction between PTS and TTS is based on whether there is a complete recovery of a TS following a sound exposure. If the TS eventually returns to zero (that is, the threshold returns to the pre-exposure value), the TS is a TTS. If the TS does not return to zero but leaves some finite amount of TS, then that remaining TS is a PTS.

Figure 3 shows two hypothetical TSs, one TS that completely recovers, TTS, and one that does not completely recover, leaving some PTS. Although both auditory trauma and auditory fatigue may result in hearing loss, the mechanisms responsible for auditory fatigue differ from those that are responsible for auditory trauma and would primarily consist of metabolic fatigue and exhaustion of the hair cells and cochlear tissues. Note that the term auditory fatigue is often used to mean TTS; however, the Navy analyses use a more general meaning to differentiate fatigue mechanisms (for example, metabolic exhaustion and distortion of tissues) from trauma mechanisms (for example, physical destruction of cochlear tissues occurring at the time of exposure). Auditory fatigue may result in PTS or TTS but is always assumed to result in a stress response. The actual amount of TS depends on the amplitude, duration, frequency, and temporal pattern of the sound exposure.

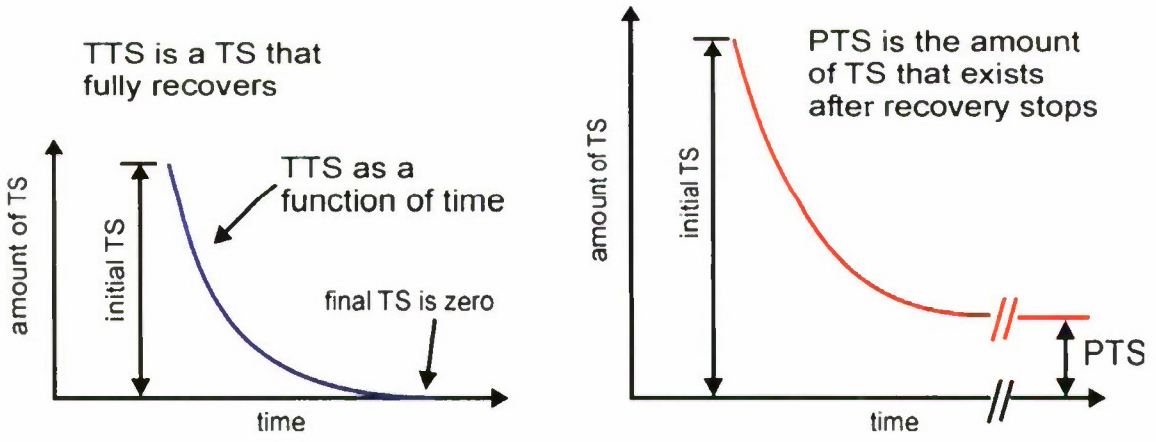


Figure 3. Relationship of TTS and PTS Recovery Characteristics[44]

Some physiological responses to sound exposure can occur that are noninjurious, but they can potentially disrupt the behavior of a marine mammal. These responses include temporary distortions in sensory tissue that alter physiological function but are fully recoverable without tissue replacement or regeneration. For example, an animal that experiences a TTS suffers no injury to its auditory system, but may not perceive some sounds because of the reduction in sensitivity. As a result, the animal may not respond to sounds that would normally produce a behavioral reaction. This lack of response qualifies as a temporary disruption of normal behavioral patterns—the animal is impeded from responding in a normal manner to an acoustic stimulus. Navy analyses assume that all levels of TTS (slight to severe) are considered Level B harassment, even if the effect from the temporary impairment is biologically insignificant.

The harassment status of slight behavior disruption (without physiological effects) has been addressed in workshops, previous actions, and previous NMFS rulings. The conclusion is that a momentary behavioral reaction of an animal to a brief, time-isolated acoustic event does not qualify as Level B harassment. A more general conclusion, that Level B harassment occurs only when there is a potential for a significant behavioral change or response in a biologically important behavior or activity, is found in recent NMFS rulings. Public Law 108-136[45] amended the definition of Level B harassment for military readiness activities, which applies to sonar training activities as described above. These conclusions and definitions, including the 2004 amendments to the definitions of harassment, were considered in developing conservative thresholds for behavioral disruptions.

The volumes of ocean in which Level A and Level B harassment are predicted to occur are described as harassment zones. The Level A harassment zone extends from the source out to the distance and exposure at which the slightest amount of injury is predicted to occur. The acoustic exposure that produces the slightest degree of injury is therefore the threshold value defining the outermost limit of the Level A harassment zone. Use of the threshold associated with the onset of slight injury as the most distant point and least injurious exposure takes account of all more serious injuries by inclusion within the Level A harassment zone. For mysticetes (baleen whales) and odontocetes (toothed whales, dolphins, and porpoises), Level A harassment is predicted to occur when animal exposure has an accumulated received SEL of 215 dB re 1 μPa^2-s), defined as onset PTS. The Level B harassment zone begins just beyond the point of

slightest injury and extends outward from that point to include all animals with the potential to experienee Level B harassment. The animals predieted to be in the portion of the zone where temporary impairment of sensory function (altered physiologieal funetion) is expeeted are all assumed to experience Level B harassment because of the potential impediment of behaviors that rely on acoustic eues. Beyond that distanee, the Level B harassment zone eontinues to the point at whieh no behavioral disruption is expected to occur. There are two measures of Level B harassment, TTS and non-TTS. TTS includes any act that results in a temporary, noninjurious reduction in hearing sensitivity and is predieted to oeeur when animal exposure has an aeeumulated reeeived SEL of 195 dB re 1 μPa^2-s. Non-TTS is a Level B harassment that results in a behavioral reaetion without a threshold shift.

At exposure levels below those whieh ean eause TTS, animals may respond to the sound and alter their natural behaviors. Whether or not these alterations result in a potential for a significant behavioral change or response in a biologically important behavior or activity depends on the physieal eharaeteristies of the sound (for example, amplitude, frequeney charaeteristics, temporal pattern, and duration) as well as the animal's experience with the sound, the eontext of the exposure (for example, what is the animal doing at the time of the exposure), and the animal's life history stage. Responses will be speeies-speeifie and must consider the aeoustie sensitivity of the speeies.

For Navy analyses, a risk funetion is used to determine the outer limit of the portion of the Level B harassment zone attributable to significant changes in biologieally important behaviors, but not a funetion of TTS. The risk funetion defines a probability of a significant change in biologically important behaviors as a funetion of the reeeived SPL, consistent with the eoneept that the probability of a behavioral response generally declines as a funetion of deereasing exposure level. Figure 4, a two-dimensional depietion of exposure zones from a notional sound source, illustrates the general relationships between harassment zones and does not represent the sizes or shapes of the actual harassment zones. The Level A harassment zone extends from the souree out to the distance and exposure where onset-PTS is predicted to occur. The Level B harassment zone begins just beyond the point of onset-PTS and extends outward to the distanee and exposure where no (biologically signifieant) behavioral disruption is expeeted to oeeur. The Level B harassment zone ineludes both the region in whieh TTS is predicted to occur and the region in whieh signifieant behavioral responses without TS are predieted to oeeur. As already mentioned, this latter zone of non-TTS is based on a probabilistie risk function.

The exposure zone for non-TTS exposure is depicted in three dimensions in figure 5, along with PTS and TTS exposure zones.[46] Note that, for PTS and TTS exposures, the probability limits are based on a Heaviside funetion (namely, 100 % exposure within boundary limits and 0% exposure outside the limits). For a non-TTS exposure the likelihood of exposure follows a probability distribution funetion that drops off with increasing range.

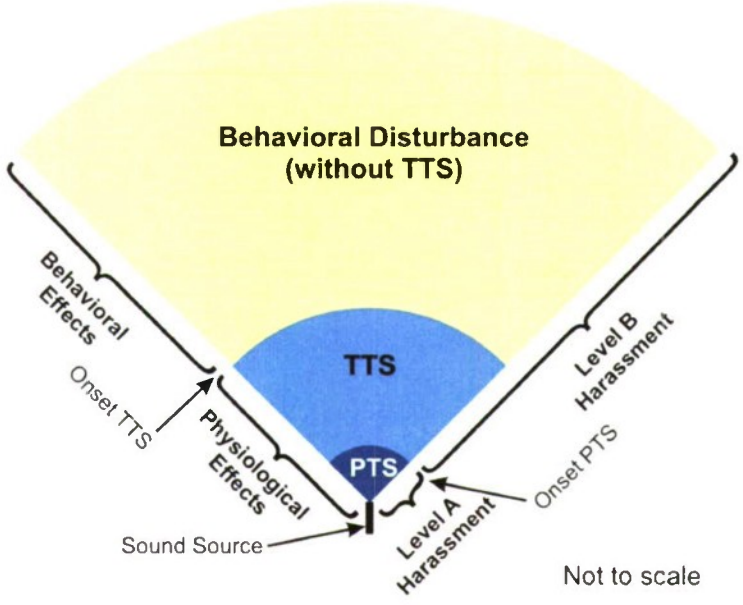


Figure 4. Two-Dimensional Depiction of Exposure Zones from a Notional Sound Source

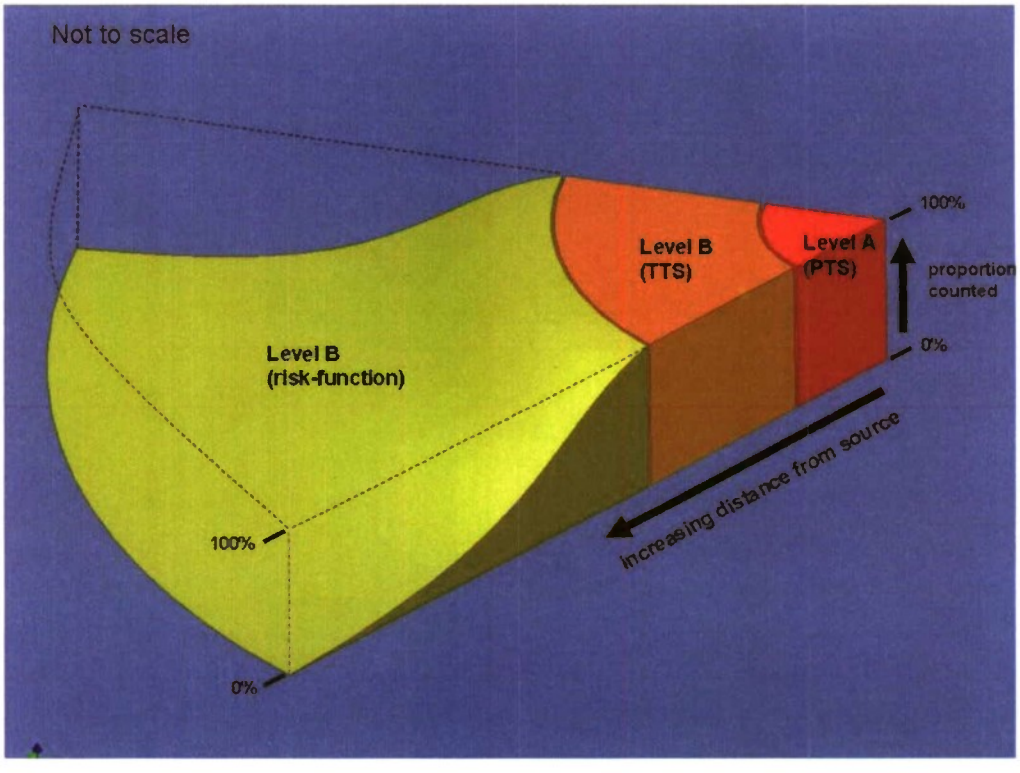


Figure 5. Notional Depiction of Exposure Zones for PTS, TTS, and Non-TTS in Marine Mammals[*]

[*] This figure, provided by Colin Lazauski of the Naval Undersea Warfare Center, Division Newport, RI, was published in "NAVSEA NUWC Keyport Range Complex Extension Environmental Impact Statement/Overseas Environmental Impact Statement," Keyport, WA, May 2010.

Illustrated examples of the type of risk function from which the non-TTS exposures are generated are provided in figures 6a and 6b for odontocetes and mysticetes, respectively (figure 6a also includes pinnipeds).

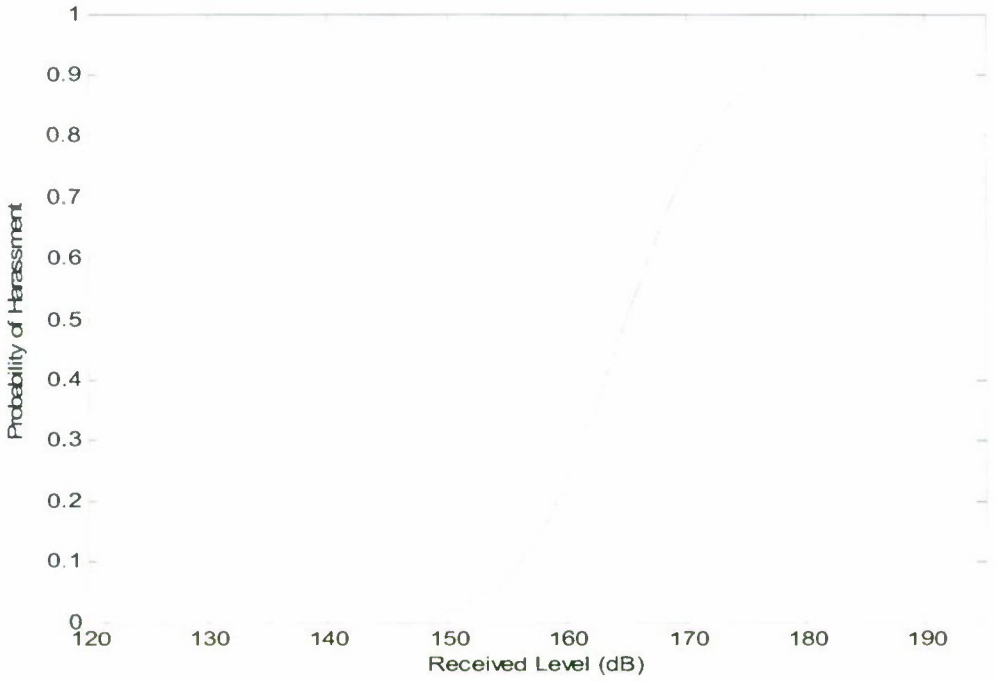


Figure 6a. Notional Example of Risk Function Curve for Odontocetes (Toothed Whales Except Harbor Porpoises) and Pinnipeds

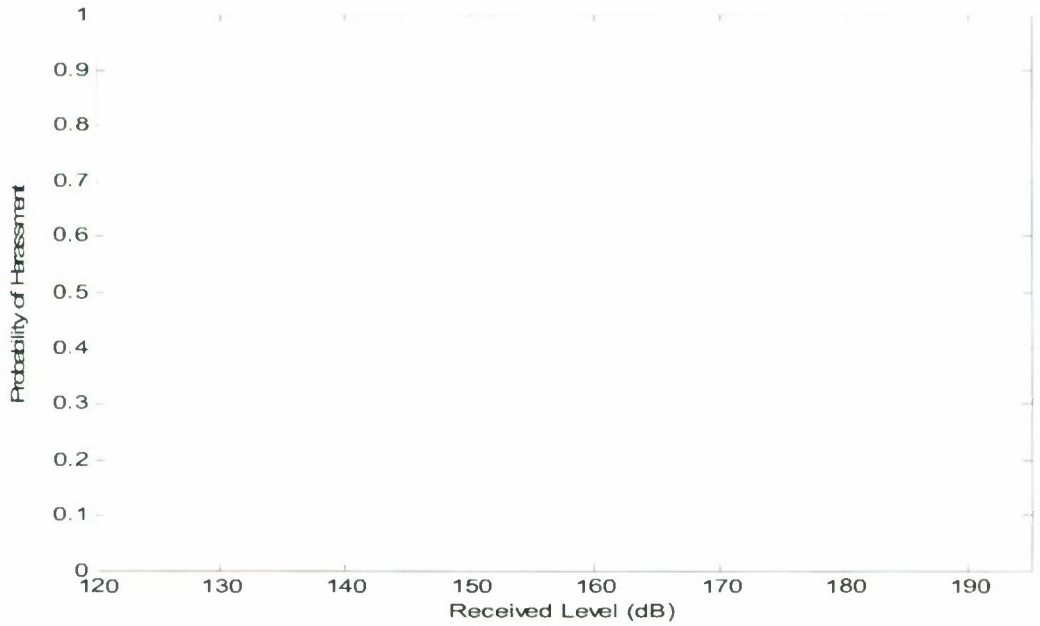


Figure 6b. Notional Example of Risk Function Curve for Mysticetes (Baleen Whales)

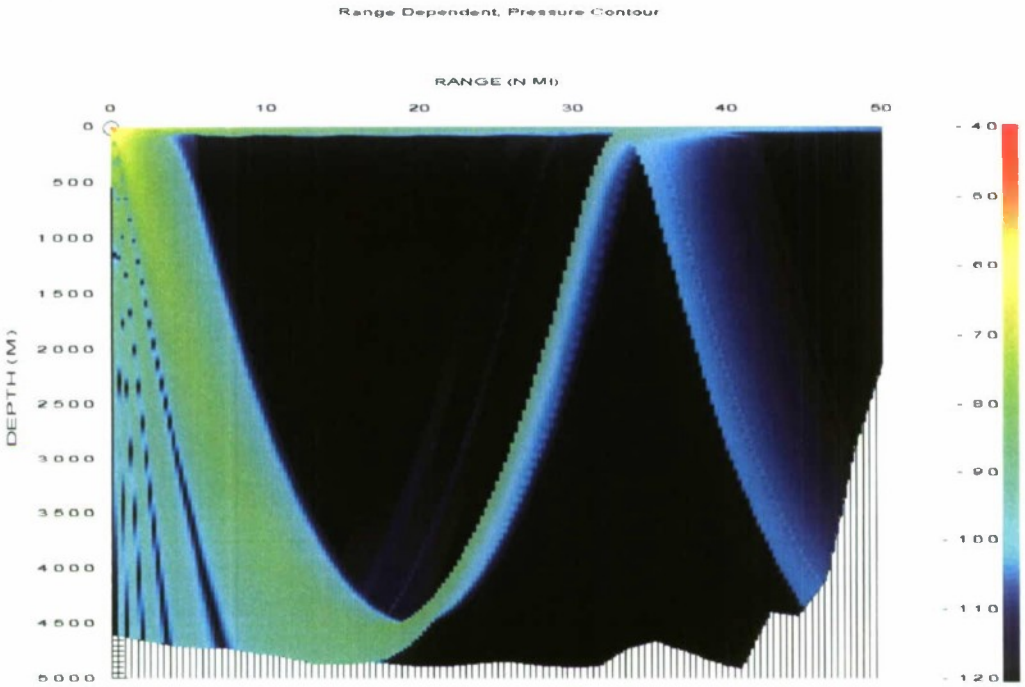
Level B harassment from behavioral harassment (non-TTS) is predicted when the modeled maximum received SPL exposure to a marine mammal results in a probability of greater than 0.5 based on the risk function. The risk function, as illustrated in figures 6a and 6b, that defines the probability of behavioral response of a marine mammal, given a specific maximum received SPL, is provided below:

$$R = \frac{1 - \left(\frac{L - B}{K}\right)^{-A}}{1 - \left(\frac{L - B}{K}\right)^{-2A}}, \tag{47}$$

where R = risk (0 – 1.0); L = received SPL in dB re 1 μPa; B = basement received SPL in dB, (B = 120 dB re 1 μPa); K = received SPL increment above basement in dB at which there is 50% risk (K = 45 dB re 1 μPa); and A = risk transition sharpness parameter (A = 10 for pinnipeds and odontocetes (except harbor porpoises (*Phocoena phocoena*)) and A = 8 for mysticetes).

The actual modeled exposure zone is three dimensional and thus will depend on the sound propagation characteristics of the undersea environment. Underwater sound propagation can be very complicated. Figure 7 illustrates the intricacy of acoustic sound rays as they propagate through the undersea channel. The three-dimensional exposure zones are determined by computing SELs and SPLs as a function of range and depth from the radiating acoustic source.

(a)



(b)

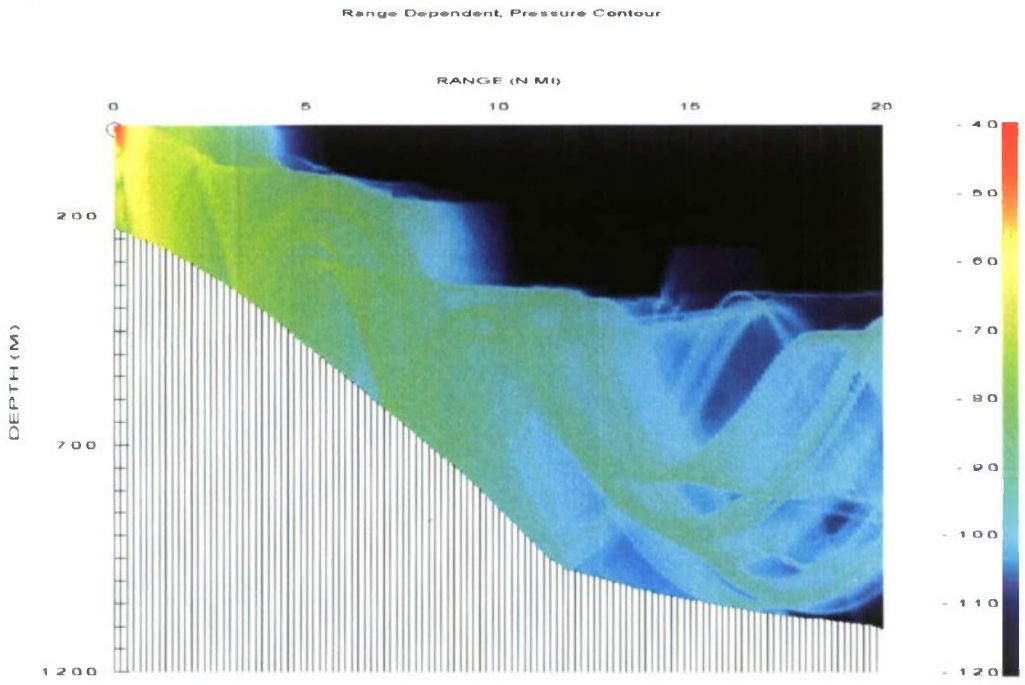


Figure 7. Illustrated Acoustic Sound Pressure Field in the Marine Environment for (a) Deep-Water Conditions and (b) Shallow-Water Conditions)*

(Red, yellow, and green show the highest intensity levels; light and dark blue show the lowest levels.)

* Figures provided by Joanne Santaniello of the Naval Undersea Warfare Center Division, Newport, RI.

The Level A exposure zone extends from the source out to the distance and exposure at which the slightest amount of injury is predicted to occur, the threshold value defining the outermost limit of the Level A exposure. The Level B exposure zone begins just beyond the point of slightest injury and extends outward from that point to include all animals that may possibly experience Level B harassment (TTS and non-TTS). Because of the Level B exposure zone using accumulated sound energy (TTS) and the risk function (non-TTS), there is a partial overlap with the consideration of potential behavioral disturbance assessed using the risk function, which is a received SPL. This overlap is considered conservative in that it may "double-count" potential exposures, and ensures both physiological and behavioral effects are sufficiently considered.

Ascertaining levels of disturbance is a challenging problem for the Navy, the marine mammal science community, and the regulators. Figure 8 illustrates the full spectrum of behavioral responses that are possible. A clear picture of behavioral significance and insignificance is yet to be resolved among the community stakeholders and remains the top research priority. Recommendations for ascertaining marine mammal exposure criteria are synopsized in a comprehensive report by B. L. Southall, et al.[13]

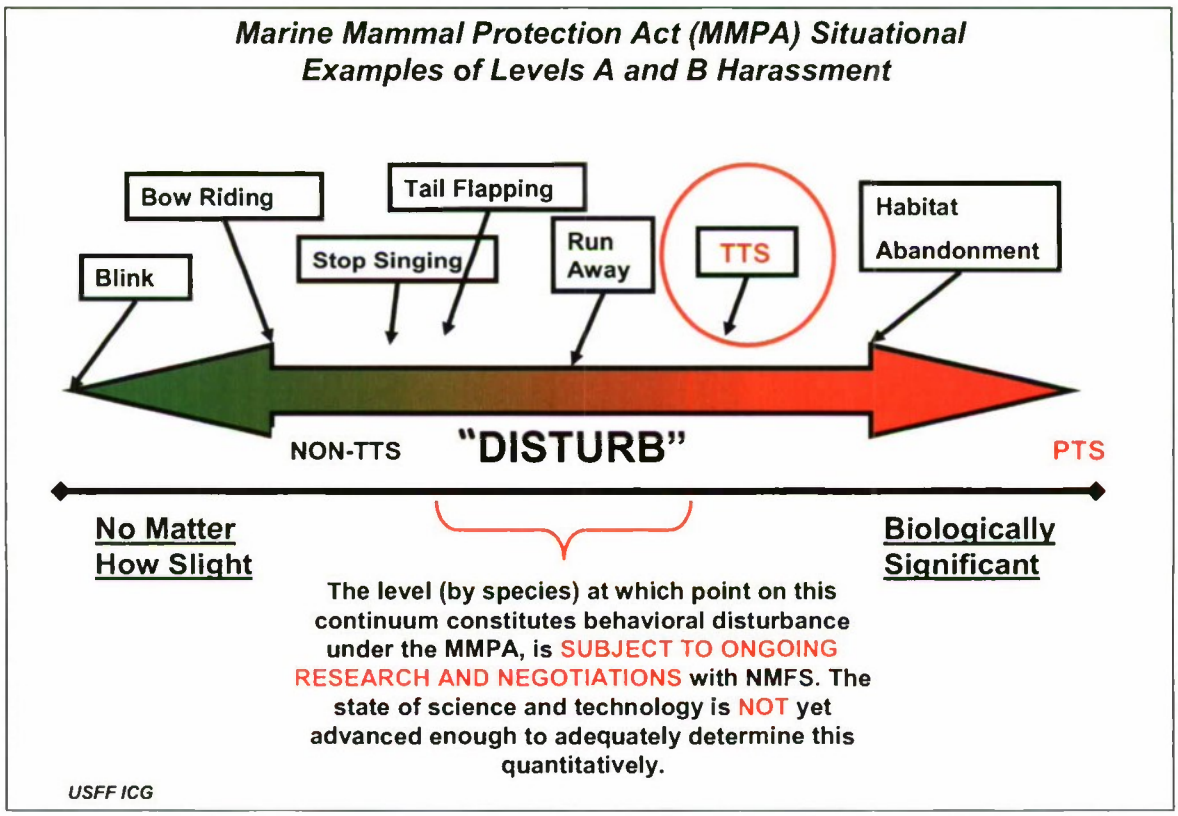


Figure 8. Spectrum of Possibilities for Ascertaining Biological Significance

5.3 AMBIENT NOISE MODELING

Modeling ocean noise to evaluate the effects of sonar on marine mammal behavior is an important contributing factor to accurate sonar prediction. Variations in measured or estimated contributions to ambient noise levels in ocean ambient noise (that is, those contributions to the sonar equation that are independent of the transmit and receiving array and target parameters) can have a direct impact on the overall sonar performance.

The receiving sensitivity of the marine mammal is estimated based on the minimum sound level at which the animal can detect an incoming signal, be it manmade or conspecific to a particular species or groups of species. The level of animal sensitivity will vary over a broad range of frequencies, as depicted in the figure 9, which shows estimated hearing thresholds for three groups of marine mammals: odontocetes (toothed whales), mysticetes (baleen whales), and pinnipeds (seals and sea lions). Superposed on these graphs are estimates of average minimal ambient noise levels worldwide. The y-axis for the ambient noise curve is spectral level in 1-Hz frequency bands with units of dB re 1 $\mu Pa^2/Hz$. The x-axis (horizontal) is the frequency of a sound on a logarithmic scale.

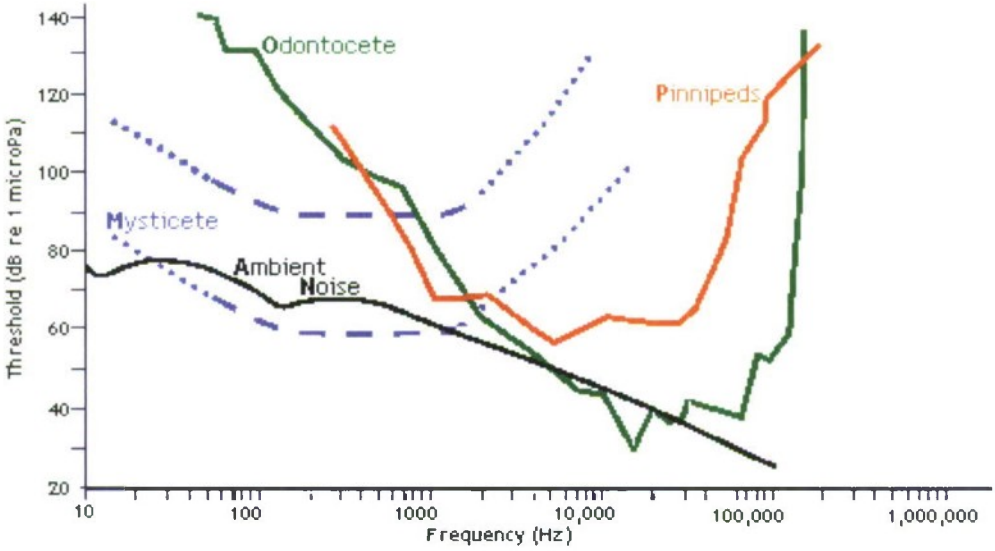


Figure 9. Hearing Sensitivities of Selected Species of Marine Mammals Superposed on Low-Level Ambient Noise

Note that practically all levels of animal sensitivity in the frequency band of approximately 15 Hz to 200 kHz, except for the region between 5 kHz and 50 kHz, are above minimum ambient levels by as little as 3 – 5 dB to greater than 60 dB—suggesting a wide range of adaptation to changes in sounds in the ocean environment. The average sensitivity levels shown in figure 9 do not necessarily stay the same with increased ambient levels. It is not unlikely that sensitivity levels shown in figure 9 will change based on the animal's ability to mask unwanted noise. Figure 10 demonstrates the variability in ocean ambient noise from a host of different source mechanisms. Figure 11 demonstrates ambient noise variability based on sea state and rain-dependence alone. Both sets of curves (figures 10 and 11) were obtained from the National Research Council (NRC) report on ocean noise and marine mammals.[47]

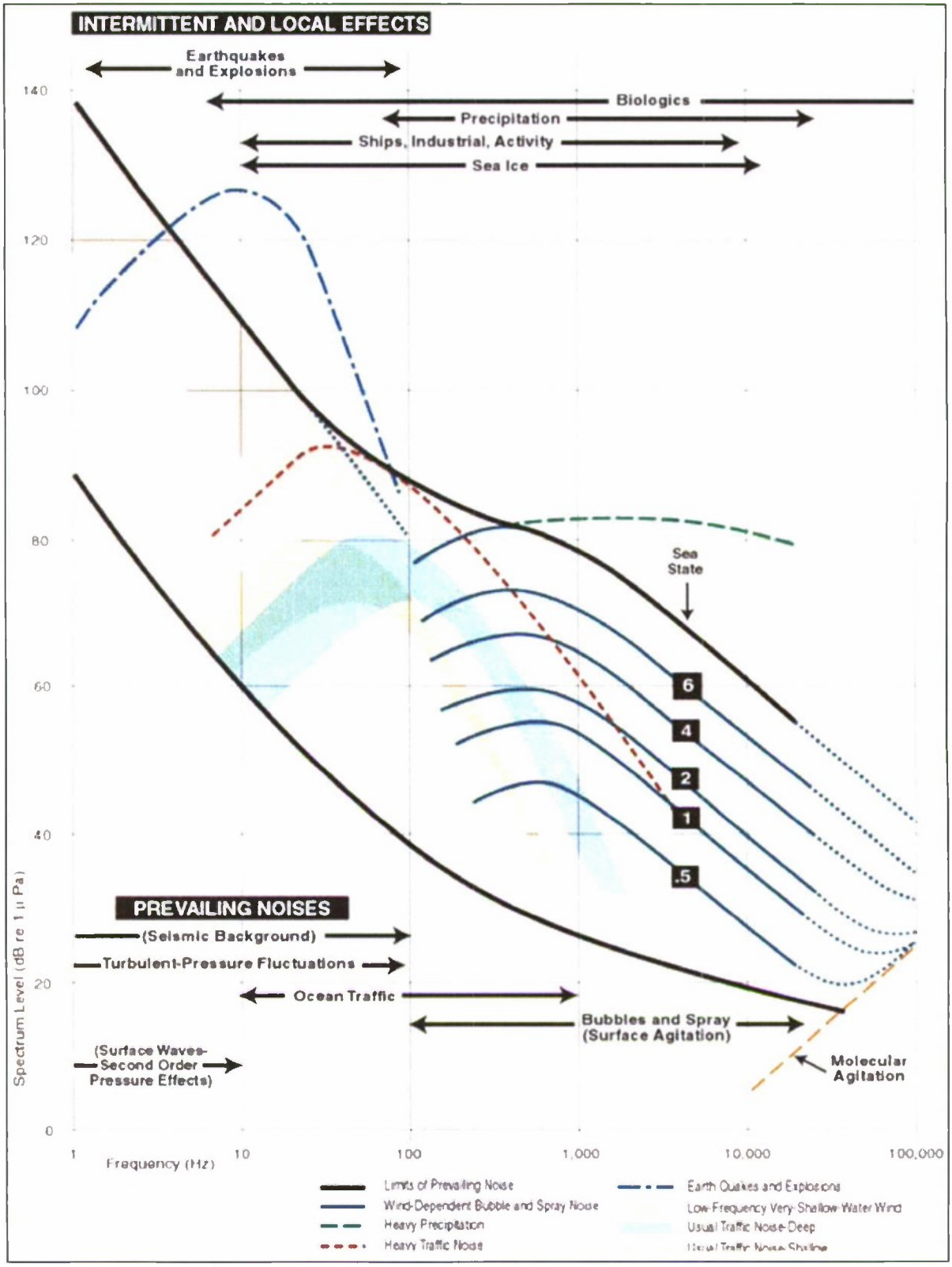


Figure 10. Wenz Ambient Noise Curves[47]

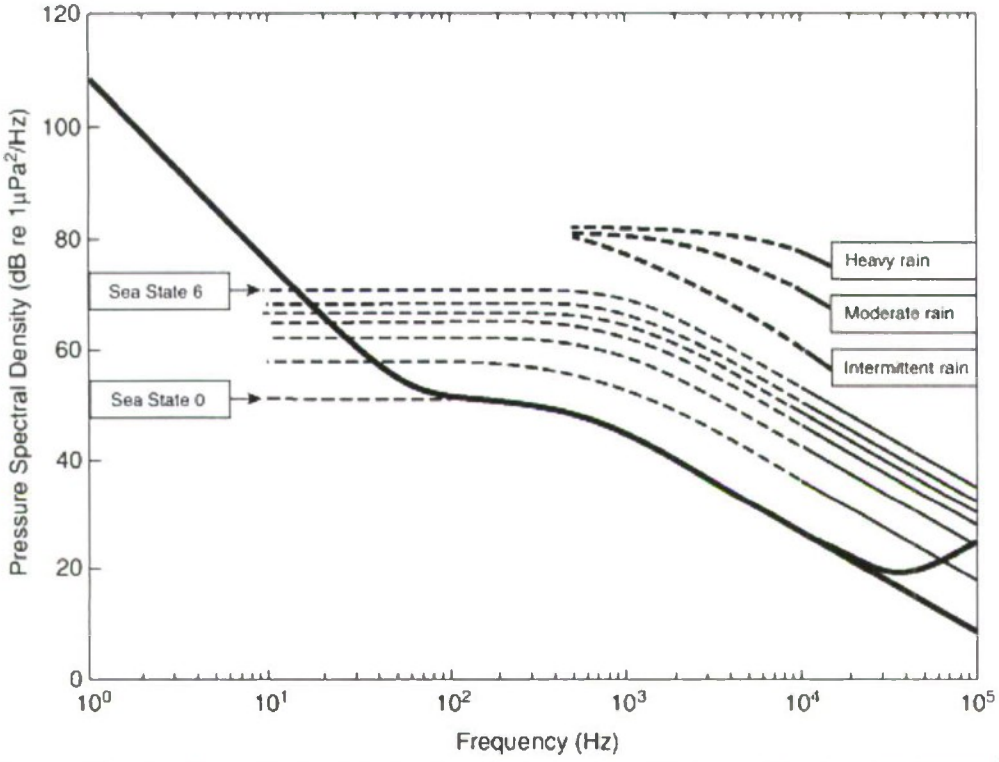


Figure 11. Ambient Noise Model for Various Sea State and Rain Conditions[47*]

Paul Naehtigall has demonstrated in experiments with live animals that some species of whales adapt to the environment by adjusting their hearing sensitivity, akin to an automatic gain control mechanism in man-made systems.[48] The animal's adjustable "gain control," however, covers a wide dynamic range (for example, greater than 30 dB in some cases). As a wide range of ambient levels are known to exist worldwide, as exemplified by figure 10, it is not unusual to surmise that over the span of evolving marine biological systems, such a capability would be developed in marine species over time.

The animal's ability to hear or even mask signals coming from anthropogenic and biological sound energy sources will likely depend on the surrounding conditions of the ocean environment and how well the animal is able to adapt to dynamic changes in the ocean environment. Hence, accurate modeling of the ambient noise component of the sonar equation may be crucial to the overall sonar prediction when behavioral effects due to sonar emissions are being considered. Excellent references pertaining to this subject are the NRC's "Ocean Noise and Marine Mammals"[47] and Carey and Evan's book on ocean ambient noise measurement and theory.[49]

In the former reference, the NRC recognizes the importance of balancing the relationships of environmental stewardship and national security:

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* The curves in this plot were originally developed by W. Sadowski, R. Katz, et al. in the 1980s and were incorporated for standard use in the Comprehensive Acoustic System Simulation/Gaussian Ray Acoustic Bundle (CASS/GRAB) software model.

> ". . . sound is an essential tool for ensuring national security. The development of underwater sound as a method for detecting submarines began during World War I and accelerated rapidly during World War II. During the Cold War, acoustic antisubmarine warfare became the principal deterrent against missile-carrying submarines roaming the high seas. Since the end of the Cold War ocean acoustics has continued to retain its military significance, but now militaries seek to expose submarine and mine threats in shallow water areas."[47]

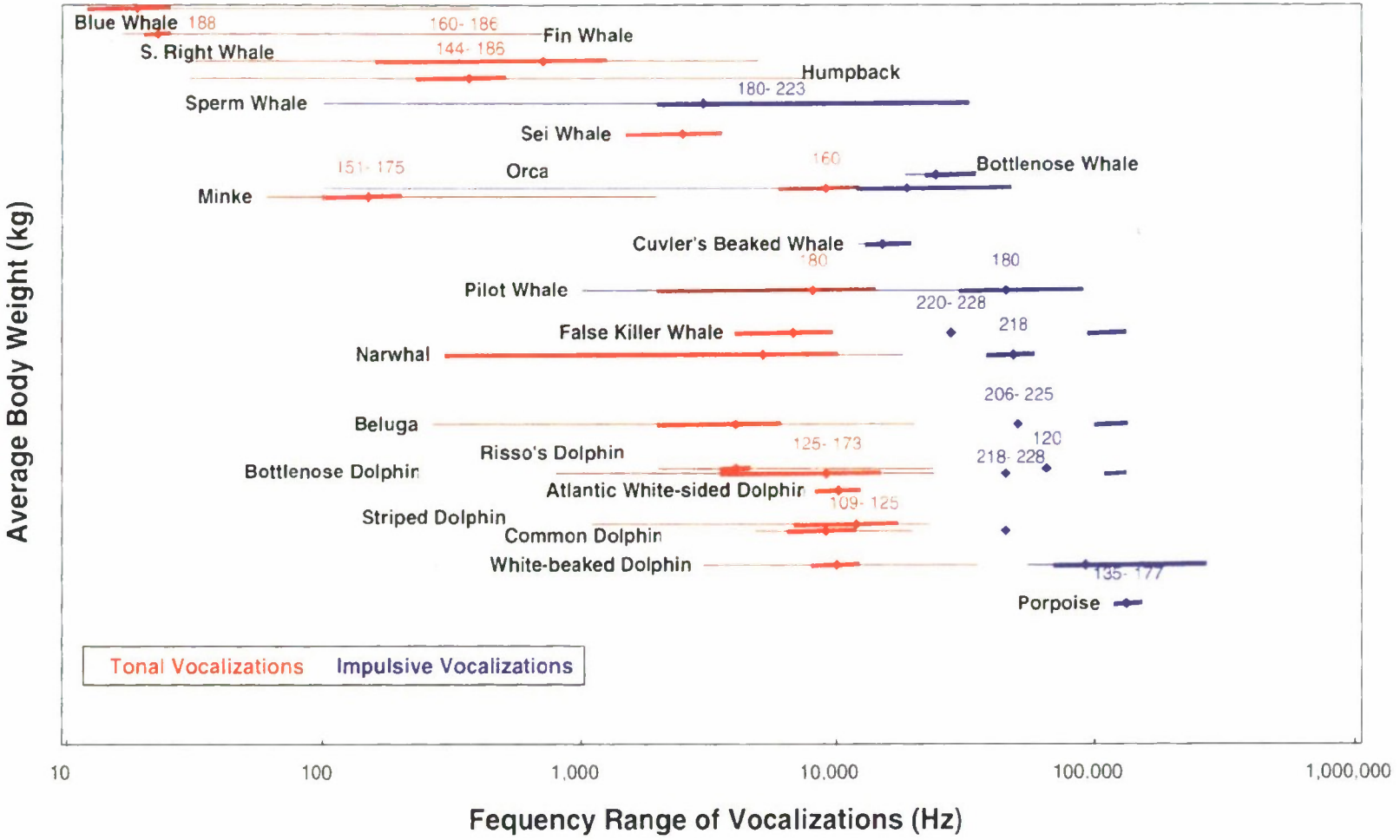
The NRC elaborates on the effects of sound on marine animals:

> "Although there is an extensive literature on the effects of sound on marine mammals, it is patchy and inconclusive. A tremendous amount of work remains to be done to determine the effects of sound on marine mammals. In particular, there have been few studies to relate specific dosage of sound to effects likely to be of biological significance."[47]

Since the publication of the NRC report,[47] attempts have been made to fill in some of the gaps. Research continues at an accelerated pace with some degree of success.[6, 44, 48] During the 2008 Acoustical Association of America (ASA) joint conference in Paris, an estimated 5000 participants—many with specialties in sonar, underwater acoustics, and marine sciences—gathered to share their research. Many of the presentations were given under U.S. Navy sponsorship; Peter Tyack of Woods Hole Oceanographic Institute (WHOI) gave a lead plenary presentation on marine mammals and active sonar. Since 2008 several more national and international conferences have been held, including back-to-back conferences in Italy in early Fall of 2009, both co-sponsored by the U.S. Navy. The first of these was an intergovernmental conference hosted by the National Undersea Research Center (NURC) in La Specia. The second was an academic and Navy laboratory research conference held at the University of Pavia. Additionally, the U.S. Navy has formed a coalition of scientific leadership from the highest echelons of the Navy in the formation of the Sonar and Living Marine Resources Oversight Group (SLMROG), whose charter is to steer scientific research forward by identifying the needs to fill the knowledge gaps and prioritize research requirements and funding.[50]

5.4 LOUDNESS VERSUS INTENSITY LEVEL

Loudness is a function of a particular animal's hearing perception, which varies from species to species. It is important, therefore, to distinguish between loudness and acoustic intensity, the standard reference quantity used in the calculation of sound-level quantities expressed in decibel units. Loudness differs from acoustic intensity in that loudness is a measure of physiological and neural responses (that is, receive mechanisms) of a particular animal. In humans, the critical bandwidth of hearing perception is roughly between 20 Hz and 20,000 Hz. High-intensity levels of sound energy above 20 kHz (ultrasonic sound) and below 20 Hz (infrasonic sound) are generally not heard by humans without the aid of special sound equipment. Other animals, including marine mammals, have hearing sensitivities and perceptions very different from humans. Dogs, for example, can hear sounds above the human range of hearing; elephants can hear sounds well below the human range. Figure 12 shows that a wide variety of marine mammal species communicates sounds over a wide range of frequencies from very low (infrasonic) to very high (ultrasonic). It is unwise, therefore, to directly compare signal intensities of one animal species to another without considering the critical bandwidths of individual species.



Note: The thicker lines indicate frequencies near maximum energy; the numbers above the lines indicate measured source levels in dB re 1 µPa @ 1 m.

Figure 12. Representative Vocalizations of Marine Mammals As a Function of Frequency and Average Body Weight [46, 47]

As shown in figure 12, in marine mammals, generally the frequency of sound energy generation correlates with size and body mass. In humans, the sensitivity to sound level is also dependent on frequency, but differs from marine mammals. The set of curves in figure 13, referred to as "equal loudness contours" illustrate the dependency of frequency in humans.[51] These curves are based on human hearing response to specific tones (that is, individual frequencies). The vertical axis is represented by relative intensity level expressed in decibels with reference to 20 μPa, the standard reference for measurements in air. The horizontal axis plots sound frequency on a logarithmic scale. The contour lines are lines of equal perceived loudness for sounds at different frequencies. For example, a sound at a frequency of 100 Hz and a measured relative intensity of 60 dB (relative to 20 μPa), has the same perceived loudness as a sound at a frequency of 1000 Hz and a measured relative intensity level of about 51 dB re 20 μPa.

The relative sound intensity level, therefore, has to be much greater for a low-frequency sound to be perceived to be as loud as a sound at a frequency of 1000 Hz in humans. The corresponding SPL in dB for a 1000-Hz tone has been defined as the "loudness level in phons."[51, 52] From the example, figure 13 indicates that a 100-Hz tone at a sound level of 60 dB has a loudness level of 51 phons. The weighting networks in human sound measuring devices are based on similar contours first constructed by Fletcher and Munson.[23] The so called A- and B-weighting characteristics are consistent with the 40- and 70-phon Fletcher-Munson contours taking into account random fluctuations in a sound field.

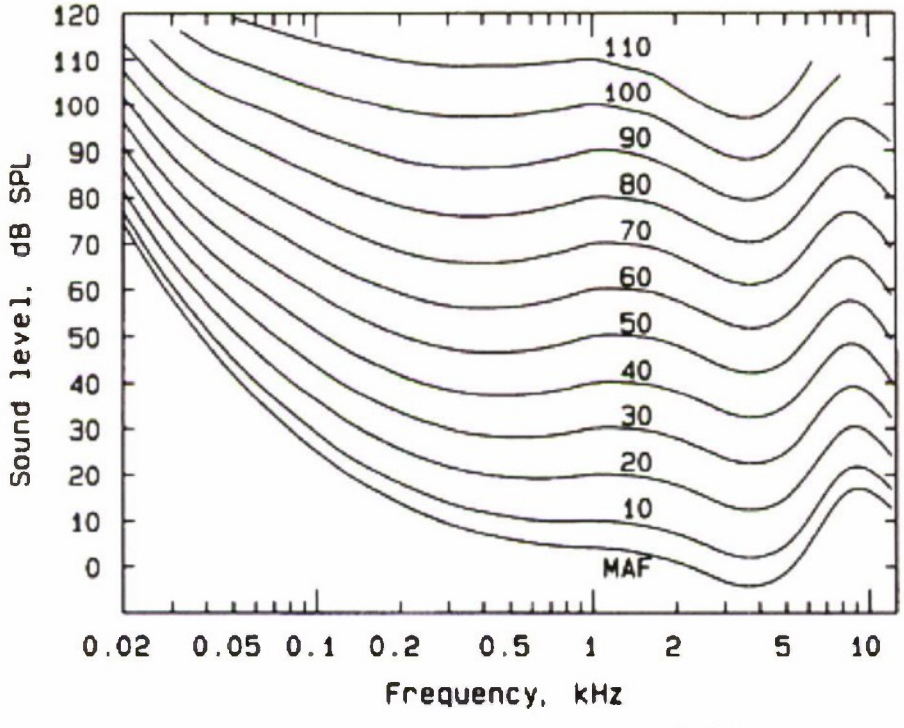


Figure 13. Equal Loudness Contours[23, 51, 52]

The loudness at which humans can just barely hear a sound is known as the threshold of hearing. Dr. Charles Liberman of the Harvard School of Medicine and Massachusetts Eye and Ear Infirmary (MEEI) has provided the Navy with a set of curves (figure 14[53]) depicting sensitivities to a number of sounds in humans and other animals. The bottom-most curve in figure 14 represents the nominal threshold-of-hearing in humans below which level sounds are typically not heard; the upper-most curve represents an annoyance level above which physical harm can occur. Note that the data represented in figure 14 are based on human responses to individual tonal sounds. Figure 15, also provided courtesy of the MEEI Group,[53] shows some examples of A-weighted disturbance thresholds in humans.

For broadband sounds—sounds covering a wide range of frequencies simultaneously (60 Hz to 5800 Hz)—a new set of equal loudness contours is required. Another aspect of hearing sensitivity is the duration of sound. These other factors of hearing sensitivity in humans are described by Peterson and Gross.[46]

At the Living Marine Mammal Research Center (LMRC) in San Diego, CA, the U.S. Navy has been performing research on bottlenose dolphins in an attempt to obtain the first set of equal loudness contours for a marine mammal. This research, sponsored jointly by the ONR and OPNAV N45, has been ongoing for a number of years and has produced some amazingly accomplished results. J. Finneran of SPAWAR San Diego, has shown through experiments with live animals that TTSs in certain species of marine mammals are frequency dependent, as can be seen from figure 16. Hearing was tested using behavioral and electrophysiological methods. The onset of TTS exposures at increasingly higher frequencies was significantly lower than the onset of TTS for 3-kHz exposures.[44]

Figure 17 shows preliminary equal-loudness contours measured in a dolphin subject identified as "TYH." Finneran's data[44] represent the first direct measurement of equal-loudness curves in any animal. The shape of the equal-loudness contours can be used to create weighting functions to properly emphasize frequencies at which auditory sensitivity is highest and lessen the importance of other frequencies, similar to human A- and C-weighting networks.

Finneran concludes:

> "Weighting functions created from these data may be more appropriate to assessing behavioral effects of sounds, under the assumption that the reactions of animals are more strongly related to the loudness of a sound compared to the SPL of the sound."[44]

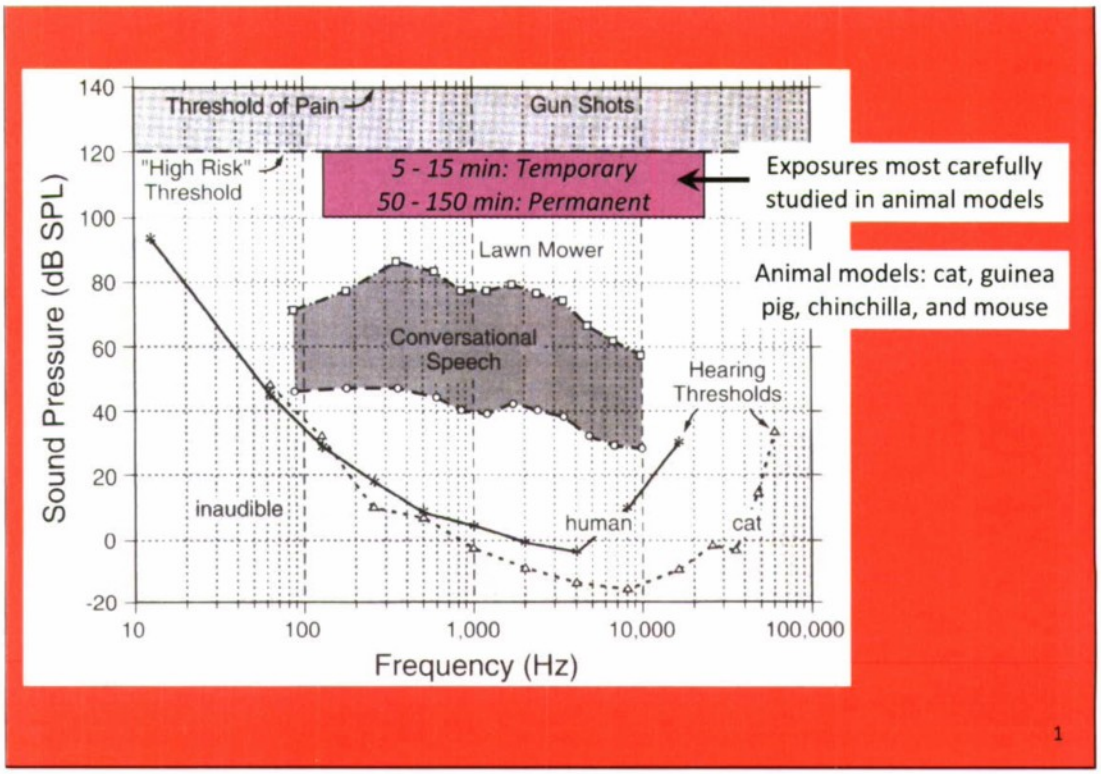


Figure 14. Hearing Sensitivities of Some Terrestrial Animals[53]

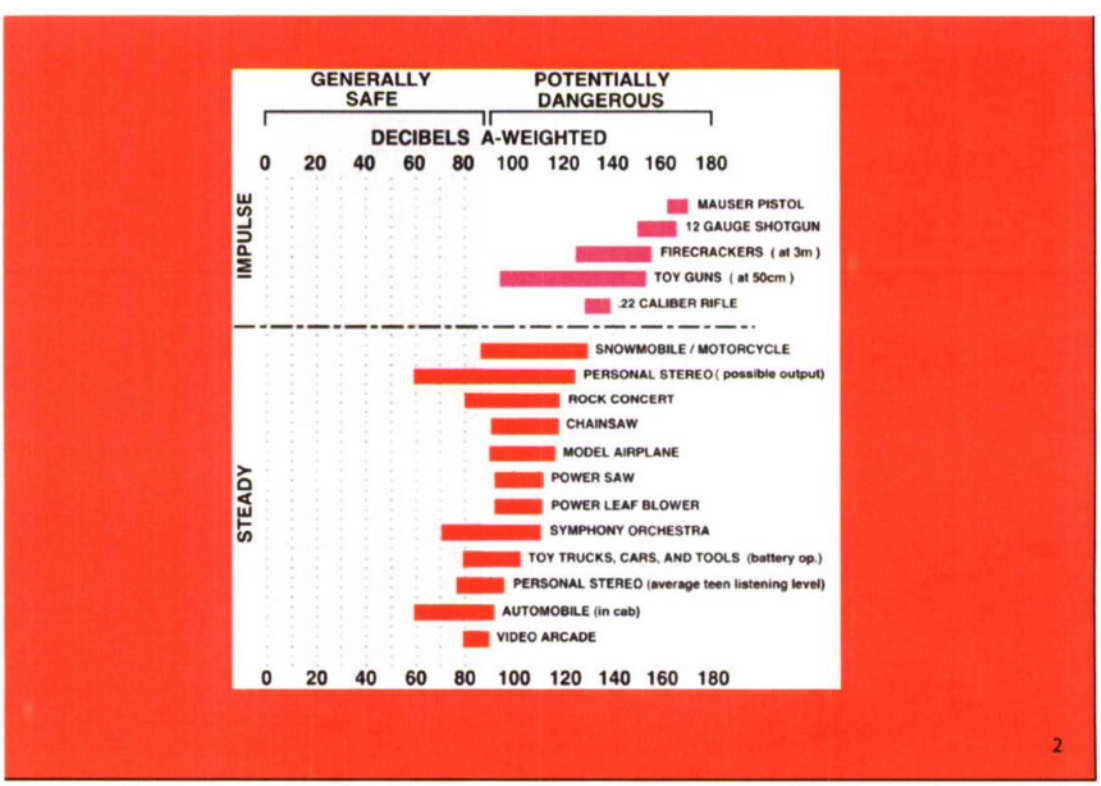


Figure 15. A-Weighted Disturbance Thresholds in Humans[53]

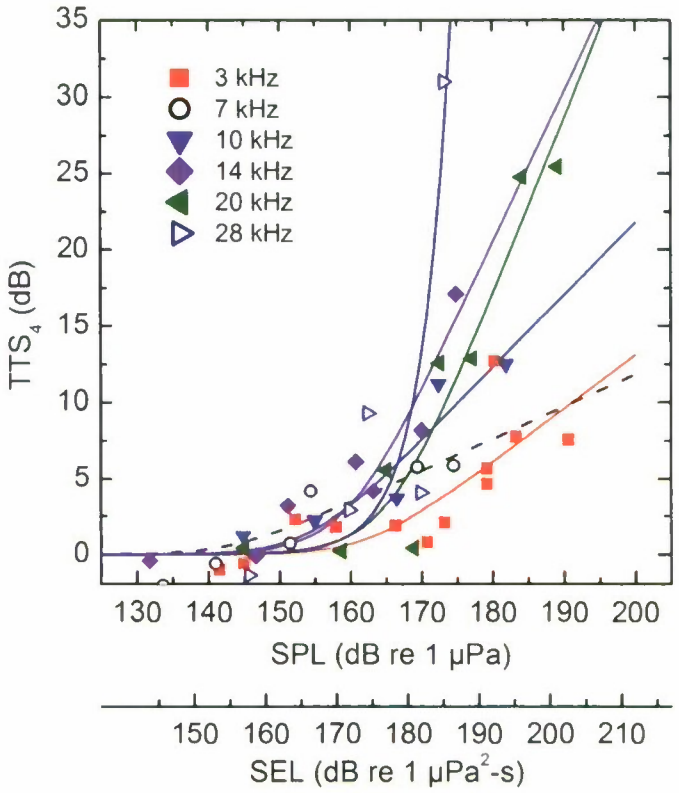


Figure 16. TTS As a Function of SEL Measured in a Dolphin Subject (Identified As "BLU") for 16-s Exposures at 3, 7, 10, 14, 20, and 28 kHz[44]

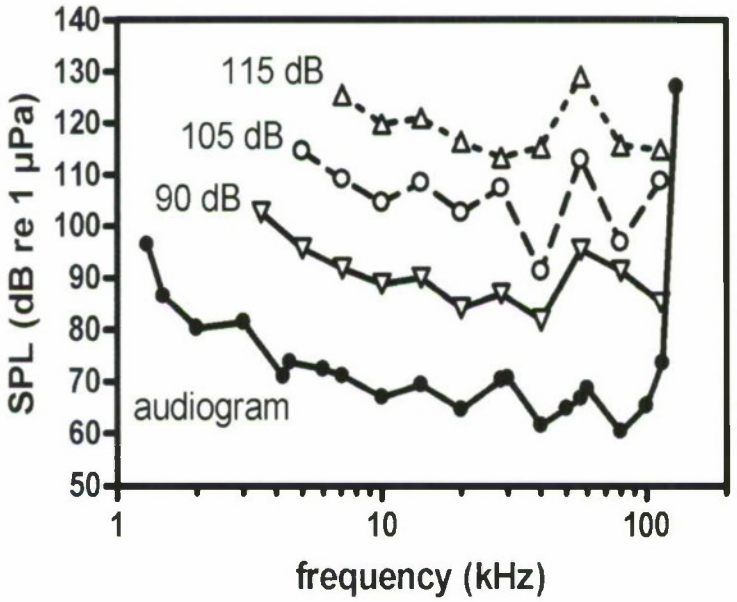


Figure 17. Preliminary Equal-Loudness Contours Obtained from a Dolphin Subject (Identified As "TYH") Passing Through 10 kHz at 90, 105, and 115 dB SPL

(The equal-loudness contours tend to parallel the audiogram (the hearing threshold as a function of frequency), but diverge at the highest frequencies.[44])

6. DECIBEL CORRECTIONS FOR SOUND INTENSITY LEVEL IN AIR TO SOUND INTENSITY LEVEL IN WATER AND VICE VERSA

6.1 INTRODUCTION TO AIR-TO-WATER AND WATER-TO-AIR SOUND ENERGY CONVERSIONS

Sound intensity values given in dB in air are not directly comparable to sound intensity values given in dB in water because of (1) the differences in sound pressure reference quantities p_{ref} between air and water, and (2) the differences in the acoustic impedances ρc between air and water propagating media (see equations (32) – (33)). Generally, there is a 26-dB correction required to account for differences in sound pressure reference quantities and a 35.5-dB correction to account for differences in acoustic impedances between air and seawater sound propagation media, yielding a composite correction factor of 61.5 dB.

The 61.5-dB correction factor between air and seawater is based on theoretical considerations, given the starting assumption that absolute intensities be equivalent in air and seawater (see the derivation in the appendix). Using intensity as the standard reference quantity for an air-to-seawater correction instead of the pressure alone has caused some confusion in some factions of the acoustics community, yet it is fair to say that intensity has been the preferred standard reference quantity for sound energy in underwater acoustics applications and is likely to remain so for the foreseeable future—even though the use of units for a pressure quantity is commonly used. Pressure quantities are more typically used than are intensity quantities because practically all sonar calculations are derived from the same (underwater) medium where the intensity is directly proportional to the square of the pressure, and the impedance cancels out whenever ratios of the intensity are computed. Canceling of the impedances, however, does not occur with air-to-seawater conversions because impedances are highly disparate between the two media.

Even with a 61.5-dB correction added to measurements taken in air to obtain equivalent measurements taken in seawater, through the use of equations (32) – (33), the answer is not simple. The reasons are threefold: (1) many measurements for sound in air quoted in the literature, although referred to a pressure quantity, do not always specify the distance of the measuring device to the acoustic source—a crucially important factor; (2) sounds in air and seawater can occur over a wide-ranging and often disparate band of frequencies and signal durations—another factor often overlooked when air and seawater comparisons are made, and (3) loudness and hearing sensitivities between humans and undersea life differ substantially, and consequently the effects of anthropogenic sound on marine life are not in one-to-one correspondence from air-to-seawater. Hearing sensitivities in seawater can be achieved through experimentation on marine life over time as scientific methods improve and repositories of new scientific information become available.[5, 7, 8, 44, 54] Moreover, researchers have shown that hearing sensitivities in certain species of marine mammals are environmentally adaptive to their incoming sounds.[48, 55]

With these caveats in mind, the examples in subsection 6.2 illustrate how one might attempt to translate an absolute sound intensity that is the same in air and seawater to the respective decibel equivalents in air and seawater. The relative intensities used to compute

decibels are different for air and seawater. For sound propagation in air, scientists have arbitrarily agreed to use a reference intensity associated with a standard pressure of 20 μPa. Scientists selected this value because sounds in air at a frequency of 1000 Hz and with a pressure of 20 μPa are barely discernable by humans under controlled laboratory conditions. In seawater, however, a much smaller pressure quantity of 1 μPa has been chosen as the preferred standard because electronic and mechanical devices can easily discern these smaller quantities. In years past, the preferred pressure standard for in-water calculations was the microbar (μbar); however, such quantities, in many cases, produced negative decibel results. To invoke positive-valued solutions for the same physical calculations, over time the micropascal (μPa) gained favor over the microbar (μbar). One μbar is the equivalent of 1 dyne per square centimeter. One μPa equals 10^{-5} dynes per square centimeter. Therefore 100 dB must be added to relative quantities expressed in microbars in order to convert them to equivalent quantities expressed in micropascals.

The intensity of a sound wave depends not only on the pressure of the wave, but also on the density and sound speed of the medium through which the sound is traveling. Sounds in water and sounds in air that have the same pressures have very different intensities because (1) the density of water is much greater than is the density of air and (2) the speed of sound in water is much greater than the speed of sound in air. For the same pressure, higher density and higher sound speed both give a lower intensity in water (equation (32)). The acoustic impedance ρc in air is equal to approximately 42 g/(cm^2)(sec). In seawater, ρc approximately equals 1.5×10^5 g/(cm^2)(sec). The ratio of impedances from air-to-seawater is approximately 1/3600. Because intensity, the governing parameter, is inversely proportional to the acoustic impedance, in terms of a reference conversion factor, it is the ratio of 3600 air-to-seawater that must be applied for converting decibels from air-to-seawater calculations. Conversely, going from decibel calculations taken in water and extended to air, a ratio of 1/3600 must be applied.

6.2 EXAMPLES OF AIR-TO-WATER AND WATER-TO-AIR SOUND ENERGY CONVERSIONS

In the following examples, it is assumed that all calculations are made in equivalent energy frequency bands.

6.2.1 Example 1

For an acoustic intensity associated with a 215-dB SEL referenced to 1 μPa^2-sec at 1 meter from an acoustic source in seawater, what is the equivalent SEL in air? An SEL of 215 dB is a threshold level that is sometimes associated with the PTS—a level that can cause physical harm in some species of cetaceans. SEL for a 1-meter reference location is assumed to have been back-calculated using a spherical spreading law from a receive level measuring device of some further distance outward from the source, a distance that is equal in both media and not influenced by media boundaries.

The value of 215 dB re 1 μPa^2-sec represents a threshold value used by regulators to determine PTS in some species of cetaceans.

There are two steps to this conversion:

1. First convert 215 dB SEL re 1 μPa^2-sec in seawater to SEL re 20 μPa^2-sec in air. The conversion correction uses the intensity equation (32):

$$I(\text{dB}) = 10\log_{10}\left(\frac{p_{\text{ABS}}^2}{p_{\text{REF}}^2}\right) = 20\log_{10}\left(\frac{p_{\text{ABS}}}{p_{\text{REF}}}\right). \tag{48}$$

$$20\log(p_{\text{SEA}}/p_{\text{AIR}}) = 20\log(1\,\mu\text{Pa}/20\,\mu\text{Pa}) = -26\,\text{dB}. \tag{49}$$

$$I(\text{dB re } 1\,\mu\text{Pa}_{\text{SEA}}) = 215\,\text{dB}. \tag{50}$$

$$I(\text{dB re } 20\,\mu\text{Pa})_{\text{AIR}} = I(\text{dB re } 1\,\mu\text{Pa})_{\text{SEA}} - 26 = 189\,\text{dB re } 20\,\mu\text{Pa at 1 m}. \tag{51}$$

Note that the denominator term (equations (48) and (49)) represents the resultant (new) pressure reference quantity, which, in this case, is 20 μPa.

2. Now convert the resultant level of 189 dB re 20 μPa from step 1 to an equivalent intensity level in air. To perform this calculation, take the ratio of acoustic impedance between seawater and air. As already mentioned, the ratio of impedances from seawater-to-air is approximately 3600; however, because intensity is inversely proportional to the acoustic impedance, a ratio of 1/3600 for converting from seawater-to-air must be applied.

Hence from equations (32) and (33):

$$I(\text{dB re } 20\,\mu\text{Pa})_{\text{AIR}} = 189\,\text{dB} + 10\log\left(\frac{[1/\rho c_{\text{SEA}}]}{[1/\rho c_{\text{AIR}}]}\right) \tag{52}$$

$$= 189\,\text{dB} + 10\log\left(\frac{\rho c_{\text{AIR}}}{\rho c_{\text{SEA}}}\right) \tag{53}$$

$$= 189\,\text{dB} - 35.5\,\text{dB} = 153.5\,\text{dB re } 20\,\mu\text{Pa at 1 m}. \tag{54}$$

Unlike the case for the reference pressure correction (equation (49) computed in step 1), because of the inverse proportionality between intensity and acoustic impedance, the denominator term (equation (53)) represents the acoustic impedance level of the originating medium before conversion. The resultant ratio of impedances for the present example is 1/3600.

It is assumed in this illustrated example that the conversion of 215 dB in seawater to 153.5 dB in air represents a position in space translated to a 1-meter distance away from the acoustic source in either environment, and time duration parameters for determining SEL (dB re 1 μPa^2-sec)$_{\text{SEA}}$ or SEL (dB re 20 μPa^2-sec)$_{\text{AIR}}$ have not influenced the conversion calculation. No corrections, however, have been made to account for propagation effects in either

environment (seawater or air), nor have any corrections been made for signal frequency duration, and receiver sensitivity characteristics. Even with all these caveats in mind, it is interesting to note that the 153.5-dB in-air equivalent of a 215-dB in-seawater PTS level is a very loud signal and is within the realm of jet aircraft noise and thresholds of pain in humans for these stated values very close to the acoustic source (1 meter). On the other hand, for a signal as high as 215 dB in the seawater as well as 153.5 dB in air, the signal strength is greatly diminished as it propagates over increasing distances. Even at very close range, within a ship's striking distance of an animal, say a mere 50 feet from the emitting source position, the in-water signal is reduced by 24 dB, resulting in a receive SEL of 191 dB at that range. Notably 191 dB is appreciably below the TTS level of 195 dB established as a guideline for some species of cetaceans.

6.2.2 Example 2

Ignoring surface boundary effects, what is the in-water SEL equivalent of a hypothetical Saturn rocket acoustic noise source that emits 195 dB SPL re 20 μPa in the first 3 seconds following ignition (at an assumed distance of 1 meter)? Equations (55) through (57) pertain to SPL; equation (58) pertains to SEL.

$$I(\mathrm{dB}) = 10\log_{10}\left(\frac{p_{\mathrm{ABS}}^2}{p_{\mathrm{REF}}^2}\right) = 20\log_{10}\left(\frac{p_{\mathrm{ABS}}}{p_{\mathrm{REF}}}\right). \tag{55}$$

$$20\log\left(\frac{p_{\mathrm{AIR}}}{p_{\mathrm{SEA}}}\right) = +26\ \mathrm{dB}. \tag{56}$$

$$I(\mathrm{dB\ re\ 1\ \mu Pa\ at\ 1\ m})_{\mathrm{SEA}} = 195(\mathrm{dB\ re\ 20\ \mu Pa\ at\ 1\ m})_{\mathrm{AIR}} + 20\log\left(\frac{20\ \mu\mathrm{Pa}}{1\ \mu\mathrm{Pa}}\right)$$

$$+10\log\left(\frac{\rho c_{\mathrm{SEA}}}{\rho c_{\mathrm{AIR}}}\right)$$

$$= 195\ \mathrm{dB} + 26\ \mathrm{dB} + 35.5\ \mathrm{dB} = 256.5\ \mathrm{dB\ re\ 1\ \mu Pa\ at\ 1\ m}. \tag{57}$$

$$\mathrm{SEL} = \mathrm{SPL} + 10\log T = 256.5\ \mathrm{dB} + 5\ \mathrm{dB} = 261.5\ \mathrm{dB\ re\ 1\ \mu Pa^2\text{-}sec\ at\ 1\ m}. \tag{58}$$

(See equation (46).)

6.2.3 Example 3

How does an automobile horn sounding in air at 112 dB SPL re 20 μPa compare to a horn sounding at a comparable level in water?

$$I(\text{dB re 1 μPa at 1 m})_{\text{SEA}} = 112(\text{dB re 20 μPa at 1 m})_{\text{AIR}} + 20\log\left(\frac{20\,\mu\text{Pa}}{1\,\mu\text{Pa}}\right)$$

$$+10\log\left(\frac{\rho c_{\text{water}}}{\rho c_{\text{air}}}\right) \tag{59}$$

$$= 112\,\text{dB} + 26\,\text{dB} + 35.5\,\text{dB} = 173.5\,\text{dB re 1 μPa at 1 m.} \tag{60}$$

Note that a hypothetieally eonverted (in-water) horn sound level of 173.5 dB SPL is approximately 21.5 dB lower than TTS levels established for eertain eetaeeans.

6.2.4 Example 4

If an orchestra has a relative intensity level in air of 125 dB SPL re 20 μPa at 1 meter, then what is the hypothetieal undersea equivalent intensity level?

$$I(\text{dB re 1 μPa at 1 m})_{\text{SEA}} = 125(\text{dB re 20 μPa at 1 m})_{\text{AIR}} + 20\log\left(\frac{20\,\mu\text{Pa}}{1\,\mu\text{Pa}}\right)$$

$$+10\log\left(\frac{\rho c_{\text{SEA}}}{\rho c_{\text{AIR}}}\right) \tag{61}$$

$$= 125 + 26 + 35.5 = 186.5\,\text{dB re 1 μPa at 1 m.} \tag{62}$$

If the sound intensity level were held over a crescendo of 5 seeonds or greater, then SEL would be inereased 7 dB or more above SPL in aeeordanee with equation (46). In the latter ease, these orchestral sounds, when converted from air to seawater, would approaeh with inereasing time duration of the signal, the established TTS threshold of 195 dB for eertain eetaeeans.

The general result, not taking into aeeount signal eharaeteristies and propagation effects, is that sound waves in seawater and air will have relative intensities that differ by 61.5 dB. To convert from air to seawater, one should add 61.5 dB to the sound intensity level in air. To eonvert from seawater to air, one should subtraet 61.5 dB from the sound intensity level in seawater. This amount must be subtraeted from relative intensities in seawater refereneed to 1 μPa to obtain the relative intensities of sound waves in air refereneed to 20 μPa that have the same absolute intensity in watts per square meter. The differenee in referenee pressures aeeounts for 26 dB of the 61.5 dB differenee. The differenees in densities and sound speeds aecount for the other 35.5 dB.

6.3 AIR-TO-WATER AND WATER-TO-AIR DECIBEL CONVERSIONS: LIMITATIONS AND CAUTIONS

In reality, for a large number of sounds, these types of conversions are difficult, if not impossible, to make because of the complexities of the signal and the environment in which the signal propagates. The acoustician making such calculations should proceed with caution when making any of these types of extrapolations. Additionally, not all sound intensity levels are reported with the same accuracy. Values taken from the literature are dependent on the experience level of the people conducting the measurements, the equipment from which the data are collected, how well the measurements are calibrated, and distance (not always stated) from the emanating acoustic source. Based on these and other considerations mentioned in the beginning of this section, it is not unreasonable to assume a ±10-dB variability above or below any of the specific levels that may be quoted in a majority of the published scientific literature—unless the measurement details are specifically described. When the relative intensity of a sound is being reported, it is important to indicate both the dB and reference level—often written as "dB re 1 μPa" for sounds in water that are measured relative (re) to 1 μPa and "dB re 20 μPa" for sounds in air that are measured relative (re) to 20 μPa.

6.4 SOUND TRANSMISSION THROUGH THE AIR-WATER INTERFACE AT THE OCEAN SURFACE

Computing the air-to-water or water-to-air relative decibel level equivalencies for sound transmission through an air-water interface poses an entirely different question from the starting condition of equal absolute intensities in air and water—the two different situations should not be confused. Nonetheless, it is useful to ask the question how sound energy is affected as it passes from one medium to another, seawater-to-air or air-to-seawater in vicinity of the ocean surface. It is well known that active underwater sound transmissions can be heard audibly above the ocean surface, however, it is less known how far away from the source can the audible signals be heard. Much research[56 - 62] has been done in this area, and it has been shown that an acoustic signal penetrating the ocean surface will generally suffer a loss in SPL of about 55 dB.

On the other hand, a sound source originating in the atmosphere just meters above the ocean surface will generally experience a much lower loss of approximately 6 dB as it penetrates into the ocean medium. While these empirical measurements do not in and of themselves provide direct measurement of the relative sound intensity levels between spatial locations in the air and water media, environmentalists who monitor underwater sonar transmissions can get a "ball park" sense of how far away these sounds may be heard audibly from shore or nearby surface craft..

7. MODELING IMPROVEMENTS

Current regulatory practices require that the received SEL and SPL at the animal be assessed through modeling prior to the approval of training operations by the regulatory authority. The assessment is compared with various thresholds of behavioral disturbances. These are PTS and TTS for physiological disturbances and non-TTS for non-physiological disturbances as described earlier. As the understanding of the science of marine mammal behavior continues to mature, so, too, will there be similar enhancements to the physics-based models. In the past 5 years, beginning with the introduction of the BRS program, the M3R program, and other major research and development initiatives undertaken by the Navy, NOAA, and other research institutions, the ability to improve modeling the behavior piece of the puzzle (figure 2) is just on the horizon (less than 5 to 10 years away). The following subsections give a glimpse of where some of these fascinating discoveries are leading toward.

7.1 PARADIGM FOR CURRENT AND IMPROVED MODELING PRACTICES

Figure 18 applies the paradigm illustrated in figure 2 to a simple problem in sonar modeling for ascertaining behavioral effects. For simplicity, equal numerical values of 140 dB are applied to both receive level (L_{REC}) SEL and SPL quantities.

Source	Propagation	Receiver	Perception	Behavior
Source Level (L_S)	– Propagation Loss (N_{TL})	= Receive Level (L_{REC})		
200 dB	– 60 dB (@ 1000 m)	= 140 dB		
			versus	
			PTS = 215 dB (SEL) TTS = 195 dB (SEL) Non-TTS = 120 dB (SPL)	

Note: At a distance of 1000 meters from the radiating source, the estimated L_{REC} 140 dB at the animal's ears is below minimum required mitigation threshold for SEL of 195 dB re 1 μPa²-sec TTS and 215 dB re 1 μPa²-sec PTS; therefore, under these conditions, physiological effects are deemed insignificant. Non-physiological disturbances for an SPL of 120 dB re 1 μPa non-TTS, however, are predicted.

Figure 18. Notional Problem Using Sonar Equation Model (Units in Decibels)

Note that figure 18 gives an inadequate picture of reality. Sonar equation terms not used in this calculation are the animal's array gain (N_{AG}) and recognition differential (N_{RD}) and the ambient noise level (L_N). Variations in the ambient noise can affect animal receive sensitivity and hence can affect recognition differential. Marine mammal science has not yet matured to the level where scientists can ascertain with a degree of certainty how the animal processes, perceives, and responds to the many different kinds and levels of anthropogenic sounds it is capable of receiving. For that reason, models today conservatively estimate animal behavioral effects based on the "precautionary principle" standard. For example, using the seawater-to-air correction formula described in the appendix at comparable frequencies and reference distances, the minimum exposure level for non-TTS of 120 dB re 1 μPa in seawater would compare to an A-weighted disturbance threshold in humans, according to figure 15, in the category of "Generally Safe."

7.2 IMPORTANT AREAS OF FUTURE RESEARCH

7.2.1 Near-Term Horizon (1 – 5 Years into the Future)

Besides the general difficulty in applying best available science to grapple with the N_{RD} term in the sonar equation, there are other reasons why sonar and environmental analysts seem to bypass N_{RD}. One reason is that, at relatively short ranges (inside 10,000 yards), the signal typically reaches the animal's ears at a sufficiently high signal-to-background ratio (SBR)—in excess of 10 dB—where, under certain circumstances, relatively high signal levels diminish the relative significance of N_{RD} and the ambient background interference level L_N. Once the receive level surpasses a 10-dB SBR threshold level, there is no practical reason to differentiate the N_{RD} because the signal is generally assumed to be recognizable.

Research conducted by Nachtigall[48] and Au[55] proved this assumption to be false because they have shown that, at least for some marine mammal species, the processing capabilities of the animal are much more sophisticated. Nachtigall's experiments on live animals demonstrate how some marine mammals can "self-mitigate" their own loud vocalizations and environmentally adapt and adjust their own receiving sensitivity levels by 30 – 40 dB.[48] Self-mitigation of an animal's own loud vocalizations is, in a sense, a reverse (or negative) N_{RD}.

Application of "negative N_{RD}" is a term unfamiliar to underwater acousticians, yet if it was applied appropriately in future models, negative N_{RD} could aid scientists in resolving the unanswered question of why some marine mammals are behaviorally affected by certain anthropogenic sound emissions while others are not. Au's team, at the University of Hawaii, has demonstrated experimentally how dolphins use an internal gain control mechanism in which their outgoing echolocation levels automatically adjust to range of transmission in seeking out objects. Close-in objects are interrogated at lower levels than objects farther out in range.[55]

An important consideration is how to best model the internal signal processing capability (N_{RD}) of the animal. In classical passive sonar equation terminology, the array gain is a processing term that is associated with the sonar system's ability to discriminate directed incoming sound energy from omnidirectional sound energy in the surrounding noise field. This term is referred to as "receiving directivity index" (N_{DI}), or, if the directivity is measured through a sonar array, the term is referred to as "array gain" (N_{AG}). The N_{DI} or N_{AG} is typically treated independently of N_{RD} (signal recognition differential), in classical sonar terminology (see section 4). The treatment of terms in the sonar equation is modeled somewhat differently for a marine mammal's sonar.

Signal processing performed by the animal contains both a physiological component (for example, body mass, distribution of auditory system, influencing appendages, and body structures) and a neural component (for example, how the signal is processed via the neural system). The signal processing component in the sonar equation, therefore, should include both N_{DI} (or N_{AG}) and N_{RD} combined. Even though the two terms are lumped together, the modeling of each subcomponent is still treated separately. N_{DI} (or N_{AG}) takes into account how the animal forms a directional beam for receiving incoming sound energy, while N_{RD} accounts for how the signal is processed internally to either enhance or reject sound energy. The research work by

Nachtigall, Suprin, Au,[48, 55] and others are beginning to provide the data and analytical means to address N_{DI} (or N_{AG}) and N_{RD}, so that the best available science will allow researchers to address these issues.

Another important aspect of behavioral response is the frequency bandwidth with which marine mammals receive signals and communicate. As mentioned in subsection 5.4, pioneering research performed at SPAWAR, San Diego has demonstrated in controlled experiments that the animal sensitivity to sound energy reception can be highly variable depending on the particular portion of frequency spectrum in which the sound emission occurs.[44] To date, this work has been done for only a few selected species. As the science matures, researchers should be better equipped to model behavioral responses, not only on the basis of sound intensity, but also based on weighting functions in relation to an animal's perceived loudness.

Specific changes in animal sensitivity and behavioral response with increases in ambient noise level as well as ecological changes are not well captured in the available scientific data and remain a priority item for current and future research activities. Although some research has been conducted (Nachtigall,[48] Finneran,[44] and Au,[55] for example), much more is needed; moreover, increased ambient noise levels[63] and increases in ocean acidification over time have raised new concerns over their impact on the balance of the ocean's ecosystem,[64, 65] resulting in new areas of study that will require careful attention and monitoring.

A final area of research in the near term that will demand serious attention is the investigation of nonlinearity and harmonic signal generation for both marine mammal communications and anthropogenic sound generation. There is ample evidence in the scientific literature that marine mammals use harmonics in their acoustic vocalizations for interspecies communications.[66] An open question, yet to be fully explored, is why beaked whales tend to vocalize around 20 kHz and above and modeled resonant frequencies based on structural acoustics[67] begin around 12.5 kHz; yet the sonar frequency by which these animals seem to be most affected is perceived to be lower.[3] Moreover, marine mammals possess dual vocalization passageways that enable them to transmit dual signals simultaneously and independently. These vocal structures, typically called "monkey lips," enable the animal to emit sounds through each passageway while modulating independent sounds in both frequency and amplitude. This type of sound-generation mechanism is akin to nonlinear, parametric sonar generation—a technology that is well established and understood by the U.S. Navy through many years of extensive Navy research, development, test, and evaluation (RDT&E) funding.

7.2.2 Far-Term Horizon (6- to 10-Year Horizon and Beyond)

Ari Shapiro and Peter Tyack, in collaboration with the Massachusetts Institute of Technology (MIT) and WHOI, have investigated Norwegian killer whale vocalizations to develop a syntactic vocabulary based on acoustic recordings of these animals.[68] Killer whale vocal production has traditionally been categorized by human observers into a set of discrete call types. These call types often contain internal spectral shifts, silent gaps, and synchronously produced low- and high-frequency components. Such features motivated an analysis to test whether call types could be represented by a set of flexibly arranged and smaller phonemic

segments. Calls composed of shared segments may provide a more parsimonious approach to capturing the vocal stream since there were fewer segments than call types. For example, nearly 75% of all call types contained at least one shared syllable, and some syntactic patterns were evident. Such a system could flexibly generate new call types and contain the killer whale vocal repertoire within a subset of the possible combinations of segments.

Researchers F. Li and J. Allen at the University of Illinois at Urbana-Champaign have been studying consonants in natural human speech as a codification of human vocal sounds.[69] One research area under consideration is combining the efforts of the Urbana group and the MIT/WHOI group to trace the evolution of human speech and language to that of marine mammals, looking for generic similarities in the syllabic vocalization patterns. Detecting such similarities could lead toward unlocking the secrets to mammalian interspecies communications.

8. SUMMARY

This report began by diseussing the dual responsibility of the U.S. Navy: ensuring that national seeurity interests are upheld in accordance with U.S. Code, Title 10 and safeguarding the well-being of the marine habitat in aeeordanee with environmental regulations and statutes sueh as the Marine Mammal Proteetion Aet of 1972. The Navy's obligation to maintain a war-ready status of its deployed forees—ineluding deployment of its sonar, if neeessary—while providing model stewardship of the marine habitat is no easy task.

The Navy balanees these responsibilities by applying best available scienee and scientific praetiees. The goal is to optimize (1) sonar system development, acquisition, and operations—a cornerstone in the Navy's ASW defense eapability—and (2) environmental practiees of good stewardship to minimize the effeets of Navy-generated anthropogenie sound in the marine environment. Beeause the nation's defense and the oeean environment are at issue, eommunieation of the best available seienee is essential to all vested stakeholders in sonar training and the marine environment, ineluding professionals working in these areas and the nation at-large (that is, the tax payers).

In the past, there has been diffieulty among seientists, regulatory professionals, and even the eourts, in interpreting the best available seienee pertaining to the behavioral effeets of sonar on marine mammals. This report artieulates the physieal quantities (namely, the deeibel and sonar equation parameters), methodologies, models, and metrics that are used for explaining the best available seienee. Additionally, this report diseusses how sound energy traverses the undersea environment, and how that sound energy is estimated and interpreted by the regulatory bodies in terms of impaets on marine mammal behavior. Energy level conversions for propagating sound in and between air and water media are also diseussed, and the distinetion is made between sound intensity levels and loudness levels.

Finally, this report coneludes with a glimpse of some of the promising areas of seientifie researeh in the near term and far term that will potentially result in an improved understanding of the effeets of sonar on the marine environment. These areas will improve on the best available seienee and further reinforee the Navy's ongoing eommitment to balanee Title 10 obligations to proteet national seeurity with stewardship of the seas and proteetion of natural resourees.

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APPENDIX
AIR-TO-SEAWATER AND SEAWATER-TO-AIR SOUND ENERGY CONVERSIONS: MATHEMATICAL DERIVATION*

* The basic equations for this derivation were initially provided by Anthony Yang.

A.1 INTRODUCTION

Underwater acoustieians and sonar speeialists typieally deal with sound measurement and estimation in the underwater environment while audiologists, a large number of noise monitoring and control speeialists, and arehitectural aeoustieians are most interested in human sounds in air. The question is often asked, how do sounds in air, such as jet engine noise or noise from a Saturn roeket, compare to sounds in water of the same likeness in intensity? Beeause deeibels are used for measuring sound in these two media, both the professionals and lay publie ean often get eonfused when sueh eomparisons are made in terms of their deeibel equivalents. In reality, some extrapolated eomparisons may be totally meaningless—espeeially where different energy frequeney bands between two media are being eompared or the relative measurement level in one medium or the other is not well-ealibrated, such as in the ease of negleeting the distanee from the aeoustie souree to the measurement apparatus.

Beeause of the insistenee, and, in many eases, failed attempts at making sueh eomparisons expressed in the publie news media as well as in some professional artieles, this appendix is provided to help professionals better artieulate in semi-quantifiable terms how one might begin to eonsider the use of deeibels for making sueh eomparisons.

A.2 PROBLEM STATEMENT AND DERIVATION OF DECIBEL AIR-TO-SEAWATER AND SEAWATER-TO-AIR CORRECTION FORMULAE

The stated problem is as follows: Given the same absolute intensity of sound energy in two separate media, air and seawater, what are the relative equivalent levels of intensity expressed in deeibel units for eaeh medium? Within the eontext of this appendix, the term "absolute" refers to a "measured or estimated physieal quantity." The physieal quantities in this problem and their typieally assoeiated units are as follows: (1) power in units of watts, (2) intensity in units of watts per meter-squared, (3) pressure in units of mieropaseals, (4) fluid density of medium ρ in units of kilograms per eubie meter, (5) the speed of sound c in the medium in units of meters per seeond. The last two quantities are multiplied to yield the aeoustie or eharacteristie impedanee of the medium (ρc). In eontrast to absolute quantities, the term "relative" refers to those quantities that are expressed in units of deeibels and are defined by 10 times the common logarithm (to base 10) of a ratio of two powers or two other proportional quantities.

Absolute intensity (symbol I_{ABS}) ean be considered to be the average intensity of a plane wave having a root-mean-squared (rms) pressure p_{rms} in a medium of density ρ and sound speed c. I_{ABS} is related to the acoustic power P_{ABS} in watts divided by unit area and can be expressed in physieal units of watts per meter-squared (W/m^2):

$$I_{\mathrm{ABS}}\left[W/m^2\right] = P_{\mathrm{ABS}}[W] / \mathrm{Area}\left[\mathrm{m}^2\right], \tag{A-1}$$

where P_{ABS} is the (absolute) power in physieal units of watts.

A generalized formula relating the average acoustic intensity I_{ABS} to pressure and characteristic impedance is

$$I_{ABS} = p_{ABS}^{\ 2}/(\rho c)_{ABS}\left[W/m^2\right], \tag{A-2}$$

where p_{ABS} is the absolute pressure and $(\rho c)_{ABS}$ is the absolute characteristic impedance of the medium (for example, air or seawater).

If one were to conjecture the absolute intensity of sound energy I_{ABS} to be the same for two media, air and seawater, say, for example, the equivalent intensity of sound from a notional symphony orchestra, in air, then one can describe equal intensities by the following expression:

$$I_{ABS(AIR)} = I_{ABS(SEA)}\,, \tag{A-3}$$

where $I_{ABS(AIR)}$ is the (absolute) intensity for a plane wave in air with respect to a characteristic or reference impedance in air and $I_{ABS(SEA)}$ is the (absolute) intensity of a plane wave in seawater with respect to a characteristic or reference impedance in seawater.

Equation (A-3) specifies the underlying assumption for this problem of comparing relative decibel quantities for two media, air and seawater, namely, that the (absolute) intensity I_{ABS} is the same for both media.

One also obtains a generic expression similar to equation (A-3) for "reference" intensity:

$$I_{REF} = p_{REF}^{\ 2}/(\rho c)_{REF}\left[W/m^2\right], \tag{A-4}$$

where, in air, typically

$$p_{REF} = p_{REF(AIR)} = 20\mu Pa, \tag{A-5}$$

and

$$\rho c_{REF} = (\rho c)_{REF(AIR)} = 42\ g/(cm^2)(sec).^{*} \tag{A-6}$$

Alternatively, in seawater, typically

$$p_{REF} = p_{REF(SEA)} = 1\mu Pa, \tag{A-7}$$

and

$$\rho c_{REF} = (\rho c)_{REF(SEA)} = 1.5\times10^{5}\ g/(cm^2)(sec).^{*} \tag{A-8}$$

---

* Numerical values of ρc are obtained from Urick[37] in centimeter-gram-second (CGS) system of units. To convert ρc values to meter-kilogram-second (MKS) units, apply the following formula: $1\ gm/(cm^2)(sec) = 10\ kg/(m^2)(sec)$. For ρc values expressed in MKS, see L. E. Kinsler, A. R. Freye, A. B. Coppers, and J. V. Sanders, *Fundamental of Acoustics*, Third Edition, John Wiley & Sons, Inc., 1982.

The relative intensity level I_{REL} expressed in decibel units is calculated as 10 times the common logarithm (to the base 10) of the ratio of two quantities, the estimated or measured (absolute) intensity I_{ABS} and the reference intensity I_{REF}. Hence the relative intensity in decibel units is:

$$I_{\text{REL}}(\text{dB}) = I(\text{dB}) = 10\log_{10}(I_{\text{ABS}}/I_{\text{REF}}),^{*} \tag{A-9}$$

where I_{ABS} is the (absolute) intensity from equation (A-2) and I_{REF} is the reference intensity from equation (A-4). Note that for a ratio of intensities (equation A-9) taken for the same medium, the characteristic impedance term (equations (A-2) and (A-4)) drops out.

From equations (A-4) through (A-9), one obtains expressions in decibels for the relative intensities $I_{\text{REL(AIR)}}$ and $I_{\text{REL(SEA)}}$ in air and seawater, respectively:

$$I_{\text{REL(AIR)}}[\text{dB}] = 10\log_{10}\left[\frac{(p_{\text{ABS(AIR)}})^2}{(\rho c)_{\text{ABS(AIR)}}}\right] / \left[\frac{(p_{\text{REF(AIR)}})^2}{(\rho c)_{\text{REF(AIR)}}}\right] = \frac{(p_{\text{ABS(AIR)}})^2}{(p_{\text{REF(AIR)}})^2}, \tag{A-10}$$

$$I_{\text{REL(SEA)}}[\text{dB}] = 10\log_{10}\left[\frac{(p_{\text{ABS(SEA)}})^2}{(\rho c)_{\text{ABS(SEA)}}}\right] / \left[\frac{(p_{\text{REF(SEA)}})^2}{(\rho c)_{\text{REF(SEA)}}}\right] = \frac{(p_{\text{ABS(SEA)}})^2}{(p_{\text{REF(SEA}})^2}, \tag{A-11}$$

where absolute and reference acoustic impedances are equal when they are applied to the same medium.

From the descriptions of $(\rho c)_{\text{REF}}$ for air and water, equations (A-6) and (A-8), the ratio of characteristic impedances, air-to-water, is

$$R(\rho c)_{\text{air-to-water}} = \frac{(\rho c)_{\text{REF(AIR)}}}{(\rho c)_{\text{REF(SEA)}}} = 0.00027, \tag{A-12}$$

and the ratio of characteristic impedances, water-to-air, is

$$R(\rho c)_{\text{water-to-air}} = 3600. \tag{A-13}$$

Reference quantities are physical quantities and therefore absolute quantities. The reference pressure, density, sound speed, and characteristic (acoustic) impedance for air and seawater are, therefore, stated in absolute terms.

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* Shorthand notation is used here: $I(\text{dB}) = I_{\text{REL}}(\text{dB})$.

Equation (A- 9) can be manipulated to solve for I_{ABS}:

$$I_{ABS} = I_{REF} \times 10^{I[dB]/10}. \tag{A-14}$$

Upon substitution of equation (A-4) into (A-14), one obtains:

$$I_{ABS} = \frac{p_{REF}^{2}}{\rho c_{REF}} \times 10^{I[dB]/10}. \tag{A-15}$$

Equation (A-15) should be true in both air and seawater calculations—but with different reference values for p, ρ, and c.

Now recall (from equation (A-3)), the underlying assumption that absolute intensities are the same in water and air, namely, $I_{ABS(SEA)} = I_{ABS(AIR)}$, which means

$$\frac{p_{REF(SEA)}^{2}}{\rho c_{REF(SEA)}} \times 10^{I(dB_{SEA}/10)} = \frac{p_{REF(AIR)}^{2}}{\rho c_{REF(AIR)}} \times 10^{I(dB_{AIR}/10)}. \tag{A-16}$$

Progressively reducing equation (A-16) to solve for $I(dB_{SEA})$ yields the following progressive sets of equations:

$$10^{I(dB_{SEA}/10)} = \frac{p_{REF(AIR)}^{2}}{\rho c_{REF(AIR)}} \times \frac{10^{I(dB_{AIR}/10)}}{p_{REF(SEA)}^{2} / \rho c_{REF(SEA)}}, \tag{A-17}$$

$$10^{I(dB_{SEA}/10)} = 10^{I(dB_{AIR}/10)} \times \left(\frac{p_{REF(AIR)}}{p_{REF(SEA)}}\right)^{2} \times \frac{\rho c_{REF(SEA)}}{\rho c_{REF(AIR)}}, \tag{A-18}$$

$$I(dB_{SEA}) = 10\log\left[10^{I(dB_{AIR}/10)} \times \left(\frac{p_{REF(AIR)}}{p_{REF(SEA)}}\right)^{2} \times \frac{\rho c_{REF(SEA)}}{\rho c_{REF(AIR)}}\right], \tag{A-19}$$

$$I(dB_{SEA}) = 10\log\left[10^{I(dB_{AIR}/10)}\right] + 10\log\left[\left(\frac{p_{REF(AIR)}}{p_{REF(SEA)}}\right)\right]^{2} + 10\log\left[\frac{\rho c_{REF(SEA)}}{\rho c_{REF(AIR)}}\right], \tag{A-20}$$

$$I(dB_{SEA}) = I(dB_{AIR}) + 20\log\left(\frac{p_{REF(AIR)}}{p_{REF(SEA)}}\right) + 10\log\left(\frac{\rho c_{REF(SEA)}}{\rho c_{REF(AIR)}}\right). \tag{A-21}$$

From equations (A-5) and (A-7):

$$\frac{p_{\mathrm{REF(AIR)}}}{p_{\mathrm{REF(SEA)}}} = 20, \tag{A-22}$$

$$20\log\left(\frac{p_{\mathrm{REF(AIR)}}}{p_{\mathrm{REF(SEA)}}}\right) = 26\,\mathrm{dB}. \tag{A-23}$$

Because ratio of the charaeteristie impedanee (ρc) of water to air is about 3600 (equation (A-13)), the relative differenee in impedanee between these two media equals:

$$10\log\left(\frac{\rho c_{\mathrm{REF(SEA)}}}{\rho c_{\mathrm{REF(AIR)}}}\right) = 35.5\,\mathrm{dB}. \tag{A-24}$$

By substituting equations (A-23) and (A-24) into equation (A-21), one obtains

$$I(\mathrm{dB_{SEA}}) = I(\mathrm{dB_{AIR}}) + 26\,\mathrm{dB} + 35.5\,\mathrm{dB} = I(\mathrm{dB_{AIR}}) + 61.5\,\mathrm{dB}\,. \tag{A-25}$$

Alternatively,

$$I(\mathrm{dB_{AIR}}) = I(\mathrm{dB_{SEA}}) - 61.5\,\mathrm{dB}\,. \tag{A-26}$$

If the absolute intensity in air (in $\mathrm{W/m^2}$) is the equal to that in water (also in $\mathrm{W/m^2}$), then 61.5 dB must be added to the relative intensity level (expressed in deeibels) in air to realize an equivalent relative intensity level (expressed in deeibels) in seawater. Conversely, for the same absolute intensity, 61.5 dB must be subtraeted from the relative intensity level in seawater to realize the same relative decibel equivalent in air.

If a notional symphony orehestra emits a relative intensity level (for example, SPL) of 125 dB re 20 μPa @ 1 m in air, then the equivalent in-water intensity level would be 61.5 dB higher. Namely,

$$\begin{aligned} I(\mathrm{dB_{SEA}}) &= 125(\mathrm{dB\ re\ 20\ \mu Pa\ at\ 1\ m}) + 20\log(20\ \mu\mathrm{Pa}/1\ \mu\mathrm{Pa}) + 10\log(\rho c_{\mathrm{SEA}} / \rho c_{\mathrm{AIR}}) \\ &= 125\,\mathrm{dB} + 26\,\mathrm{dB} + 35.5\,\mathrm{dB} = 186.5\,(\mathrm{dB\ re\ 1\ \mu Pa\ at\ 1\ m}). \end{aligned} \tag{A-27}$$

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