



Applied Physics Laboratory

University of Washington

1013 NE 40th Street
Box 355640
Seattle, WA 98105-6698

206-543-1300
FAX 206-543-6785
www.apl.washington.edu

March 24, 2022

To: Dr. Raymond Soukup
Office of Naval Research (Code 322)
875 North Randolph Street
Arlington, VA 22203-1995

From: Dr. Dajun Tang, Principal Investigator

Subj: ONR Grant# N00014-17-1-2229, "Shallow water reverberation: data analysis/modeling and S. Korea experiments"

Encl: (1) Final Technical Report for Subject Grant
(2) SF298 for Enclosure

Enclosure (1) is the Final Technical Report for the subject grant along with enclosure (2) being the SF 298 form. These documents constitute the Final Technical Report and deliverable for ONR Grant# N00014-17-1-2229.

cc: Grant & Contract Administrator, APL-UW
Office of Sponsor Programs, UW
ONR Seattle
Naval Research Laboratory
Defense Technical Information Center

Shallow water reverberation: data analysis/modeling and S. Korea experiments

Dajun (DJ) Tang
Applied Physics Laboratory
University of Washington
Seattle, WA 98105

25 March 2022

Final Report
Award Number N00014-17-1-2229

Long-term goals:

We envision that in 10-20 years, we will have developed the following capability: For given operational area, predict signal excess and its uncertainty for a required duration (ex. 72 hours). Mid-frequency active sonar (MFAS, 1 kHz-10 kHz) is a central component of the Navy's tactical sonar systems aboard its vessels. However, the performance of the sonar in shallow water shows strong variability. The understanding of the mechanisms responsible for the variability and measures based on the understanding to optimize sonar performance are the major goals for this research. To that end, environmental measurements at the right scales should go hand-in-hand with acoustics measurements in order to learn the driving physical mechanisms through model/data comparison.

Scope of the proposed work:

Our main area of study is to understand why mid-frequency (1-10 kHz) sound suffers from environmental variability, which limits system performance. Our unique experimental approach is to investigate transmission loss (TL) and reverberation level (RL) simultaneously with fixed-fixed source and receivers, so platform variability will be confused with environment variability. The proposed project is a joint effort between APL-UW and the Agency for Defense Development, Republic of Korea. The plan was to conduct a pilot experiment in S. Korea in 2017 (KOREX17), followed by a main experiment at the same location in 2020. However, COVID-19 made the second experiment impossible. Instead, we conducted an experiment in Dabob Bay, Washington, in collaboration with NUWC-Keyport Division in early 2020 (Dabob2020). Through the two experiments, we systematically investigated transmission and reverberation in bay settings, which enabled us to confidently move to conduct experiments on the continental shelf under ONR TFO planned for 2022.

Accomplishments in KOREX17:

KOREX-17 was conducted off the island of Geoje, Republic of Korea, 23-31 May 2017. It was a

joint shallow water reverberation experiment with participation of three groups: Agency for Defense Development (ADD), The Applied Physics Laboratory, University of Washington (APL-UW), and Hanyang University (HYU). The experiment was performed onboard the ADD research vessel, the R/V Mirae. For experiment site, see Figure 1. The following measurements are successfully accomplished:

- Shallow water reverberation measurements under different ocean conditions at a site with complex sandy/muddy/rocky sediments and varying water depth. This is accomplished by using the APL-UW Autonomous Reverberation Measurement System (ARMS). This system consists of a benthic lander on which is mounted a directional source and receive array on a rotating stage. It can be programmed to collect reverberation data as a function of angle at a pre-determined time and for a number of independent runs.
- Transmission measurements along different tracks to 10 km using ARMS and ADD towed SRH (Self Recording Hydrophone).
- Measure contemporaneous directional wind spectra using a directional wave buoy.
- Side scan survey by towing the HYU SonaTech sidescan sonar and grab sampling.

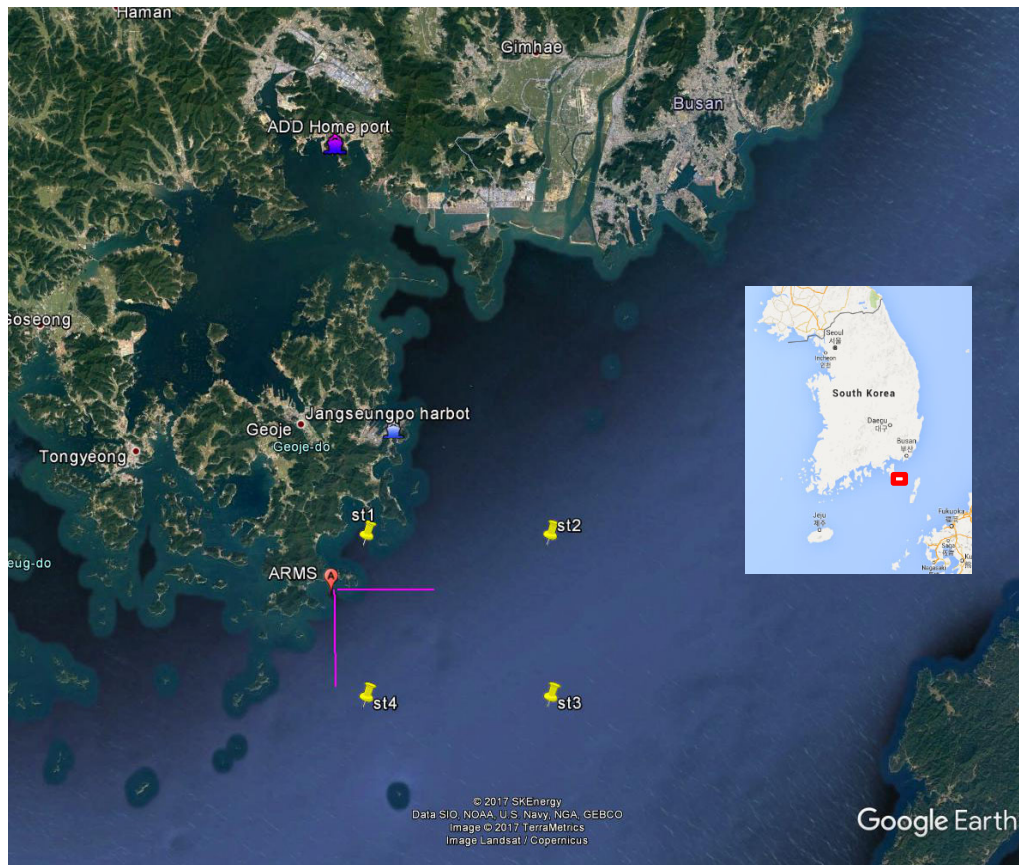


Figure 1. Locations of ADD Dock (R/V Mirae home port), Jangseungpo Harbor, and the experiment sites.

Our main area of study is to understand why mid-frequency (1-10 kHz) sound suffers from

environmental variability, which limits system performance. Our unique experimental approach is to investigate transmission loss (TL) and reverberation level (RL) *simultaneously*. Bottom mounted systems were used to eliminate variability due to platform motion; environmental data: surface, water column, and bottom were measured as a level to support model/data comparison. We also choose experimental sites which allow repeated measurements spanning seasons/years. One part of the KOREX-17 is a repeated TL and RL measurements 5 days apart. As shown in Figure 1, the reverberation source/receiver (ARMS, see next section) is deployed at the point where the red and white tracks meet. The ARMS transmitted 3.5 kHz sound at 200 dB source level and measured mono-static reverberation. Meanwhile, transmission loss measurements were taken by towing a receiver at 10 m depth by the ADD R/V Mirae. TL along two tracks were taken, the red track in Figure 1 is termed ‘East track’, and the white is termed ‘South track’. Each track is about 10 km in length. The measurement was conducted on 25 May, 2017, and the same measurement was repeated on 30 May, 2017. The idea is to examine the variability of TL and RL along the tracks in two different days.

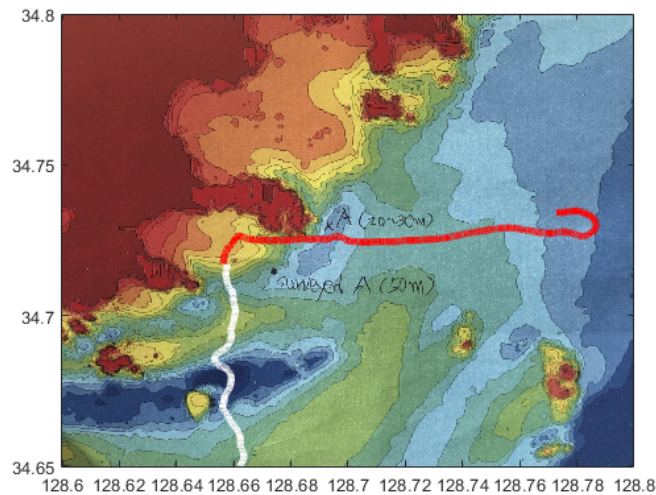


Figure 1. Joint transmission loss (TL) and reverberation level (RL) measurements. A monostatic reverberation system is at the point where the red and white tracks meet. It transmitted 3.5 kHz pulses. TL measurements were taken along the two tracks by towing a receiver and recording the same signals for the RL measurement.

A surprising result of the joint TL/RL measurement is summarized in Figure 2: While the reverberation intensity measured in the two different days are repeatable, the TL is repeatable only along the South track; TL for the East track demonstrates a 15-20 dB difference. One may have assumed that RL variation should correlate with TL variation as RL consists of a two-way propagation. The experimental data, however, clearly contradict that notion: The RL does not have nearly as much variability. For operations, this unanticipated 15-20 dB TL variation is a major challenge. Contemporaneous oceanographic measurements at isolated sites suggest that there is a tidal current front extending from the southwest to the northeast at the site. As to the lack of variation for the RL, we have reached the conclusion that while the TL is measured at a single point, hence sensitive to the relative location of the front, the RL is a sum of scattered signals from a large patch of seafloor, hence insensitive to the location of the front.

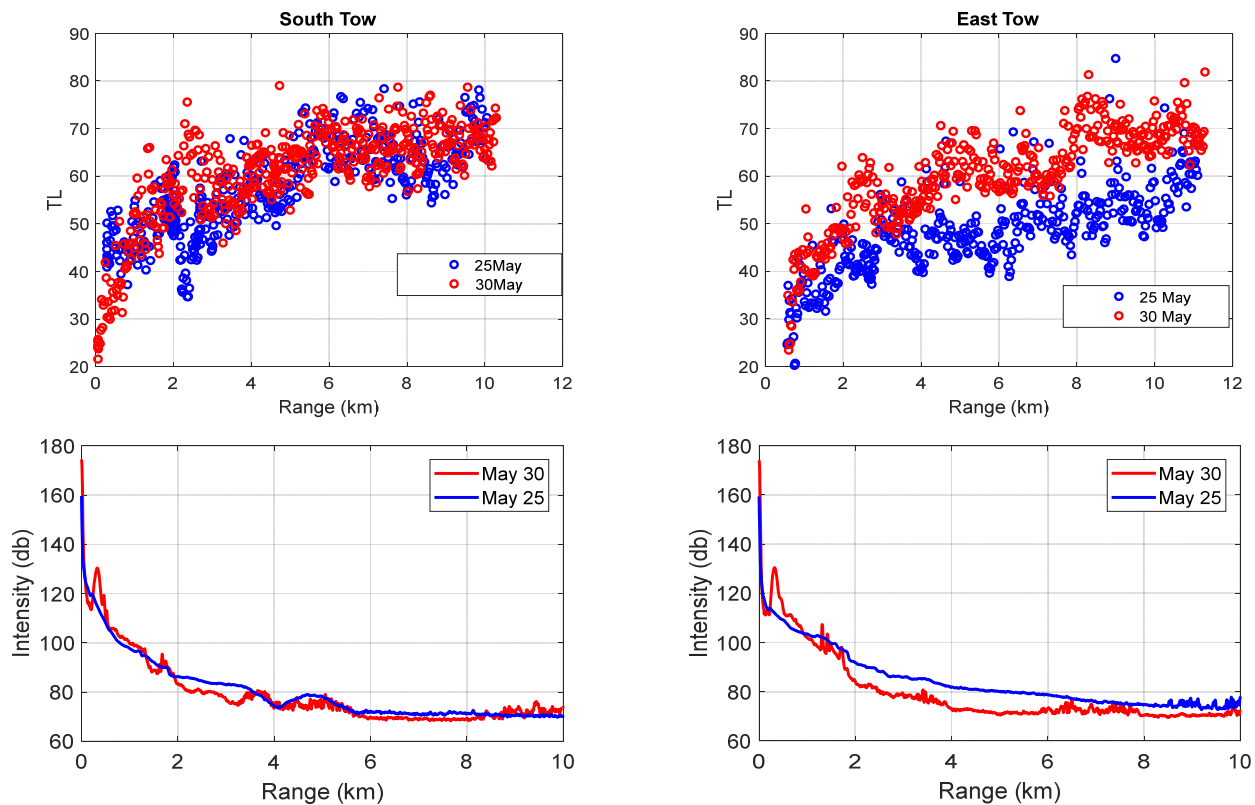


Figure 2. The top two panels show TL data. The top left is for the South track and the right for the East track. The blue circles for data taken on 25 May, 2017, and the red on 30 May, 2017. The two lower panels show RL measurements from the same transmitted signals taken in the corresponding directions and time. TL data for the South track show consistency for the two days, but the TL for the East track has 15-20 dB difference. The RL for the two tracks and two days do not have large variabilities.

Accomplishments in Dabob2020:

In January 2020, we conducted a very successful field trial: *Environmental Impact on Ambient Noise, Mid-frequency Transmission Loss and Reverberation Uncertainty at the NW Acoustic Test Range on Dabob Bay, WA*. The main focus is to study mid-frequency transmission and reverberation under the influence of varying wind conditions.

This is a joint project between Dr. Grant C. Eastland, NUWC Division, Keyport C/221 and DJ Tang, Todd Hefner, Peter Dahl, and David Dall'Osto, APL-UW. It is jointly funded by NUWC Division, Keyport and ONR Ocean Acoustics. The Immediate Goals: Measurement and modeling of mid-frequency (2-6 kHz) TL and reverberation under different wind conditions in Dabob Bay. The long-term goal: predict detectability over both space and time for both passive and active SONAR applications.

The location and layout of the experiment in Dabob Bay is shown in Figure 3. Environmental

Measurements include the Nortek Signature 500 that measures Acoustic Waves and Currents (AWAC) and Continuous data collection from 1/22-1/29, Soundnine Temperature/Pressure Chain with 10 sensors in 60 m depth and Datawell Waverider Buoy with Continuous data collection from 1/21-1/23, 1/23-1/29. As well as CTD casts along the ARMS-CAAS line. Casts taken every 500 m.

January was chosen for experiment since historically winds are typically out of the southwest. Wave generation along the Hood Canal and into Dabob bay. Preliminary analysis of Waverider data indicates dominant wave direction throughout experiment was roughly aligned with ARMS-CAAS line. Water column observations found that (Figure 4) sound speed profile was upward-refracting with a colder, fresh water layer at the surface. The layer thickness varied throughout the experiment (see current profile below) between 15 and 10 m. Slight range dependence observed between the deep and shallow regions.

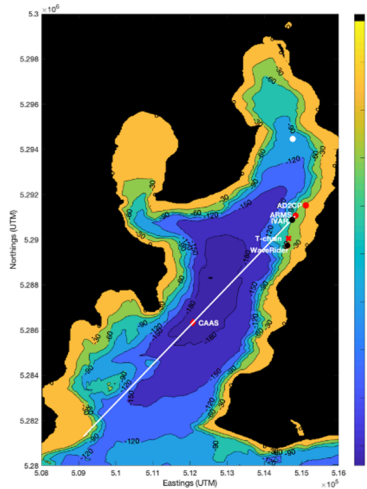


Figure 3. Site of experiment. The diagonal white line shows the main propagation direction. The northeast end has a concentration of instruments, including the ARMS (Autonomous Reverberation Measurement System), a suite of environmental measurement systems, and the IVAR, self-contained vector/acoustic receiver. In the middle of the track is a vertical line receive array from Keyport.

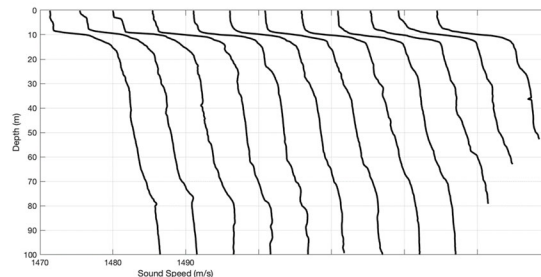


Figure 4. A typical set of CTD casts along the main acoustic track shown in Figure 3. We focused on data analysis in the past year. Here is a summary of major results:
Observations of Dabob Bay data

- Under Calm condition, TL on the VLA changes 5-10 dB over a span of 30 minutes, however, reverberation varied less.
- Under windy conditions, there is only small random fluctuations on TL, while the 30-min, large variation remains.
- Shallow phones on the VLA have less TL as compared to those on the deep phones.

Ray tracing, PE, and PE FFT synthesis to time domain are employed to help understand the observations. As shown in Figure 5, The 4 principal eigenrays from ARMS to the VLA receivers at 110 m. These are the primary arrivals. Other rays arrive late and have smaller amplitudes. There are two rays arriving from above and two from below. If one adds the energy of the 4 rays, the TL = 71 dB, or arrival energy of $200 - 71 = 130$ dB, which matches the mean level of measured data. Consider bottom/surface loss, which is small because of small grazing angles, a result is consistent with data. Because these are the main arrivals, and they are at small grazing angles, the sea surface roughness is not expected to cause appreciable TL variability. What can be expected is large ping-to-ping decorrelation. Preliminary conclusions from ray tracing are

- For the deep phones, such as the receiver setting for 29 Jan 2020, there are only a few rays which have only a few boundary interactions and which dominate the received energy. This is not a typical shallow water waveguide where sound interacts many times with boundaries. Rather this is more like a deep-water scenario.
- Matching TL level is rather straightforward. Because the rays have small grazing angles and a couple of bottom reflections, there is only some sensitivity to bottom parameters.
- Due to the dominance of the small grazing angle arrivals, the sea surface roughness is not expected to cause appreciable TL variability. What can be expected is large ping-to-ping decorrelation.
- Topography transitioning from shallow to deep, along with some small change in the SSP, may be an important factor to understand measured TL variability.

In addition, Parabolic Equation modeling is conducted to further study the variability of TL (Figure 6). We have reached the following tentative conclusions:

- Dabob is more like a deep-water scenario, not a typical shallow water channel. This scenario could also be encountered near the shelf break.
- Sound reaching the receivers only interacted with the boundaries a couple of times, so surface roughness effect is small – no accumulative effect from repeated interactions.
- The TL difference between the upper and lower half of the water column is understood.
- Tidal effect may be the main culprit for the observed TL variability. Again, this is the consequence of only a few rays reaching the receiver.
- Therefore, depth averaged TL is a more meaningful prediction – useful for Keyport applications.

- Application to detection: Our data highlights the difficulty of predicting target signal excess because its high variability. Averaging over all VLA phones helps.

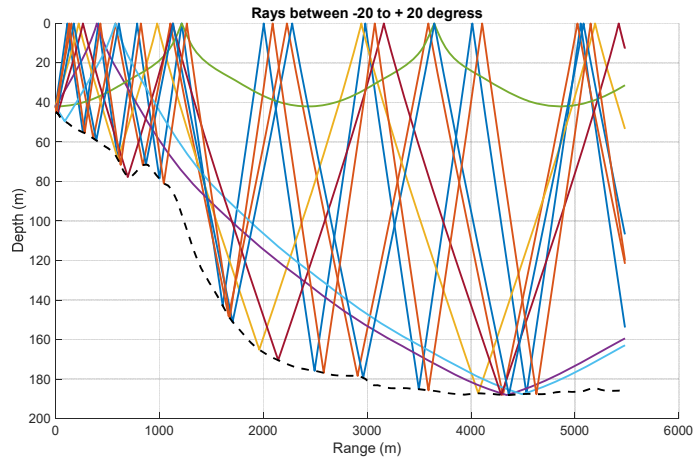


Figure 5 Ray trace between source and the VLA shows that shallow rays do not reach receivers deeper than about 80 m. Also notice the caustic at the 40 m depth near 2600 m range.

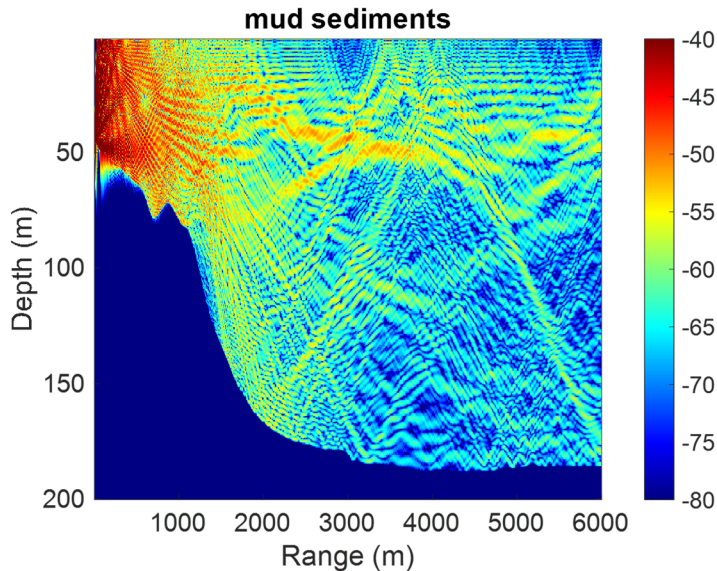


Figure 6 PE simulations between source and the VLA shows that shallow rays do not reach receivers deeper than about 80 m. Also notice the caustic at the 40 m depth near 2600 m range.

Refereed Publications

D. Tang, "Integral Equations for sound scattering by rough seafloors," *J. Acoust. Soc. Am.* Under review.

D. Tang, "Coupled mode approach to forward-scatter by sediment volume heterogeneity in shallow water." *J. Acoust. Soc. Am.* Submitted.

David Dall'Osto and D. Tang, "Acoustic resonances within the surficial layer of a muddy seabed," *J. Acoust. Soc. Am.* Under review.

Taebo Shim, Youngnam Na, Su-uk Son, Todd Hefner and D. Tang, "Contemporaneous measurements of mid-frequency transmission and reverberation in shallow water," *IEEE J. of Oceanic Engineering*. In preparation.

Brian T. Hefner, DJ Tang, David Dall'Osto, and Grant Eastland, "Temporal variability of mid-frequency sonar in a deep, freshwater bay." *J. Acoust. Soc. Am.* In preparation.

Jackson, D. R. and D Tang, "The mutual scattering cross section," *J. Acoust. Soc. Am.* 4611-4624, (2019).

Tang, D., B. T. Hefner, and D. R. Jackson, "Direct-path Backscatter measurements along the Main Reverberation Track of TREX13," Special collection on TREX13," *IEEE J. of Oceanic Engineering*, Vol. 44, NO. 4, Oct. 972-983 (2019).

Lee, Wu-Jung, D. Tang, T. K. Stanton, and E. I. Thorsos, "Macroscopic observations of diel fish movements around a shallow water artificial reef using a mid-frequency horizontal-looking sonar," *J. Acoust. Soc. Am.* 1424-1444, (2018).

Tang, D., D. R. Jackson, "A time-domain model for seafloor scattering," *J. Acoust. Soc. Am.* 142, 2968-2978 (2017).

REPORT DOCUMENTATION PAGE			<i>Form Approved</i> OMB No. 0704-0188	
Public reporting burden for this 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 this 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 Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 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 any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.				
1. REPORT DATE (DD-MM-YYYY) 24/03/2022		2. REPORT TYPE Final Technical		3. DATES COVERED (From - To) 11/01/2017 - 9/30/2021
4. TITLE AND SUBTITLE Shallow Water Reverberation: Data analysis/modeling and S. Korea experiments			5a. CONTRACT NUMBER	
			5b. GRANT NUMBER N00014-17-1-2229	
			5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Dajun Tang			5d. PROJECT NUMBER	
			5e. TASK NUMBER	
			5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Washington - Applied Physics Laboratory 4333 Brooklyn Avenue NE Seattle, WA 98105-6613			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research (Code 322) 875 North Randolph Street Arlington, VA 22203-1995			10. SPONSOR/MONITOR'S ACRONYM(S) ONR	
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT: Distribution Statement A: Approved for public release; distribution is unlimited.				
13. SUPPLEMENTARY NOTES				
14. ABSTRACT Shallow water experiments at 3.5 kHz were conducted in two bay settings, one off the Geoje Island, Republic of Korea, the other in Dabob Bay, Washington state. The goal is to investigate mid-frequency sound uncertainty under different environmental conditions, including wind and current. A key feature of the experiments is that transmission loss and reverberation are measured simultaneously in fixed-fixed arrangement. Contrary to conventional understanding, transmission loss and reverberation level respond to environmental conditions differently. Detailed mechanism behind this is complex and includes the difference of sound energy distribution near the sea surface and bottom.				
15. SUBJECT TERMS Mid-frequency SONAR, transmission loss, reverberation, environment, wind effect				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 10
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified		
			19b. TELEPHONE NUMBER (include area code) (206) 543-1300	