MODELING CORAL REEF ACOUSTIC PROPAGATION LOSS

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MODELING CORAL REEF ACOUSTIC PROPAGATION LOSS

BY

KAYLA M. THILGES

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
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OF

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DEAN OF THE GRADUATE SCHOOL

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ABSTRACT

Quantification of an acoustic metric relating sound propagation on a coral reef to ecological parameters could enhance long-term ecological studies on coral reefs. The acoustic metric constructed in this study is coral reef propagation loss, or the sound intensity reduction with range, in a coral reef environment. Establishment of this benchmark parameterizes the geometric spreading and attenuation factors of the coral reef environment.

Two analyses are conducted in which both passive and active acoustics are used to measure the sound propagation environment across different fringing coral reef sites. In the first analysis, two passive acoustic studies in the literature captured the ambient reef soundscape (abiotic and biotic factors within 0.1 - 5 kHz band) sound pressure level at various ranges offshore on six different coral reef sites worldwide. This broadband coral reef soundscape information is utilized to evaluate propagation loss. The second analysis is an active acoustic experiment conducted at two different Hawaiian coral reefs, where low-level tone transmissions (0.5, 2, 5, 10, 15 kHz) were recorded at various ranges offshore. These tones are evaluated regarding both frequency and range dependence of transmission loss.

The development of the reef propagation loss metric is explored through application of existing literature models (cylindrical spreading, spherical spreading, Roger’s Onboard Empirical Formula, Marsh-Schulkin, Extended Marsh-Schulkin, and Bellhop), as well as through nonlinear least squares inversion scheme models (sloped cylindrical spreading, spreading only, attenuation only, spreading and attenuation/Base Model) compared against the field data. Iterative minimization, performed with the nonlinear least squares method, provides indices of a geometric spreading factor and an attenuation factor of the specific environment. Root-mean-square error metric compared the accuracy of the multitude of models
to the acoustic field data for both analyses.

Results of the ambient coral reef soundscape study indicate geometric spreading factors a magnitude less than as predicted with conventional cylindrical spreading. Attenuation factors extracted correspond to dry silt sediment bottom values in the literature. Results of the transmitted tones study suggest nonlinear frequency dependence of the coral reef propagation environment. The field data indicated stronger contribution from spreading and minor contribution of attenuation in characterizing the transmission loss. Geometric spreading parameter estimates bracket that of cylindrical spreading. Broadband coral reef soundscape propagation exhibits significantly less propagation loss than a single tonal transmission within the same band and in a similar environment. These results further elucidate the complexity of the coastal environment and the frequency dependent nature of sound propagation.
ACKNOWLEDGMENTS

I would like to thank Dr. Lora Van Uffelen, my major professor, for supporting me during the past two years. I truly appreciate our insightful discussions and your mentorship throughout my graduate degree. Your positive impact has profoundly helped shape my future career endeavors.

Great appreciation to Dr. Gopu Potty for your gracious guidance, scientific advise and expert knowledge. Thank you to the other members of my thesis committee; Dr. Hollie Putnam and Dr. Jonathan Puritz. I sincerely appreciate the constructive comments and learning opportunities, as they have allowed me to greatly improve the quality of the thesis. Thank you to everyone who has supported me during my time at the University of Rhode Island.

A gracious recognition to Dr. T. Aran Mooney, Dr. Julius Piercy, and their respective research teams, for making the coral reef soundscape study (Manuscript 1) possible by allowing use of your data as well as offering insight into the compiled analysis.

I would also like to thank DARPA and the Persistent Aquatic Living Sensors (PALS) Program for their funding to support the efforts contained within Manuscript 2. Special thanks to all those involved in the PADRES group; Simon Freeman, Lauren Freeman, Sonia Rowley, Jeff Schindall, Aaron Thode, Ludovic Tenorio, Alexis Johnson, Jesse Moore, and Alexander Conrad. Your support and assistance with carrying out the field work in Hawaii made this project possible.

Thank you, last but not least, to my family and friends for your continued support of the places I’ll go and path I’ll follow.
PREFACE

This Master thesis was prepared in the manuscript format and includes two independent manuscripts. Formatting of each manuscript reflects the requirements as set out by the respective journal. The author of this thesis was the lead investigator and lead author of both included manuscripts.

The first manuscript is to be submitted for publication in IEEE OCEANS 2020-Singapore conference proceedings, © 2020 IEEE. Reprinted, with permission, from K. Thilges, G. Potty, T. A. Mooney, and L. Van Uffelen, ”Synthesis of Acoustic Propagation Loss Measurements on Coral Reefs,” OCEANS 2020-Singapore. IEEE, 2020, unpublished. This work presents a compilation study and analysis of limited available literature on propagation loss of the coral reef soundscape.

The second manuscript is to be submitted for publication in JASA Express Letters (JASA-EL). Reproduced from K. Thilges, G. Potty, S. Freeman, L. Freeman, and L. Van Uffelen, ”Measurements and models of acoustic transmission loss on two Hawaiian coral reefs,” The Journal of the Acoustical Society of America (2020), with permission of the Acoustical Society of America. Once accepted and published, it will be found at https://asa.scitation.org/journal/jel. This work presents data collected from an experiment conducted on the Big Island of Hawaii. Field data collected consists of a de minimis sound production from an underwater speaker. Transmitted tones are captured with a hydrophone at discrete ranges offshore from the source to yield measurement of transmission loss in a coral reef environment.

Appendix A includes an overall discussion, combining implications and conclusions from both manuscripts. The subsequent appendix provides an explanation of the acoustic parameter inversion technique implemented in both manuscripts.
TABLE OF CONTENTS

ABSTRACT .................................................. ii

ACKNOWLEDGMENTS ........................................ iv

PREFACE .................................................. v

TABLE OF CONTENTS ........................................ vi

LIST OF FIGURES .......................................... viii

LIST OF TABLES ........................................... ix

MANUSCRIPT

1 “Synthesis of Acoustic Propagation Loss Measurements on Coral Reefs” .................. 1
   1.1 Introduction ........................................ 2
   1.2 Study Sites ......................................... 3
   1.3 Spreading and Attenuation Parameter Estimation .......... 6
   1.4 Results ............................................. 8
   1.5 Conclusion ......................................... 11
   List of References ...................................... 13

2 “Measurements and Models of Acoustic Transmission Loss on Two Hawaiian Coral Reefs” .......... 16
   2.1 Introduction ........................................ 17
   2.2 Materials and Methods .............................. 18
      2.2.1 Site Descriptions .............................. 18
      2.2.2 Coral Reef Transmission Loss Measurements .... 19
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Study Site Locations</td>
</tr>
<tr>
<td>1.2</td>
<td>Propagation Loss as a Function of Range Off the Reef</td>
</tr>
<tr>
<td>1.3</td>
<td>Model Variants Applied to Compiled Coral Reef Propagation Loss Data</td>
</tr>
<tr>
<td>1.4</td>
<td>Cost Function Minimization</td>
</tr>
<tr>
<td>1.5</td>
<td>Spreading and Attenuation Parameter Results</td>
</tr>
<tr>
<td>1.6</td>
<td>Root Mean Square Error of Models For Each Site</td>
</tr>
<tr>
<td>2.1</td>
<td>Measurement Transects at Hapuna and Eel Cove Coral Reefs</td>
</tr>
<tr>
<td>2.2</td>
<td>Transmission Loss Field Data From Hapuna and Eel Cove Coral Reefs</td>
</tr>
<tr>
<td>2.3</td>
<td>Transmission Loss Models and Root Mean Square Error Quantification</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Coral Reef Transect Experiment Details</td>
</tr>
</tbody>
</table>
“Synthesis of Acoustic Propagation Loss Measurements on Coral Reefs”

by

Kayla Thilges¹, Gopu Potty², T. Aran Mooney³, and Lora Van Uffelen⁴

to be submitted to the IEEE OCEANS conference proceedings 2020.

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Abstract

An empirical model of propagation loss, based on acoustic characteristics of geometric spreading and attenuation, allows baseline analysis of a coral reef propagation environment. This work presents a synthesis study from published values of propagation loss as a function of range on coral reef sites in different geographic locations. The geoacoustic approach conducted evaluates spreading and attenuation values which reflect a more gradual decrease in sound intensity, relative to the sound pressure level on the reef, over ranges of 1 km, than theoretically predicted by cylindrical and spherical spreading models. These results quantify ambient coral reef acoustic propagation loss for sites of opportunity and indicate similarities between reef type and the acoustic propagation parameters.

1.1 Introduction

Eco-acoustic relationships on coral reefs could provide indication of environmental stressors such as pollution or rise in sea surface temperature [1, 2]. Improved understanding of these relationships within these richly biodiverse environments could provide additional mechanisms to track the health of the coral reef community and its relationship with a changing environment [3]. Anthropogenic influences, including divers, boat traffic, and any intrusive, unnatural sound contribution within the coral reef soundscape can also be quantified through acoustics.

Recently, providing acoustic enrichment by playing sounds recorded on a healthy reef through a speaker on a degraded coral reef has supported fish settlement [4]. Understanding directionality and functional advantages of the environment may maximize playback efforts and further support the natural regeneration of the ecosystem.

Limited work has been done to study acoustic propagation losses in a coral reef environment. Acoustic propagation models are available for predicting underwater
acoustic propagation loss in a variety of environments, but shallow water coral reef environments are particularly complicated due to the high degree of variability over very short ranges, constituting many sound interactions with surface waves and the seabed. These losses may be due to bottom attenuation, volumetric scattering from biota, and boundary scattering from complex topography and sea surface roughness in the coastal coral reef environment [5].

This paper focuses on developing a simplified empirical model of acoustic propagation loss in these coral reef environments by synthesizing measurements presented in the literature [6, 7]. Coral reef soundscape identifiers and influential parameters such as bathymetry, benthic habitat, frequency band of the source, depth-dependence, and attenuation are mined from the literature to observe similarities and differences.

Descriptions of the different study sites and the acoustic data collected is given in Section 1.2. Section 1.3 presents the methods and models used to extract attenuation and spreading parameters of each site. A discussion of the model results is provided in Section 1.4. Conclusions are stated in Section 1.5.

1.2 Study Sites

To assess the propagation environment in coastal coral reefs, six coral reef sites in three geographical areas within the tropical zone are analyzed (Fig. 1.1). This work synthesizes previously collected and reported field data [6, 7]. These data consist of sound pressure level readings at various ranges offshore from the coral reef site. This work provides a combined approach to assess similarities and differences in propagation loss across the study sites. An overview of the defining coral reef characteristics, data collection time, frequency band, and receiver depth are provided in Table 1.1 [6, 7].

Each site focuses on a frequency band within the 0.1 - 5 kHz range. This has
been noted to be a characteristic frequency band for coral reef biological soundscapes [6, 7, 9, 10, 11, 12]. Bathymetry is of a shelving coastline for the Barr Al-Hickman reef (BAHE), South Masirah Island reefs (MIS1 & MIS2), and the Olowalu reef [6, 7]. Reefs Pak Kasim (PK) and Front Beach (FB) are characterized by a shallow reef near surrounding steep drop off in topography [7]. All study sites are classified as fringing coral reefs and have a similar geomorphic zonation, in which the coral is directly adjacent to the shoreline and extends offshore ending at the reef crest [13, 14, 15, 16].

Coral reef soundscapes are characterized by a large degree of temporal variability, including crepuscular and diel variability [6, 7, 9, 11, 17, 18]. To accommodate any existing dawn and dusk reef chorus and overall temporal variability, this study estimates propagation loss between the in situ, on reef sound level at various ranges offshore instead of simply noting general sound pressure level (Fig. 1.2). An implicit assumption of this approach is that ocean dynamics do not change over the course of each transect reading offshore. This is an acceptable assumption,
Table 1.1
List of study sites; including the data extraction date and field observations of each site.

<table>
<thead>
<tr>
<th>Coral Reef Identifier</th>
<th>Time of Day</th>
<th>Name &amp; Location</th>
<th>Coral Reef Site Characteristics**</th>
<th>Frequency Band (kHz)</th>
<th>Receiver Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAHE</td>
<td>Feb-05</td>
<td>Barr Al-Hickman Reef; Masirah Channel, Oman</td>
<td>Shallow shelfing coastline reef (depth &lt; 20 m); high coral cover (&gt;50%); Montipora foliosa dominant coral species; Tropical region; Site has no official management or protection status</td>
<td>0.1 - 5</td>
<td>4</td>
</tr>
<tr>
<td>MIS1</td>
<td>Feb-05</td>
<td>South Masirah Island Reef 1; Masirah Channel, Oman</td>
<td></td>
<td>0.1 - 5</td>
<td>4</td>
</tr>
<tr>
<td>MIS2</td>
<td>Feb-05</td>
<td>South Masirah Island Reef 2; Masirah Channel, Oman</td>
<td></td>
<td>0.1 - 5</td>
<td>4</td>
</tr>
<tr>
<td>PK</td>
<td>Jun-09</td>
<td>Pak Kasim Reef; Hoga Island; Wakatobi Marine National Park; Sulawesi, Indonesia</td>
<td>Fringing reef; high biodiversity; deep surrounding waters (depth &gt; 100 m); Tropical region; West Pacific Warm Pool; Site is located in a Marine National Park</td>
<td>0.1 - 5</td>
<td>4</td>
</tr>
<tr>
<td>FB</td>
<td>Jun-09</td>
<td>Front Beach Reef; Hoga Island; Wakatobi Marine National Park; Sulawesi, Indonesia</td>
<td></td>
<td>0.1 - 5</td>
<td>4</td>
</tr>
<tr>
<td>Olowalu 1</td>
<td>Jul-15</td>
<td>Olowalu Reef; Maui, HI</td>
<td>Flat reef with dominant branching corals; sand channels between massive coral structures; high coral cover (~70%); reef is at 6-11 m depth, with ~60 m water depth at 1500 m transect position; Tropical region, Cool Tropics; Site is located in a Hawaiian Islands Humpback Whale National Marine Sanctuary</td>
<td>0.2 - 4.9</td>
<td>10</td>
</tr>
<tr>
<td>Olowalu 2</td>
<td>Jul-15</td>
<td>Olowalu Reef; Maui, HI</td>
<td></td>
<td>0.2 - 4.9</td>
<td>10</td>
</tr>
<tr>
<td>Olowalu 3</td>
<td>Jul-15</td>
<td>Olowalu Reef; Maui, HI</td>
<td></td>
<td>0.2 - 2.8</td>
<td>10</td>
</tr>
<tr>
<td>Olowalu 4</td>
<td>Jul-15</td>
<td>Olowalu Reef; Maui, HI</td>
<td></td>
<td>0.2 - 2.8</td>
<td>10</td>
</tr>
</tbody>
</table>

*Time frame is an approximate period in which data collection took place, but does not represent experiment duration.

**Characteristics represent conditions at time of experiment.

a [7], b [8], c [6]

as precautions are taken in the field efforts to assure a steady-state background environment to capture passive soundscape detection with range; these include a moored hydrophone on the reef continuously recording during transects [6], a Beaufort 2 sea state or less, dampening of surface waves effects with weighted equipment, removal of vessel noise from the data, and appreciable spatial distance from other reefs [6, 7].

The combined field data of the six coral reefs sites are shown as individual data points from the nine different transect records, clustered by range (Fig. 1.2). There is a standard deviation of less than ±3 dB for each range population. Stan-
Standard models of geometric spreading loss are spherical spreading (near field) and cylindrical spreading; differentiated by a constant coefficient (20 for spherical and 10 for cylindrical) to a common logarithm of range relative to a reference [5]. Compiled field data exhibits approximately 25 dB (re 1µPa re on reef level) less attenuation than predicted by cylindrical spreading over a 1500 m range. Deviation from these standard models has been observed at coral reefs [6, 7], and a “reef-effect” has been postulated on a temperate reef which indicates a zone surrounding the reef where sound pressure level attenuates less than predicted due to cylindrical spreading [19]. In a related study using active low-level tonal transmissions on a coral reef, transmission loss as a function of range from the source was seen to be nonlinear with regards to frequency [20]. The propagation model to enact in a coral reef environment has been inconclusive; but agreement is seen in nonconformity of a reef environment to fit classical, theoretical models due to complicated topography, bottom rugosity, tides, varying oceanography, biotic and abiotic factors all creating uncertainty in predicting sound propagation.

1.3 Spreading and Attenuation Parameter Estimation

Depth-averaged empirical models are constructed to evaluate two defining parameters of the acoustic domain; a geometric spreading parameter, $S$, which is frequency independent, and a frequency dependent attenuation parameter, $A$, as attenuation per unit length (dB/m) inclusive of all attenuation effects with range within the environment. Due to the broadband nature of the acoustic source in the analysis (the reef signal), the attenuation parameter may suggest an integrated broadband result distinctive of fringing coral reefs.

Using a non-linear least squares scheme as the parameter estimation technique [21], the algorithm iteratively minimizes the least squares error of the model.
Figure 1.2: Compiled sound pressure level off the reef [6, 7] expressed as propagation loss in reference to the in situ recorded source sound pressure level on the reef at the time of transect data collection. Box plots denote compiled data at a specific range; Central bar = median, box = 25th and 75th percentiles, whiskers = most extreme data points not considered outliers, plus markers = outlier data points. Green x marks projected propagation loss formulated cylindrical spreading based off a distance, r, from the reef.

to a data set. This objective function is represented by (1.1).

\[ f(x)_k = ||d_{model}(x, r)_k - d_{observed}(r)||_2 \]  (1.1)

Where \( k \) represents each iteration, \( d_{observed} \) is the collected field data, and \( d_{model} \) is the model evaluation for each range, \( r \), and parameter set \( x \), which are the predictor variables \( S \) and/or \( A \). Propagation loss is analyzed as separate predictions of \( d_{model} \) in the following models: Spreading-only (SO) (1.2), Spreading and Attenuation (SA) (1.3), and Attenuation-only (AO) (1.4).

\[ SO = S\log_{10}(r) \]  (1.2)

\[ SA = S\log_{10}(r) + A(r) \]  (1.3)

\[ AO = A(r) \]  (1.4)
Where: \( r = \text{range (m)} \)

\[
S = \text{Spreading Parameter}
\]

\[
A = \text{Attenuation Parameter (dB/m)}
\]

These models are applied to each individual coral reef, as well as holistically utilizing the compiled means of all reefs (Fig. 1.2) as the input data. Each data set is then fit with the least squares variant of each model (Fig. 1.3) and respective values for \( S \) and/or \( A \) are predicted.

Figure 1.3: SO, SA, and AO models as applied to the compiled means at each range from the data shown in Fig. 1.2. Bars represent one standard deviation (SD) of the SO and AO models and the grey area represents one standard deviation of the SA model.

1.4 Results

Model solutions are obtained through iterative minimization of a cost function (1.5).

\[
\text{Cost Function} = \| f(x)_k \|^2
\]

The cost function represents the squared \( L_2 \)-norm of the residual at each iteration. Fig. 1.4 describes the solution convergence through the minimization of the cost
function. With few samples in each data set, solution convergence occurred in under 31 iterations; with the SO and AO, only having a single parameter estimation, converging in under 20 iterations.

The estimated values of the spreading and attenuation parameters based on each model are indicated in Fig. 1.5. Adding an attenuation parameter had the effect of lowering the spreading parameter, as seen with the SA when compared to the SO results. The mean spreading parameter, $S$, estimated for all the coral reef sites is $2.1 \pm 0.79\sigma$ for SO and $1.4 \pm 0.93\sigma$ for SA. The mean attenuation parameter, $A$, for all the coral reef sites is $0.0031 \pm 0.0030\sigma$ dB/m for SA and $0.0076 \pm 0.0032\sigma$ dB/m for AO. The estimated $S$ and $A$ parameters using the compiled means, all fall within the standard deviation of the mean estimate of all reef sites (Fig. 1.5).
Predicted $A$ values, though indicative of all attenuation effects with range within the environment, are approximately two orders of magnitude less than published values for sand [22, 23] and experimental coral [24] bottom sediment attenuation. Suggested attenuation values from the SA and AO are consistent with literature values in the realm of dry silts [22]. Overall, the coral reef intensity level decreases significantly more gradually relative to the source level on the reef than predicted by conventional cylindrical spreading propagation loss. A root-

![Boxplots showing geometric spreading parameter, $S$, (left) and attenuation parameter, $A$, (right) from the nonlinear least squares algorithm for the six coral reef sites for the respective propagation models (SO, SA, and AO). Central bar = median, box = 25th and 75th percentiles, whiskers = most extreme data points not considered outliers, plus markers = outlier data points. Black bar represents the mean. Compiled means, 'x', of the data presented in Fig. 1.2.](image)

mean-square error (RMSE) metric is used to evaluate each model of propagation loss compared to the field data (Fig. 1.6). Of the fitted models, the SA, due to its solution dependence on two predictor variables (both a spreading, $S$, and attenuation, $A$, parameter) allowed for a refined approximation of the field data,
and has the lowest RMSE for each individual reef as well as for all reefs combined (Compiled Means). All coral reefs, except MIS1 and MIS2, have a lower RMSE with the SO (purely spreading) as compared to the AO (purely attenuation).

Figure 1.6: Root-mean-square error (RMSE) metric of each model fit to the field data. Compiled Means represent the data of Fig. 1.2.

1.5 Conclusion

The overall results indicate that the propagation environment is spreading dominated over the first 1 km range off the coral reef. Though these environments are complex, the ambient noise levels in the lower frequency range (0.1-4.9 kHz) are not seen to attenuate as rapidly offshore as theoretically predicted. Nonlinear least squares regression results of the SA provided the lowest RMSE in all cases. The synthesized empirical model for coral reef propagation loss (Reef PL), based on the SA mean values, is given by (1.6).

\[
Reef\ PL\ (dB\ re\ on\ reef) = 1.4\log_{10}(r) + 0.0031(r) \tag{1.6}
\]

This empirical model seeks to provide a baseline estimate of propagation loss in a coastal, fringing coral reef environment while challenging conventional geometric spreading estimates of propagation loss. Predicted spreading values are an order
of magnitude smaller than conventional spreading models. Attenuation values are more consistent with values of marine dry silt sediment as opposed to sand attenuation values cited in the literature.

Coral reefs presented in this study were moderate to good health (medium/high fish density, high diversity of coral and fish) at the time of the experiment [6, 7]. The Olowalu reef experienced an extreme bleaching event due to abnormally warm surface temperatures, after field data collection, during the summer of 2015 [25]. An interesting study would be to compare these propagation loss patterns to the current bleached/degraded Olowalu reef as well as to other fringing coral reefs to study the differences in the propagation environment based on a changed environment. Similarly, repeated transects, or longer timeseries data, in a larger variety of sites, may provide a more robust solution to elucidate parallelism in acoustic propagation loss patterns.

Development of an empirical model of propagation loss based on predictor variables $S$ and $A$ allows site-specific characterization of the propagation environment as well as an acoustic propagation metric for coral reefs of similar geomorphology. This approach provides a synthesis study of coral reef sites in different geographic locations through evaluation of their eco-acoustic similarities with regards to propagation loss. Passive acoustic monitoring of reef soundscapes could potentially be used to quantify changes to the reef habitat [26, 27], and provide a means of identifying exposure of coastal ecosystems to anthropogenic noise [28, 18]. The empirical model presented here synthesized limited data from the literature to provide a baseline, generalized estimate of propagation loss in a coastal coral reef environment.
Acknowledgments

The data presented here is based on published field data collected by T. Aran Mooney (Woods Hole Oceanographic Institution) and Julius Piercy (University of Essex). The authors are grateful to these researchers and their respective teams for their field efforts, data assimilation, and invaluable insight which has allowed this research. Data collection on Olowalu Reef was supported by funding from the NSF Biological Oceanography Program to T. Aran Mooney and team (Woods Hole Oceanographic Institution).

List of References


MANUSCRIPT 2

“Measurements and Models of Acoustic Transmission Loss on Two Hawaiian Coral Reefs”

by

Kayla Thilges1, Gopu Potty2, Simon Freeman3, Lauren Freeman4, and Lora Van Uffelen5

to be submitted to the JASA Express Letters (JASA-EL). This manuscript is DISTRIBUTION A. Approved for public release: distribution unlimited. This research was developed with funding from the Defense Advanced Research Projects Agency. The views, opinions and/or findings expressed are those of the author and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.

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Abstract

Acoustic transmission loss was measured as a function of range on a coral reef to better understand the propagation environment at frequencies of 0.5, 2, 5, 10, and 15 kHz. Low-level signals were projected on two contrasting coral reef sites in Hawaii, and received by a hydrophone at ranges up to 500 m. A suite of transmission loss models are tested against the field data. Geoacoustic inversion methods are used to obtain a spreading and attenuation coefficient for each site. This work challenges conventional geometric spreading models in a coral reef setting and quantifies site-specific spreading and attenuation.

2.1 Introduction

Coral reefs are an important ecosystem to provide indication of the effects of ocean environmental changes [1]. These coastal environments are acoustically complex due to spatial, temporal, and spectral variability [2] as well as anthropogenic influences [3, 4, 5]. Acoustic propagation on a coral reef is influenced by dynamic effects of physical and chemical oceanographic conditions [6], surface waves, bottom composition, and rugosity [7]. Field experiments have been conducted to measure propagation loss using passive acoustics [8, 9, 10]; however, crepuscular biologic activity and changes in ambient sound levels create inherent spatial and temporal variability making it difficult to characterize the attenuation passively [8, 9, 11, 12]. A representative attenuation estimate for a coral reef environment is desirable to assess propagation loss.

This study aims to specifically characterize the propagation environment through transmission of low-level signals on two coral reef sites in Hawaii. A suite of Transmission Loss (TL) models were evaluated and a site specific empirical Base model was developed to estimate spreading and attenuation parameters for the coral reef environment. These results could be used to estimate ranges
over which coral reef sounds may propagate and potentially assess reef health, as changes to the reef health impact the acoustic environment [13, 14, 5].

A description of each coral reef site and the methods used to measure sound propagation are described in section 2.2. Section 2.3 presents the acoustic TL models used to evaluate the data. Section 2.4 provides a comparison between the field data TL models and discusses the spreading and attenuation parameter estimation results. Conclusions are given in section 2.5.

2.2 Materials and Methods

2.2.1 Site Descriptions

Low-level signals were transmitted at two contrasting coral reef sites on the leeward side of the Big Island of Hawaii in January 2019 (Figure 2.1):

Eel Cove (19° 39.295′N, 156° 1.901′W) is characterized by a shallow complex coral reef structure with a sandy plain below steep coral walls. The site is a shallow, approximately 11 m deep reef followed by a sandy slope that drops off precipitously with increasing distance offshore to a 255 m depth at 530 m [15, 16]. At approximately 5 m depth and shallower there was 5-7% coral cover and prominent basalt rock cover. At ~15 m depth coral cover was ~20% with intermittent Crustose Coraline Algae. At ~25 m depth there is sandy substrate with occasional Pocillipora colonies [17]. Eel Cove is only accessible by boat, making it a relatively secluded site with low-medium tourism traffic impact.

Hapuna (19° 59.288′N, 155° 50.246′W) contained patchy coral reefs with sand channels between long, elevated spurs of coral. The healthy coral cover was estimated at ~40% [17]. Bathymetry of the site is gently sloping, ranging from approximately 22 m depth to 65 m depth offshore over the 466 meters of the experiment transect [18].

Conductivity, Temperature, and Depth (CTD) profiles were collected at Eel
Cove and Hapuna, showing relatively isovelocity conditions to 20 m depth. Propagation models (described in section 2.3) that required a deeper sound speed profile were supplemented with Seaglider data from a separate 2013 study off the western coast of the Big Island of Hawaii conducted at the same time of year [19].

Figure 2.1: Location of measurement transects at the Hapuna Reef and Eel Cove Reef sites. Dots represent locations where data were collected. Black outlined areas represent benthic habitat [20].

2.2.2 Coral Reef Transmission Loss Measurements

Characterization of the propagation environment was done through transmission of known low-level signals at the sites. A Lubell LL916 underwater loudspeaker system (frequency range 200 Hz - 20 kHz) was used as the source and suspended from a boat at a depth of 2 m. Frequencies of interest on a coral reef are concentrated within the 0.1 - 20 kHz band, with the lower 0.1 - 4 kHz band characteristic of reef biotic sound and the upper 2 - 20 kHz band typical of fleshy macroalgae substrate areas [7, 8, 9, 11, 21, 22]. Transmitted signals were 2 s tones at 0.5, 2, 5, 10, and 15 kHz. A receive hydrophone measured the signal at various ranges from
Recordings at Eel Cove were made with a HTI-92-WB hydrophone (High Tech, Inc.; 2 Hz - 50 kHz frequency response and -165 dB re 1V/µPa sensitivity). A TASCAM DR-05 sampled at a rate of 44.1 kHz. At Eel Cove, a single recording transect perpendicular to shore was conducted on January 21st, 2019 at 9:45am HST. The receive hydrophone was at a depth of 5.6 m. A total of 16 transmissions were conducted (Figure 2.1). A control hydrophone (HTI-92-WB) was moored at 30 m depth and approximately 29 m from the source.

The recording hydrophone at Hapuna was a HTI-96-MIN hydrophone (High Tech, Inc.; 2 Hz - 30 kHz frequency response and -164 dB re 1V/µPa sensitivity). The recording instrument was a Loggerhead LS1. Recordings were sampled at a rate of 96 kHz. This receive hydrophone was at a depth of 10 m. Another receive hydrophone (HTI-92-WB) at a depth of 21 m was also used. At Hapuna, parallel and perpendicular transects to the shoreline were conducted on January 11th, 2019 at 12:30pm HST. A control hydrophone (HTI-92-WB) was suspended at 5.6 m depth and approximately 2.7 m from the source. A total of 14 transmissions were conducted from ranges 22 m to 466 m offshore (Figure 2.1).

The sea state at both Eel Cove and Hapuna was less than Beaufort 3 (wind 7-10 knots, wave heights 0.6-1 m) during the time of the experiments. A control hydrophone provided a baseline measurement of acoustic variability during the transect measurements. The background soundscape did not substantially change over the 30 min time frame of the transect, but there was greater background noise floor fluctuations around 0.5 and 2 kHz compared with the other frequencies of interest. Signal-to-noise ratio (SNR) decreased with range for each of the frequencies of interest (2.3a). Both sites had a consistently lower SNR at 500 Hz. The background noise floor decreased with distance from the reef for the higher fre-
quencies at Eel Cove, whereas the higher frequencies exhibited a roughly constant noise floor with distance from the reef at Hapuna. Above 2 kHz, the directionality of the speaker may contribute to magnitude fluctuations [23].

2.3 Modeling of Acoustic Transmission Loss

Transmission loss (TL) was calculated for the five frequencies at each site by comparing peak pressure levels to recorded levels at 1 m from the source (Figure 2.2). At both sites, for all frequencies, the standard Spherical geometric spreading model ($\text{TL} = 20\log_{10}(r)$) overestimated TL as a function of range, $r$ [24]. The Cylindrical geometric spreading model ($\text{TL} = 10\log_{10}(r)$) provided a generalized average fit at Eel Cove, but underestimated TL at Hapuna (Figure 2.2) [24]. Divergence of propagation loss at short ranges from standard models has previously been observed [8, 9, 10]. At Hapuna, the seafloor receive hydrophone displayed more frequency dependent TL as compared to the mid-water column Loggerhead receive hydrophone. Measurements of TL did not scale linearly with frequency at both sites. In addition to the standard Spherical and Cylindrical geometric spreading models, the following models were also evaluated against the field data (2.3a):

**Bellhop Sand Model**, a numerical simulation using a geometric beam trace, provided incoherent TL values [25]. Bathymetry [15, 16, 18], sound speed, and published values for a sand bottom [26, 27] were used for Bellhop predictions. TL output of the Bellhop model is calculated for a single frequency versus range and depth slice of the receiver.

**Roger’s Onboard Empirical Formula** for propagation loss (Eq.(2.1)), [28] which is based on an isovelocity sound speed profile (Profile A Isovelocity [28]), and was derived from long range (5-100 km), shallow water numerical normal-mode
Figure 2.2: Transmission loss plots for transmitted tones (500 Hz, 2 kHz, 5 kHz, 10 kHz, 15 kHz) at Hapuna (a, b) and Eel Cove (c). Horizontal error bars denote GPS (Garmin GPSMAP 78s) positioning uncertainty. Vertical errors bars denote standard deviation of the variability in dB as measured by the control hydrophone. Cylindrical and Spherical geometric spreading models are plotted for reference.

\[
Roger \ A \ iso = 15 \log_{10}(r) + (0.0233r) + 49.84 + (-1.083 \times 10^{-4})r^2 \quad (2.1)
\]

**Marsh-Schulkin (M-S) Model**, also known as the Colossus Model, is constructed based off long-range, shallow water measurements (Eq.(2.2)) [29, 30].

\[
MS = 15 \log_{10}(r)+\alpha r+\alpha_t[(r/H)-1]+5\log_{10}(H)+60-k_L \quad \text{for} \ H \leq r \leq 8H \quad (2.2)
\]
This model uses the concept of skip distance, \( H \), which indicates the near-field region by determining the maximum range at which a ray first makes contact with either the sea surface or seafloor. The Bellhop [25] model, was also run as an eigen-ray model to obtain the skip distance parameter at each site (83 m for Hapuna and 93 m for Eel Cove). Parameter \( \alpha \) is the absorption coefficient in dB/km [26]. Variable \( \alpha_t \) is the effective shallow-water attenuation coefficient in dB/bounce calculated by determining a frequency-dependent surface loss, \( \alpha_s \), (Eq.(10) [30]), with a sea-state of 2 and a bottom loss coefficient, \( \alpha_b = 2.2 \text{ dB/bounce} \), based on a critical angle of 21.6° from a sand bottom BOUNCE [25] simulation [24]. Parameter \( k_L \) is the near-field anomaly in dB (Eq.(8) [30]). Model parameters \( \alpha, \alpha_t, \alpha_s, \) and \( k_L \) were frequency dependent and were estimated for each of the frequencies of interest based on the referenced equations.

**Extended M-S Model**, has only a modification of the near-field anomaly parameter in Eq.(2.2) to the variable \( k_{L,U} \) (Eq.(6) [30]). This incorporates the frequency dependent surface and bottom reflection coefficients and the number of bottom and surface contacts that contribute to the near field zone [30].

**Sloped Cylindrical Model**, which is a modification of standard Cylindrical geometric spreading model to include depth increase with range, \( \text{TL} = 10\log_{10}(\frac{D}{r_0 D_0}) \), where \( r_0 \) is the reference range of 1 m and \( D_0 \) is the depth at 1 m range. The depth at range, \( r \), is \( D \).

**Attenuation-Only Model**, \( \text{TL} = Ar \), which assumes TL is attenuation dominated, with attenuation parameter \( A \), and no spreading effects.

**Base Model**, \( \text{TL} = S\log_{10}(r) + Ar \), which is a purely empirical model consisting of a range dependent geometric spreading parameter, \( S \), and an attenuation parameter, \( A \).

The standard Cylindrical, Sloped Cylindrical, and Base models were analyzed.
as solely spreading models, as well as a coupled geometric spreading model with a range-dependent attenuation parameter. A nonlinear least squares parameter estimation technique, the trust-region-reflective algorithm, was used for geoacoustic inversion to estimate a spreading parameter, $S$, and a range-dependent attenuation parameter, $A$ [31]. A lower-bound of zero was specified for each parameter in the model fitting to provide a realistic constraint of spreading and attenuation effects on TL. The objective of the nonlinear least squares algorithm was to iteratively minimize the least squares error between the model and the data set, thus providing a predicted variable with the least squares variant for each model.

2.4 Model-Data Comparison

Quantification of TL model fits to the field data is represented by the Root Mean Square Error (RMSE) metric. The Base Model with the added attenuation parameter provided the best fit of the data overall (2.3b). The Cylindrical Spreading and Sloped Cylindrical Spreading Models provided a better fit at Hapuna versus Eel Cove which may be due to the more gently sloping topography of the Hapuna environment. All models, except for the Attenuation Only and Base Model variants, provided a better fit at Hapuna versus Eel Cove. At Eel Cove the Attenuation Only model had lower RMSE at the higher frequencies, indicating an attenuation dominated environment at the higher frequencies. The M-S and M-S Extended Models in every case overestimated the TL and had the greatest RMSE. The M-S model, constructed based off long-range, shallow water data, provided significant deviation in the short ranges ($\sim 500$ m) explored in this paper. The Extended M-S Model had a slightly lower overall RMSE value than the M-S Model. The Roger Model provided comparable results to the Bellhop Sand Model.

An attenuation parameter encompassing all attenuation effects with range within the environment was estimated for each site. Geoacoustic inversion results
obtained from the Base Model indicate an overall mean estimate of the attenuation parameter, $A$, of $0.0051 (\pm 0.0048 \sigma)$ dB/\(\lambda\) at Eel Cove and $0.0056 (\pm 0.0081 \sigma)$ dB/\(\lambda\) at Hapuna. These attenuation parameters are about three orders of magnitude less than published values for sand sediment \cite{24, 26, 27} and experimental coral \cite{32} bottom attenuation values, indicating that these shallow water, coastal coral reef environments can be modeled as spreading dominated. The mean Base Model geometric spreading parameter, $S$, estimate was $9.6 (\pm 2.8 \sigma)$ at Eel Cove and
12 (±1.9σ) at Hapuna. Eel Cove has more bathymetric variability which may contribute to the wider range of geometric spreading parameter values across the different frequencies transmitted.

### 2.5 Conclusions

Two coral reef sites of distinct bathymetric profiles, but with relatively isove-locity sound speed profiles, were analyzed in this study in terms of TL as a function of frequency and range. Conventional Spherical spreading overestimates TL for all cases explored here. Cylindrical spreading provided a rough approximation of TL, but the empirical Base Model, which estimates an attenuation and spreading coefficient, provided the overall best fit with relatively minor contributions of attenuation and stronger contribution from spreading. Disregarding the attenuation, the geometric spreading model of the coral reef propagation environments can be estimated as $12 \log_{10}(r)$ at Hapuna, and $9.6 \log_{10}(r)$ at Eel Cove.

Similar spreading coefficients have been estimated in estuarine oyster reef environments, where habitat configuration has been linked to acoustic propagation variability [33]. The Eel Cove and Hapuna site results do bracket the Cylindrical spreading model, but disparity in the spreading coefficients are presumably due to combined effects of benthic habitat type, bathymetry, and reef structure.

This study analyzes a 2-D slice of the environment, but the propagation in these coastal environments may be influenced by the 3-D spatial structure. Including more receive hydrophones at various depths within the water-column would also further inform depth dependence of TL. Further work to incorporate longer time-series data at a variety of coral reef sites of different geographic location would provide broader reaching correlations between acoustic measurements and changes in a coral reef ecosystem, whether anthropogenic or otherwise [34, 35]. Understanding of the acoustic propagation environment of a coral reef provides indication of
not only ambient reef sound detectability with range, but may also inform offshore anthropogenic sound influence on these important coastal ecosystems.

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List of References


28


APPENDIX A

Discussion and Conclusions

Underwater acoustics can be used to provide an assessment of the in situ oceanographic environment. Coral reefs present an early warning sign of the impact thermal and anthropogenic stressors can rapidly and detrimentally have on a natural ecosystem. Acoustic analyses on coral reefs may provide a tool for monitoring habitat characteristics and trait shifts including degradation rate and regeneration capacity. Computational acoustic models exist, but the littoral coral reef environment presents a complicated oceanic waveguide to model due to multivariate sound scattering effects within the environment; such as topography, rugosity, and sea surface waves. Coral reefs thus require an empirical model to serve as a representative acoustic baseline to better understand sound impact within and around these coastal ecosystems for conservation efforts which may affect communication and navigation channels.

By combining a suite of transmission loss models from the literature, as well as development of a site-specific empirical base model, a spreading and attenuation parameter indicative of the coral reef environment are estimated. These parameter estimations capture the in situ reef condition to provide a baseline if the reef undergoes degradation. Repeated propagation loss studies may yield a benchmark for coral reef regeneration efforts as healthy coral reefs could potentially be identified and statistically described for comparison with other coral reefs. This potential is supported by recent playback studies\textsuperscript{1} of healthy coral reef soundscapes, which demonstrated the impact that sound has within the coral reef environment on

biological resettlement on the reef.

The passive coral reef soundscape study (Manuscript 1) yields different results of the mean spreading and attenuation coefficients as compared to the active transmission, tone study (Manuscript 2). The broad-band passive study (Manuscript 1) was based on a comparison to sound levels on the reef whereas the tone study (Manuscript 2) was based on a comparison to sound levels 1 m from the source (speaker). The geometrical spreading model formulation describes spreading from a point source in which the sound travels outward from a single point in space on the reef. This may hold true for the active acoustic transmission study, but is an overly simplistic view of the reef sound as passive study where sound is generated from multiple locations on the reef and it is difficult to pinpoint a singular source.

In the tone study (Manuscript 2), frequency dependent transmission loss was apparent; with higher frequency tones not necessarily exhibiting the greatest transmission loss. In both studies presented here transmission loss estimates are inherently affected by multipath propagation. Here, the source and receiver, being located at different depths, yield a depth-independent analysis.

Placing a variety of acoustic sources and receivers at different depths can yield a better measurement of spatially varying transmission loss. Incorporating a linear array of hydrophones to sample the acoustic field at the reef and at various ranges offshore would also enable the transmission loss to be spatially measured across the domain. Along with spatial measurements, acoustic timeseries measurements could suggest impacts of seasonality and oceanographic and weather conditions on the propagation loss. Seasonal environmental change has direct effects on the sound speed profile, influencing acoustic propagation. Acoustic propagation studies incorporating more expansive spatial and temporal sampling could reveal correlations between acoustic variability and other environmental indicators of reef health.
A reef propagation loss empirical model, and associated geometric spreading and attenuation parameters, was specifically constructed from fringing coral reef habitats of different geographic locations. This empirical model development seeks to provide a benchmark of propagation loss in coral reef ecosystems to provide an insight into the complex reef dynamics and initiate a baseline characterization for future observational studies.
APPENDIX B

Acoustic Parameter Inversion Technique

Both Manuscript 1 and Manuscript 2 evaluate empirical models comprised of a geometric spreading parameter, $S$, and an attenuation parameter, $A$. To yield estimates of these parameters, a non-linear least squares scheme is implemented. The Trust-Region-Reflective least squares algorithm is used to solve the nonlinear data-fitting between a provided set of data and a propagation loss model.\(^1\)

Through iterative minimization of the least squares error of the model to a data set, the desired $S$ and $A$ parameters are estimated. The objective function is represented by (B.1).

$$f(x)_k = \|d_{\text{model}}(x)_k - d_{\text{observed}}\|_2$$  \hspace{1cm} (B.1)

Where $k$ represents each iteration, $d_{\text{observed}}$ is the input data, and $d_{\text{model}}$ is the model evaluation for each parameter set $x$, which are the predictor variables $S$ and/or $A$. Propagation loss models are analyzed as separate predictions of $d_{\text{model}}$. A lower bound constraint of zero was specified for parameter set $x$. This requires the solution values of $S$ and $A$ to be greater than or equal to zero. Applying this constraint limits the algorithm to produce realistic predictions of a spreading and attenuation parameter and how they affect the acoustic transmission loss within an underwater environment. The algorithm requires initial guesses of the predictor variables ($S$ and $A$). Varying the starting values provides indication of the sensitivity of the input parameters and of the algorithm to potentially find other local minima solutions. Initial values are specified as the following set: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 40. Results of the predicted parameters $S$ and $A$

---

are compared for each initial value to indicate solution convergence sensitivity to initial parameter input.

Model solutions are obtained through iterative minimization of a cost function (B.2).

\[
Cost \ Function = \| f(x)_k \|_2^2
\]  

(B.2)

The cost function represents the squared \(L_2\)-norm of the residual at each iteration. Solution convergence is thus achieved through the lowest resulting residual of the cost function, therefore providing the best match of \(S\) and/or \(A\) results. The input data set is then fit with the optimal model, the least squares variant of each propagation loss model, and respective values for \(S\) and/or \(A\) are predicted. A root-mean-square error (RMSE) metric is then used to evaluate each propagation loss model. RMSE provides an error measure of the predicted model, based off solutions of \(S\) and/or \(A\), in replicating the acquired field data. Solutions with the lowest RMSE are the most desirable, as it quantifies prediction error.