Principles of Sonar Performance Modeling

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To Anna

Preface

The science of sonar performance modeling is traditionally separated into a ''wet end'' comprising the disciplines of acoustics and oceanography and a ''dry end'' of signal processing and detection theory. This book is my attempt to bring both aspects together to serve as a modern reference for today's sonar performance modeler, whether for research, design, or analysis, as Urick's *Principles of Underwater Sound* did for sonar engineers of his day. The similarity in the title is no accident.

During the process I made some valuable discoveries that I now share with the reader. The radar literature provides a deep mine of resources, with applicable results from the theories of wave propagation, signal processing, and (an especially rich vein, largely unexploited in the sonar literature) statistical detection. From oceanography we learn that each of the world's oceans has its own unique physical, chemical, and biological signature, with sometimes profound consequences for sonar.

Marine mammals have evolved a sonar of their own, the remarkable properties of which we are only beginning to unravel, as reported in the increasingly sophisticated bioacoustics literature. Governments and industry around the world have begun to take seriously the environmental consequences of man's use, whether deliberate or incidental, of sound in the sea. I have done my best to provide a representative snapshot of this rapidly developing field.

Some readers will treat this book as a repository of facts, figures, and formulas, while others will seek in it explanations and clarity. It has been my intention to satisfy the needs of both types of reader by including mathematical derivations and worked examples, supplemented with measurements or estimates of relevant input parameters. Of all readers I request the patience to overlook the flaws that undoubtedly remain, despite my best attempts to weed them out.

Michael A. Ainslie
TNO, The Hague, The Netherlands, March 2010

Foreword

Underwater acoustics is largely a branch of physics, perhaps merging with geophysics and oceanography, but as soon as one attempts to assess a sonar's performance under realistic conditions, a host of other engineering factors come into play. Is the desired target signal louder than all the other natural noise from wind, waves, ship engines, strumming cables? Is it louder than sound scattered from other distant objects? How do the standard signal-processing techniques such as beamforming, spectral analysis, and statistical analysis influence the probability of achieving a target detection and the probability of a false alarm?

The author, Dr. Mike Ainslie, is a physicist with a considerable academic publication record and many years' hands-on experience in sonar assessment for the U.K.'s MOD and for TNO in The Netherlands. Through a firm foundation in physics, always taking great care over the physical units, *Principles of Sonar Performance Modeling* introduces rigor and clarity into the traditional sonar equation while still answering the fundamental engineering questions. As well as dealing with the more pure disciplines of sound generation, propagation, and reverberation, it tackles sound sources, targets, signal processing, and detection theory for man-made and biological sonar.

Underlying all this is a desire "to see the wood for the trees". For instance, it is often the case with propagation that, despite all the complexities of refraction, reflection, diffraction, scattering, and so on, some simple mechanism dominates, and sometimes one can express the entire transmission loss, ambient noise level, or reverberation level by a simple formula. This insight, or even revelation, is an important bonus and check if one is to have faith in numerical assessment of complicated search scenarios. It can also become a useful shortcut when a particular scenario is to be investigated under many different acoustic, or processing, conditions. Examples of such insights will be found throughout.

The cornerstone is the derivation of the sonar equations—too often presented as indisputable fact—from simple physical principles. The derivation is presented initially in terms of ratios of simple physical quantities, and converted to decibels only at the end. Such an approach provides both clarity and a systematic rationale for determining how to evaluate each sonar equation term, and occasionally throws up unexpected new corrections.

The book will provide a useful reference for acousticians, engineers, physicists, mathematicians, sonar designers, and naval sonar operators whether working in research labs, the defense industry, or universities.

Chris Harrison
NATO Undersea Research Centre (NURC), Italy, March 2010

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The eight years it has taken me to write this book were spent working at TNO in The Hague. It has been a pleasure and a privilege to do so. The Sonar Department, despite two changes of name and two changes of leadership in that time, has provided constant support and understanding for the necessary extra-curricular activities. I wish to thank all at TNO—too many to mention all by name—who helped to make it possible.

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Through his written publications, David Weston is an eternal inspiration—I have lost count of the number of times his name is cited. I also benefited from discussions with Chris Harrison, Chris Morfey, Christ de Jong, Dale Ellis, Frans-Peter Lam, Mario Zampolli, Peter Dahl, and Tim Leighton.

Data or artwork were made available to me by Pascal de Theije (Figure 7.6), Peter Dahl (Figure 8.3), Alvin Robins (Figure 8.5), Vincent van Leijen (Figure 8.13), Peter van Holstein (Figure 8.14), Henry Dol (Figures 9.24 and 9.25), Mathieu Colin (all figures in Chapter 9 making use of either BELLHOP or SCOOTER), Robbert van Vossen (Figures 9.28 and 9.29), Wim Verboom (miscellaneous seal and porpoise audiograms), Garth Mix (thumbnail images of marine mammals), and Paul Wensveen (Figure 11.20).

The computer model INSIGHT (version 1.4.2) was used, with permission of CORDA Ltd., to illustrate many of the sonar performance calculations. Also used were the acoustic propagation models SCOOTER and BELLHOP from the Ocean Acoustics Library (*http://oalib.hlsresearch.com*). Other valuable Internet resources include FishBase (*www.fishbase.org*), the Ocean Biogeographic Information System (*www.iobis.org*), Mathworld (*http://mathworld.wolfram.com*) and Wikipedia (*www.wikipedia.org*).

Phillipe Blondel and Clive Horwood were always available when needed for advice. Neil Shuttlewood is responsible for a professional end-product.

Last but not least, none of this would have been possible without the unquestioning love and support from my wife Pilar and patience of my daughter Anna, whose teenage years are forever tinted with shades of sonar performance.

Michael A. Ainslie
TNO, The Hague, The Netherlands, March 2010

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Part I

Foundations

1

Introduction

Wee represent Small Sounds as Great and Deepe; Likewise Great Sounds, Extenuate and Sharpe; Wee make diverse Tremblings and Warblings of Sounds, which in their Originall are Entire. Wee represent and imitate all Articulate Sounds and Letters, and the Voices and Notes of Beasts and Birds. Wee have certaine Helps, which sett to the Eare doe further the Hearing greatly. Wee have also diverse Strange and Artificiall Eccho's, Reflecting the Voice many times, and as it were Tossing it; And some that give back the Voice Lowder then it came, some Shriller, and Some Deeper; Yea some rendring the Voice, Differing in the Letters or Articulate Sound, from that they receyve. Wee have also meanes to convey Sounds in Trunks and Pipes in strange Lines, and Distances.

Francis Bacon (1624)

1.1 WHAT IS SONAR?

Sonar can be thought of as a kind of underwater radar, using sound instead of radio waves to interrogate its surroundings. But what is special about sound in the sea? Radio waves travel unhindered in air, whereas sound energy is absorbed relatively quickly. In water, the opposite is the case: low absorption and the presence of natural oceanic waveguides combine to permit propagation of sound over thousands of kilometers, whereas the sea is opaque to most of the electromagnetic spectrum.

The word *sonar* is an acronym for *so*und *na*vigation and *r*anging. The primary purpose of sonar is the detection or characterization (estimation of position, velocity, and identity) of submerged, floating, or buried objects. Electronic systems capable of underwater detection and localization were developed in the 20th century, motivated initially by the sinking of RMS *Titanic* in 1912 and the First World War (WW1), and spurred on later by the Second World War (WW2) and the Cold War. Nevertheless, by comparison with marine fauna, man remains a novice user of underwater sound. Deprived of light in their natural habitat, dolphins have evolved a sophisticated form of sonar over millions of years, without which they would be almost blind. They transmit bursts of ultrasound, and sense the world around them by interpreting the echoes. Many fish and other aquatic animals are also capable of both producing and hearing sounds.

1.2 PURPOSE, SCOPE, AND INTENDED READERSHIP

This book is aimed at anyone, novice and experienced practitioner alike, with an interest in estimating the performance of sonar, or understanding the conditions for which a particular existing or hypothetical system is likely to make a successful detection. This includes sonar analysts and designers, whether for oceanographic research, navigation, or search sonar. It also includes those studying the use of sound by marine mammals and the impact of exposure of these animals to sound. Regardless of application, the objective of sonar performance modeling is usually to support a decision-making process. In the case of man-made sonar, the decision is likely to involve the optimization of some aspect of the design, procurement, or use of sonar. (What frequency or bandwidth is appropriate? How many sonars are needed to complete the task in the time available?) For bio-sonar there is increasing interest in the assessment (and mitigation) of the risk of damage to marine life due to anthropogenic sources of underwater sound. (What level of sound might disrupt a dolphin's ability to locate and capture its prey? How can the risk of hearing damage be prevented or minimized?)

The nature of the sought object, known as the sonar *target*, depends on the application. Examples include man-made objects of military interest (a mine or submarine), shipwrecks (as a navigation hazard or archeological artifact), and fish (the target of interest to a whale or fisherman).

In general, sonar can be grouped into two main categories. These are *active sonar* and *passive sonar*, which are distinguished by the presence and absence, respectively, of a sound transmitter as a component of the sonar system.

- An *active sonar* system comprises a transmitter and a receiver and works on the principle of echolocation. If a signal (in this case an echo from the target) is detected, the position of the target can be estimated from the time delay and direction of the echo. The echolocation principle is also used by radar, and by the biological sonar of bats and dolphins.
- A *passive sonar* includes a receiver but no transmitter. The signal to be detected is then the sound emitted by the target.

Examples of man-made sonar include

- *Echo sounder*: perhaps the most common of all man-made sonars, an echo sounder is a device for measuring water depth by timing the delay of an echo from the seabed. The strength and character of the echo can also provide an indication of bottom type.
- *Fisheries sonar*: sonar equipment used by the fisheries industry exploits the same principle as the echo sounder, except that the purpose is to detect fish instead of the sea floor.
- *Military sonar*: modern navies deploy a wide variety of sonar systems, designed to detect and track potential military threats such as surface ships, submarines, mines, or torpedoes. The diverse nature of these threats and of the *platforms* on which the sonar systems are mounted means that military sonars are themselves diverse, with each specialized system dedicated to a particular task.
- *Oceanographic sensor*: scientific work aimed at understanding and surveying the sea (*acoustical oceanography*) makes extensive use of a variety of different kinds of sonar, many of which are variants of the echo sounder.
- *Shadow sensor*: in exceptional cases, the sonar "signal", instead of being the sound emitted or scattered by the target, might actually be some perturbation to the expected *background*. For example, the shadow of an object lying on the seabed might be detectable when the object itself is not.

Many readers will be familiar with Urick's classic *Principles of Underwater Sound for Engineers*,[1] which provided its readers with the tools they needed to carry out sonar design and assessment studies. These tools come in the form of a set of equations relating the predicted signal-to-noise ratio to known parameters such as the radiated power of the sonar transmitter, or the size and shape of the target. This set of equations is known as the "sonar equations". The same basic requirement remains today, but the modeling methods have increased in sophistication during the 25 years that have elapsed since Urick's third and final edition, with a bewildering array of computer models to choose from (Etter, 2003). The present objective is to meet the needs of the modern user or developer of such models by documenting established methods and relevant research results, using internally consistent definitions and notation throughout. The discipline of sonar performance modeling is perceived sometimes as a black art. The purpose of this book is, above all, to demystify this art by explaining the jargon and deriving the sonar equations from physical principles.

The book's scope includes underwater sound, the properties of the sea relevant to the generation and propagation of sound, and the processing that occurs after an acoustic signal has been converted to an electrical one[2] and then digitized. The estimation of sonar performance is taken as far as the detection (and false alarm) probability, but no further than that. While the scope excludes localization,

[1] See Urick (1967) and two later editions (Urick, 1975, 1983).

[2] Conversion between electrical and acoustical energy (known as transduction), whether on transmission or reception, is excluded from the scope. The interested reader is referred to Hunt (1954) and Stansfield (1991).