

## **Mid-Frequency Propagation Modeling Using the Waveguide Invariant**

Daniel Rouseff

Department of Electrical and Computer Engineering, Portland State University  
1900 SW Fourth Avenue  
Portland, OR 97207

phone: (206) 685-3078 fax: (206) 543-6785 email: [rouseff@apl.washington.edu](mailto:rouseff@apl.washington.edu)

Award Number: N000141310187

<http://nearlab.ece.pdx.edu>

### **LONG-TERM GOALS**

Random variability in shallow water will induce variability in a propagating acoustic field. The long-term goal of this research is to quantify how random variability in the ocean environment translates into random variability in the acoustic field and the associated signal processing algorithms in the mid-frequency (1-10 kHz) band. In the present funding cycle, the emphasis is on the waveguide invariant.

### **OBJECTIVES**

Constructive and destructive interference is an inevitable consequence of multipath acoustic propagation in shallow water. If the ocean environment is sufficiently benign, the so-called waveguide invariant describes the resulting interference pattern. The waveguide invariant, usually designated as “beta,” has traditionally been regarded as a low-frequency phenomenon. The objectives of the present work are twofold: first, to extend the waveguide invariant concept so it may be incorporated into mid-frequency signal processing algorithms, and second to quantify the limitations on these algorithms imposed by shallow-water internal waves.

### **APPROACH**

The approach is a mixture of data analysis, theoretical development, and numerical modeling. Dr. Dajun Tang of the University of Washington Applied Physics Laboratory (APL-UW) is a key individual in acquiring suitable acoustical and environmental data sets that can be used in the analysis. Dr. Lisa Zurk of Portland State University is a key individual in developing the signal processing algorithms. Dr. Andrey Lunkov of the General Physics Institute, Moscow, has been a key individual in developing theoretical models for calculating array coherence. Dr. Lunkov received support for the collaboration from ONR-Global.

### **WORK COMPLETED**

Under previous support, the author developed a signal processing method for calculating the waveguide invariant distribution [Rouseff and Spindel, 2002]. In this approach, rather than try to assign a single value to the waveguide invariant, a distribution of possible values is calculated. The

# Report Documentation Page

Form Approved  
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE <b>30 SEP 2014</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2014 to 00-00-2014</b>	
4. TITLE AND SUBTITLE <b>Mid-Frequency Propagation Modeling Using the Waveguide Invariant</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Portland State University, Department of Electrical and Computer Engineering, 1900 SW 4th Ave, Portland, OR, 97207</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

distribution may be broad or sharply peaked depending on the environment. Numerical simulations showed how shallow water internal waves could broaden the distribution and possibly shift the peak [Rouseff, 2001]. The waveguide invariant was incorporated into signal processing algorithms for coherent processing of array data. A method called striation-based beamforming was developed to improve array gain [Rouseff and Zurk, 2011; Zurk and Rouseff, 2012]. It was also shown theoretically how striation-based beamforming permits one to estimate both the source-to-receiver range and the waveguide invariant; it had previously been thought that only the ratio between the two quantities was accessible

Under current support, striation-based beamforming was tested using data collected during the 2011 Gulf Experiment (GulfEx11). Both the source-to-receiver range and the numerical value of the waveguide invariant were estimated every 0.5 Hz over a 200 bandwidth centered at 3.5 kHz. Results were presented at the *2<sup>nd</sup> International Workshop on Acoustic Interference Phenomena and Signal Processing* [Rouseff, Zurk and Tang, 2013]. The workshop was held in Moscow in 2013 with the PI serving as co-chair and co-organizer.

Efforts in FY14 returned to studying how shallow-water internal waves affect the waveguide invariant. An analytical expression was derived for the average waveguide distribution in the presence of random internal waves described by a modified Garrett-Munk spectrum. Analytical expressions were also derived for the expected array coherence length using the same statistical model for the internal waves.

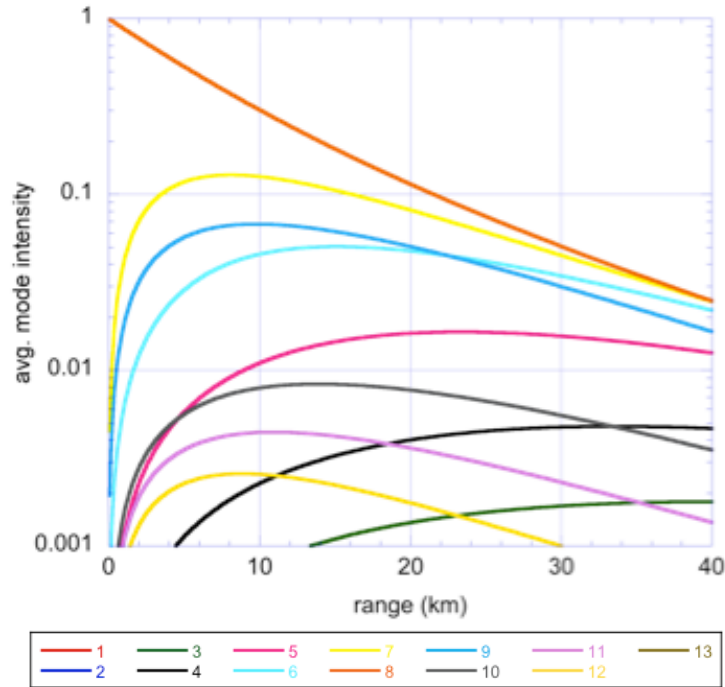
## **RESULTS**

Figure 1 is a sample calculation showing how shallow water internal waves cause coupling between acoustic modes. The plot shows the intensity of the propagating acoustic modes as a function of range for a typical shallow water scenario. The starting field is the eighth acoustic mode, a mode that is bound from above by the sea surface. As the range increases, energy leaks out of the eighth mode into lower order modes. These lower-order modes are bound from above by the thermocline rather than the sea surface. The result is significant as refracted lower-order modes have a different value for the waveguide invariant than higher-order reflected modes. Consequently, at sufficient range, the apparent value for the waveguide invariant will change.

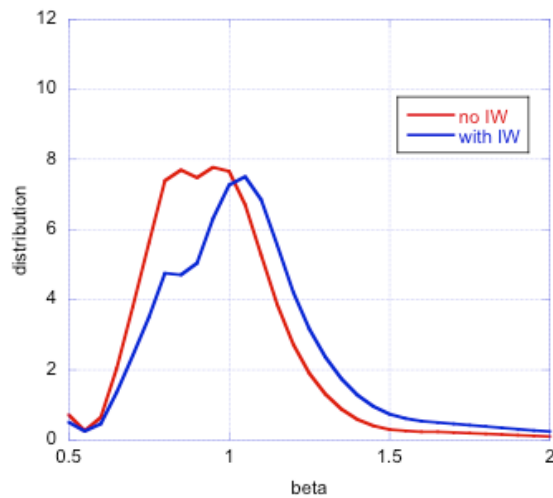
Figure 2 is a sample calculation showing how shallow water internal waves can change the waveguide invariant distribution. The calculation uses the analytical expression derived during the current fiscal year. Internal waves broaden the distribution and shift the peak to larger values of beta.

The calculations in Figures 1 and 2 were performed assuming acoustic frequency 400 Hz. At present, we are working to extend the calculations to the mid-frequency (1-10 kHz) regime. These extensions are necessary as the acoustic waveguide will support many more modes at the higher frequency and, without modification, the calculation becomes cumbersome. The analytical predictions can then be tested using towed-source data collected during the 2006 Shallow Water (SW06) experiment.

Results derived during FY14 have been presented at two conferences [Rouseff, 2013; Lunkov and Rouseff, 2014]. Efforts in FY15 will include documenting these results in refereed journal publications.



**Figure 1: Average modal intensity as a function of range. Plot shows how energy that starts in mode 8 leaks into other modes as the range increases due to ocean internal waves. The calculation is for a typical shallow-water environment in the summer. Results are for 400 Hz.**



**Figure 2: Average waveguide invariant distribution. Calculation for a source in the surface mixed layer and a receiver 20 km downrange and below the thermocline. Plot shows internal waves broaden the distribution and shift it to higher values of the waveguide invariant, beta.**

## IMPACT/APPLICATIONS

The waveguide invariant is currently applied in practical sonar signal processing algorithms. Extending its usages to the mid-frequency regime is desirable.

## RELATED PROJECTS

This project uses acoustical and environmental data collected in ONR-supported experiments like SW06, GulfEx and TReX. Collaboration with investigators from APL-UW in using these data sets will continue. Collaboration with investigators from Portland State University supported by the ONR Underwater Signal Processing will also continue.

## REFERENCES

- D. Rouseff, "Effect of shallow water internal waves on ocean acoustic striation patterns," *Waves in Random Media* **11**, 377-393 (2001).
- D. Rouseff and R. C. Spindel, "Modeling the Waveguide Invariant as a Distribution" in *Ocean Acoustic Interference Phenomena and Signal Processing*, edited by W. A. Kuperman and G. L. D'Spain (American Institute of Physics, New York, 2002) 137-148.
- D. Rouseff and L. M. Zurk, "Striation-based beamforming for estimating the waveguide invariant with passive sonar," *J. Acoust. Soc. Am.* **130**, EL76-EL81 (2011).
- L. M. Zurk and "D. Rouseff, Striation-based beamforming for active sonar with a horizontal line array," *J. Acoust. Soc. Am.* **132**, EL264-EL270 (2012).
- D. Rouseff, L. M. Zurk, and D. Tang, "Demonstration of striation-based beamforming in a shallow water waveguide," *2<sup>nd</sup> International Workshop on Acoustic Interference Phenomena and Signal Processing*, Moscow (2013).

## PUBLICATIONS

- X. Zou, J. A. Ritcey, and D. Rouseff, "Experiment results of iterative block-based decision feedback equalizer with spatial diversity in underwater acoustic channels," *2013 Asilomar Conference on Signals, Systems and Computers*, p. 728-730 (2013). [non-refereed]
- D. Rouseff, "Counterintuitive results in underwater acoustic communications," *Proc. 4<sup>th</sup> Pacific Rim Underwater Acoustics Conference* (2013). [in press, non-refereed]
- D. Rouseff, "Effect of internal waves on the waveguide invariant distribution," *J. Acoust. Soc. Am.*, **134**, p. 4079 (2013). [non-refereed]
- M. Xia, D. Rouseff, J.A. Ritcey, X. Zou, C. Polprasert, and W. Xu, "Underwater acoustic communication in a highly refractive environment using SC-FDE," *IEEE J. Oceanic Eng.* **39**, pp. 491-499 (2014) [refereed].

A. Lunkov and D. Rouseff “Estimation of the sound field transverse coherence length in shallow water in the presence of background internal waves”, *Proc. 1<sup>st</sup> All-Russian Acoustics Conference* (2014). [in press, non-refereed]

### **HONORS/AWARDS/PRIZES**

Excellent Reviewer Award, *IEEE Journal of Oceanic Engineering*.