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THESIS

**BUBBLE CLOUD ACOUSTIC SPECTROGRAPHY IN
THE JAMES RIVER ESTUARY**

by

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June 2020

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**BUBBLE CLOUD ACOUSTIC SPECTROGRAPHY IN THE JAMES RIVER
ESTUARY**

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ABSTRACT

The James River Estuary hosts a salt wedge during its tidal cycle that is typical in estuarine environments but is atypical in its V-shape. Linear frequency-modulated acoustic signals in the 500–5000 Hz range were transmitted during the advance and retreat of the salt wedge during the James River Estuary acoustics field experiment from April 18–25, 2019. Using simple instrumentation, correlations were made between the acoustical characteristics and observational parameters such as current profiles and geological descriptors and features. Data analyzed included acoustic data from underwater hydrophones positioned at three depths through the water column, echosounder data collected across the front, low-angle radar images of the surface, and modeled salinity. Received signal data shows lower energy level when the front occupies the acoustic transect and higher, mixed signal levels as the front moves away from the acoustic transect. A decrease in signal level of about 8 dB within 1.25 hours was recorded due to attenuation from scattering and absorption by bubble clouds and fish, sound refraction, ducting, bottom scatter and flow noise. Understanding of these transmission and propagation loss patterns can aid in the acoustic interpretation of data collected in constrained or denied environments and facilitate a future predictive capability in autonomous underwater vehicle (AUV) sonar systems.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	3-Dimensional
ADCP	Acoustic Doppler Current Profiler
EOD	Explosive Ordnance Disposal
CTD	Conductivity, Temperature, Depth
IVO	In Vicinity Of
JRE2019	James River Estuary Field Experiment 2019
JRE	James River Estuary
LFM	Linearly Frequency-Modulated
MFO	Matched-Filter Output
Mini-cat	Mini-Catamaran
MM	Mini Mooring
MMMBT	Monitor-Merrimac Memorial Bridge-Tunnel
NAVSPEC- WARCOM	Naval Special Warfare Command
NEL	Noise Energy Level
NNP	Newport News Point
NOAA	National Oceanic and Atmospheric Administration
ONR	Office of Naval Research
PI	Principal Investigators
PSD	Power Spectral Density
R/V	Research Vessel
SEL	Sound Energy Level
SNR	Signal-to-Noise Ratio
SOF	Special Operations Forces
TIF	Tidal-Intrusion Front
TL	Transmission Loss
USRS	Undersea Remote Sensing
VIMS	Virginia Institute of Marine Science
VLA	Vertical Line Array
WHOI	Woods Hole Oceanographic Institution

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I. INTRODUCTION

A. OVERVIEW OF THE EXPERIMENT

The James River Estuary field Experiment 2019 (JRE2019) was one of a series of field experiments conducted to obtain a better understanding of the estuarine river environment and its acoustical dynamics through in situ field observations and modeling. The project was funded by the Office of Naval Research (ONR) within the Undersea Remote Sensing (USRS) program directed by Dr. Reginald Beach (ONR 322LO). The experimental data obtained in this thesis is intended to establish correlations between the acoustical and physical characteristics of the riverine environment specifically, the contribution of bubbles subducted at the tidal intrusion front (TIF) to acoustic transmission loss is of particular interest. Instrumentation in this study included single, omni-directional hydrophones, acoustic doppler current profilers (ADCP), conductivity-temperature-depth sensors (CTD) and temperature sensors deployed on anchored mini-catamarans (mini-cat) and bottom-moored tripods.

Estuaries present challenges, as they are dynamic environments in transition zones between inland rivers and the sea. Few acoustic studies have been performed in the estuarine environment and even fewer with closely linked high-resolution measurements of environmental parameters. Most work in the estuarine environment has been done at higher frequencies, in the 10s to 100s of kHz (Reeder 2016). This experiment was conducted in the mid-to-low frequency band (500-5000 Hz). Related acoustic research has been conducted to determine bubble size distribution throughout the water column and has related the associated transmission loss to swim bladders and distribution of fish. Limited research has been done to understand the acoustical characterization of the estuarine/riverine environment. Bubble acoustical effects are of interest here in relation to naval acoustic applications.

The goal of this experiment is to determine the impact on acoustic propagation (a) of the bubbles and (b) from the temperature and salinity-induced sound speed gradients across the estuarine front. This analysis will further the understanding of fine-scale

estuarine dynamics, will be used to assess Navy systems' sonar performance in energetic and constrained environments, and it will facilitate the development of a predictive capability in estuarine environments for direct application to future U.S. Navy operations (e.g. SOF, NAVSPECWARCOM special boat squadrons, Explosive Ordnance Disposal (EOD) and mine warfare assets). Research on the James River Estuary (JRE) is of particular interest due to its location, as it opens into the Chesapeake Bay by way of Naval Station Norfolk, the largest naval base in the world. The area of study for this experiment is less than 3 nm from the naval station's piers that house 75 naval ships on 14 piers. The base is also home to 124 aircraft and 11 aircraft hangars (Military.com Network). South of the JRE on the Elizabeth River is Coast Guard Sector Hampton Roads. Around the Monitor-Merrimac Memorial Bridge-Tunnel (MMMBT) is a local hub of industry, such as the Norfolk International Terminals and Newport News Shipbuilding complex, which all rely on the James River Estuary. Collecting data amid the naval and commercial activity was a challenge amplifying the reasons to understand this estuary and others like it.

B. PREVIOUS RESEARCH

Some of the previous research in the field of fish and bubble acoustics has been conducted with the specific goal of characterizing attenuation due to swim-bladder fish in the field of fisheries science and stock management. Studies funded through the Naval Research Laboratory interpreted the acoustic spectroscopy of anchovies and the distribution of anchovy length and depth in the water column based on spectral spreading and the bio and geo-acoustic parameters in relation to transmission loss through schools of anchovies (Diachok 1999, Diachok 2001, Diachok and Wales 2005). These experiments were conducted in more open water environments than JRE2019, such as the Gulf of Lion and the Yellow Sea. Other research helped scientists in fisheries science move away from manually counting fish, such as sardines and anchovies, and deduce population through echo integration (MacLennan 1990). Research has since deduced swim bladder size through transmission loss and correlated fish age and population at their corresponding depths in the water column (Terrill and Melville 2000, Diachok 2001). In a related acoustic riverine study, a marine mammal survey was conducted by Dong et al. (2011) in an effort to track porpoise population.

Other acoustical research was conducted in confined waterways and coastal regions similar to the James River Estuary. In addition to fishery science, some acoustical research focused on characterizing tidal bores through measured sound transmission (Zhu et al. 2010). Several relevant studies focused on noise and seasonal ambient noise trends. McConnell et al. (1992) focused on a large, deep fjord; Wysocki et al. (1997) studied the impact of ambient noise level on fish. Much interest has been generated on the effect man-made noise has on marine mammals. Haviland-Howell et al. (2007) studied recreational boat noise in intracoastal waterways and its impact to dolphins. Recreational boat noise causes sound attenuation of sound due to bubbles. This attenuation type was also a big factor to the study by Poikonen (2010) done in shallow brackish water on wind-influenced ambient noise. The Hudson River was the site of a study to understand riverine acoustic attenuation (Roh et al. 2008).

Previous acoustical research conducted related to homeland security in constrained environments. Fillinger et al. (2011) offered acoustic methods to classify ship and vessel traffic in an estuary. Stolkin et al. (2006) studied the acoustical issues of identifying small targets or threats in a constrained region with a large amount of ambient noise.

Research that sought to characterize the acoustic constrained environment is sparser. Vracar and Mijic (2011) studied three large European rivers over 10 years to determine noise influences across the acoustic spectra. The Hudson River Estuary has been studied and modeled (Radhakrishnan 2009), as has the Connecticut River in terms of quantifying its stratified turbulence through acoustic backscattering collection (Lavery et al. 2013).

Acoustic propagation through the Connecticut River was conducted as part of the series of estuary projects that JRE2019 is affiliated. This experiment investigated the acoustic effects of a bubble cloud in an estuarine front (Reeder et al. 2018). The findings demonstrated that transmission loss (TL) is affected by excess attenuation and scattering by bubble clouds, all elements that are not in effect in a less constrained, or more open environment. The salt wedge that is typical of estuarine environments is in both the Connecticut River and James River. The salt wedge in the James River is in a unique V-shape as it comes in from the Chesapeake Bay around Newport News Point. This shape

adds to the complexity of the dynamics between the fresh water and salt water. This environment creates layers in the frontal region. Ducting often occurs in the upper layer and refraction or a shadow zone often forms in the lower layer. In addition, the bubble cloud subducted through the water column along the front will impact TL as it travels with the flood and ebb tides (Reeder 2016).

The majority of the related research has focused on specific sites, and the applications of understanding of geologic, hydrodynamic or thermodynamic parameters. The JRE2019 experiment attempts to characterize the overall acoustic environment of a confined, dynamic and energetic estuary with a unique bubble cloud and TL pattern.

A detailed overview of the JRE environment is included in Chapter II of this thesis. Chapter III details the experiment and data collection methods. Chapter IV presents the results of the acoustic survey collection, and Chapter V provides conclusions.

II. ENVIRONMENT

A. DESCRIPTION OF THE ESTUARINE AREA OF STUDY

This experiment was conducted over a 9-day period at a depth of ~8-10 m near the mouth of the James River in the greater Chesapeake Bay region in the vicinity of (IVO) Newport News Point (NNP) near Hampton, VA. Figure 1 shows an overview of the area.

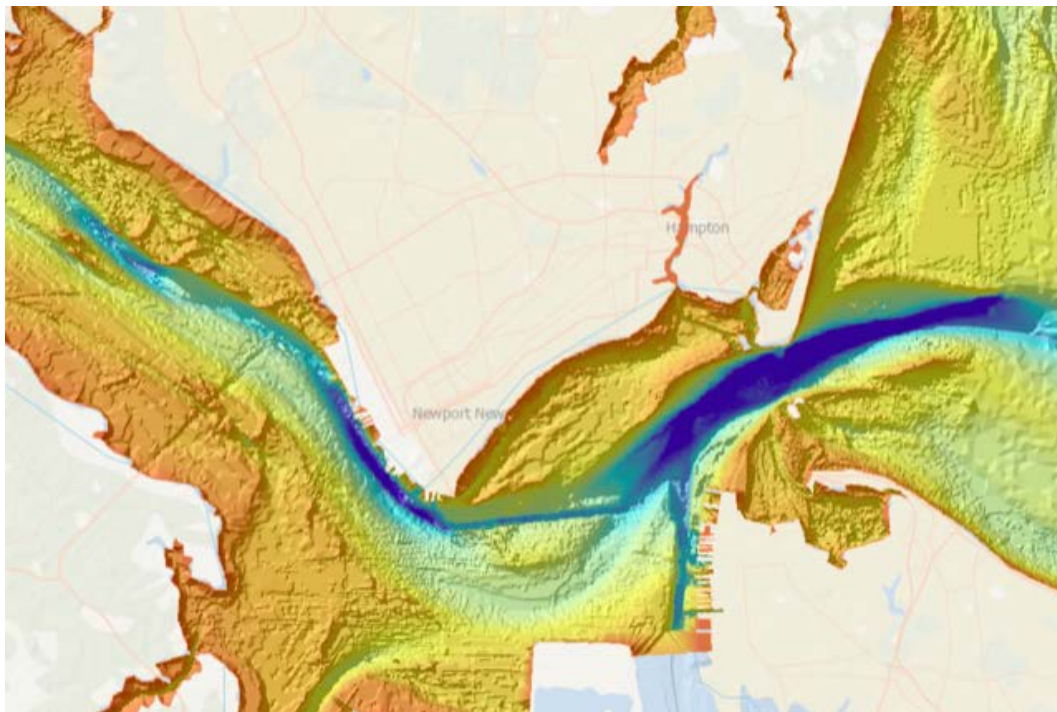


The experiment was conducted within the white box above. The James River separates the cities of Newport News (to the north) and Portsmouth (to the south). Adapted from Google Earth Pro.

Figure 1. James River Estuary Experiment Area

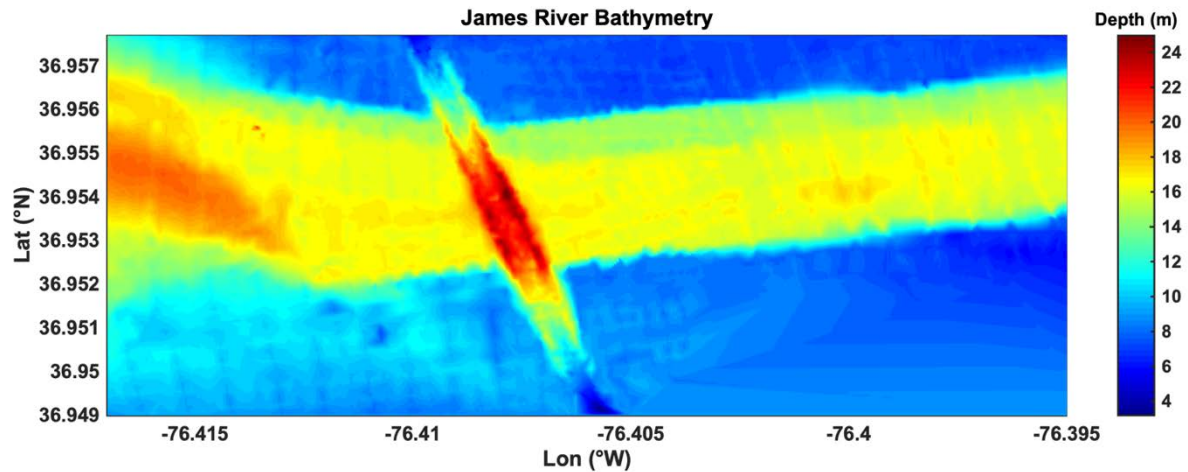
The James River is the southernmost drowned-river valley tributary to Chesapeake Bay with its fluvial source to the west (Nichols et al. 1991). It has a channel-shoal bathymetry, consisting of a main channel bounded on the northern and southern sides by shallow shoals (Li et al. 2017). The natural channel is clearly seen throughout the estuary; the dredged navigation channel is evident in the center of the plot near NNP in Figure 2. What this 50 m resolution bathymetry does not show is the MMMBT trench in which the tunnel lies. The MMMBT tunnel trench is evident in Figure 3, which displays 5 m

resolution bathymetry obtained by the Humminbird SOLIX15 sonar system. The water depth was approximately 17 m to the immediate west and east of the tunnel trench and exceeded 17 m in some areas of the trench itself. It appears that after the tunnel trench was dredged and the tunnel sections laid down and connected, the tunnels were only partially covered with sediment and rock. The MMMBT is a four-lane dual-tunnel system. One tunnel is for northbound traffic and the other is for southbound traffic, and each are 12.7 m diameter (Personal Communication, Kenneth Reynard, Facility Manager, Hampton Roads Harbor Tunnels, 30 August 2019). The tubes are separated by approximately 1 m, making the center-to-center separation to be about 13.5 m. Figure 4 displays a visual of the tunnels as seen during construction of the MMMBT. There appears to be a small ridge between the tunnels visible with the underwater Humminbird sonar mapping system. The sharp discontinuities in the riverbed affect the current flow during both flood and ebb. John Richardson and Jim Goins at the Virginia Institute of Marine Science (VIMS) conducted the survey with the Humminbird system shortly after the field experiment.



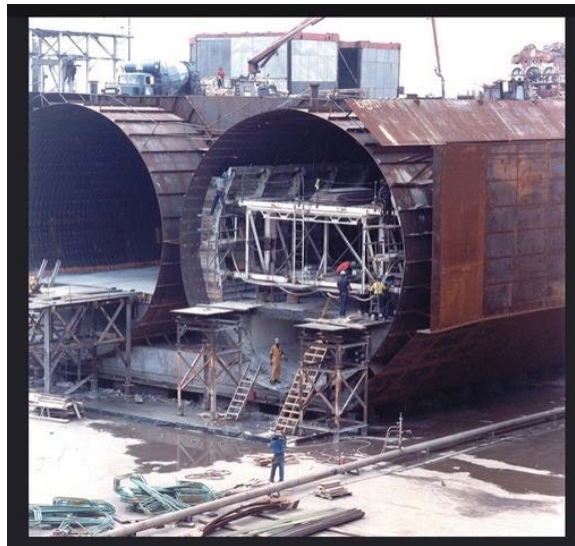
Source: NOAA NCEI (2020).

Figure 2. James River Estuary Bathymetry



James River Estuary Bathymetry IVO NNP, showing the MMMBT trench. Source: Personal Communication, John Richardson and Jim Goins, Virginia Institute of Marine Science, 31 August 2019.

Figure 3. James River Estuary Bathymetry



Source: Virginia Department of Transportation Flickr (2020).

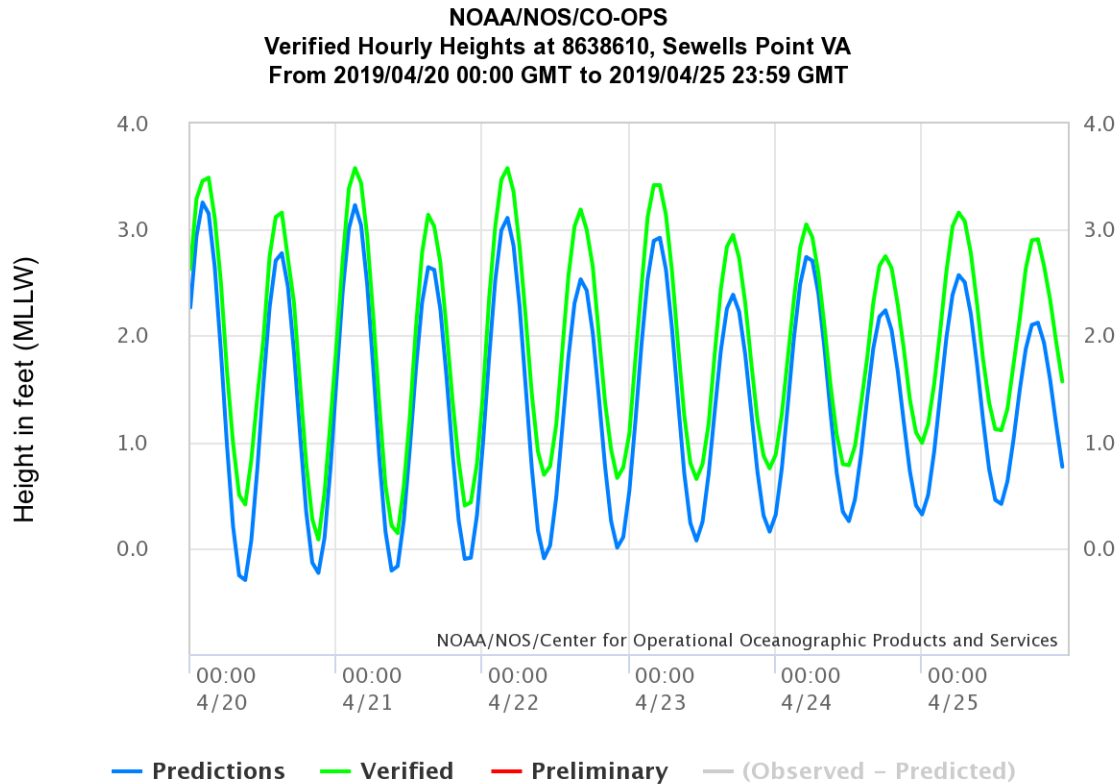
Figure 4. MMMBT During Construction

The JRE experiences semi-diurnal tides, meaning that there are two low tides and two high tides daily. The semi-diurnal tide experiences inequity in that the high and low water levels each day are not the same, and are notated as higher high water and lower low water at the extremes. Verified low and high tide times at Sewell Point Station #8638610

during the experiment are found in Table 1. Figure 5 is a visual of the tidal levels. Spring tide was on 19 April 2019, and neap tide was recorded on 26 April 2019. On the days studied closely for this paper, a tidal range of 0.67 m and 0.70 m was recorded on 23 and 24 April 2019, respectively. Over the course of the experiment it can be seen that the difference between the tidal levels gradually decreases as the tidal cycle moves from spring tide to neap tide.

Table 1. Verified High and Low Tide levels and Time during JRE2019 at Sewells Point Station #8638610. Source: NOAA/NOS/Center for Operational Oceanographic Products and Services (2020).

Date	Time (GMT)	Verified (ft)
4/20/2019	2:18	3.58
4/20/2019	8:42	0.37
4/20/2019	14: 36	3.15
4/20/2019	20:42	0.13
4/21/2019	3:00	3.61
4/21/2019	9:30	0.12
4/21/2019	15:18	3.15
4/21/2019	21:24	0.37
4/22/2019	3:42	3.6
4/22/2019	10:12	0.64
4/22/2019	16:00	3.18
4/22/2019	22:18	0.66
4/23/2019	4:30	3.46
4/23/2019	11:06	0.64
4/23/2019	16:48	2.95
4/23/2019	23:00	0.73
4/24/2019	5:06	3.03
4/24/2019	11:36	0.76
4/24/2019	17:54	2.75
4/24/2019	23:54	0.99
4/25/2019	6:06	3.18
4/25/2019	12:30	1.07
4/25/2019	18:30	2.94



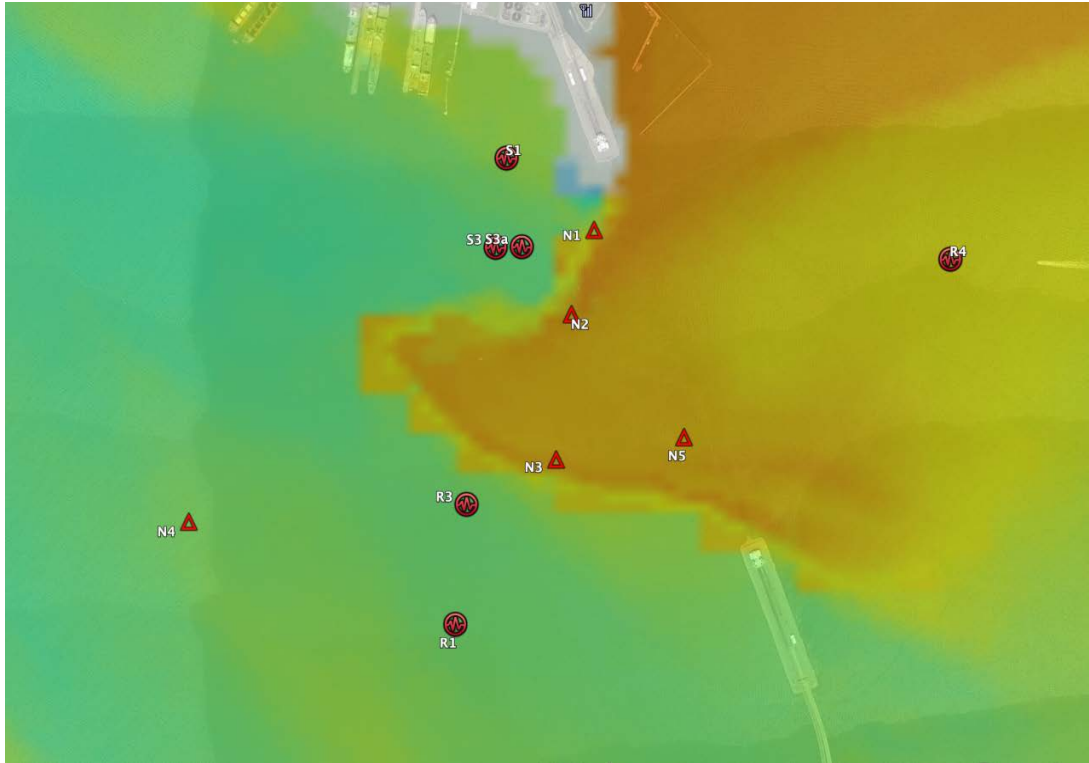
Tidal cycle heights as recorded at Sewells Point NOAA Station #8638610 during from 24–25 April 2019. The slight difference in tidal variation can be seen as the tidal cycle moves to neap tide. Source: NOAA/NOS/Center for Operational Oceanographic Products and Services (2020).

Figure 5. Tidal Cycle Heights at Sewells Point NOAA Station

The oceanographic and acoustical feature of interest was the system of tidally-induced salinity fronts that consistently develop in a small area near NNP, just to the west of the MMMBT. The front forms during the early phase of each flood tide regardless of lunar phase or tidal range, moves upriver with increasing current flow, and is bounded by a strong counter-clockwise eddy over the shoals on the north side of the river (Kuo et al. 1990, Shen et al. 1999). During early flood, the saline waters of the Chesapeake Bay initially accumulate on the northern shoals to the east of the northern MMMBT entrance, forming an east/west front along the northern bank of the navigation channel. Once the tidal forcing is sufficient to overcome the slackening ebb flow of the fresh river water, the salt water advances upriver, around the MMMBT northern entrance terminus. At the

critical depth in the slope, the flow plunges under the ebbing fresh river water, forming a three-dimensional (3D) estuarine salt wedge (Kuo, Member et al. 1990). This 3D front extends from the foot of the salt wedge at the riverbed up to the surface, forming a V-shaped surface expression called the tidal intrusion front (TIF). This front normally lasts between 1 h and 2 h (Shen et al. 1999).

Figure 6 is modeled surface salinity (Personal Communication, Chris Bassett, Woods Hole Oceanographic Institution, 22 April 2019) showing the tidal intrusion front crossing the tunnel trench and just beginning to advance west of NNP on April 19, 2019 at 1500 Z. Asset placement is in red. Triangles represent mooring locations, R1, R3 and R4 indicate locations of surface-deployed acoustic receivers, and S1, S2a and S3 indicate positions occupied by the source throughout the experiment. The TIF is characterized by lines of bubbles and foam (Figure 7) created by the energetic convergence of the two water masses; breaking waves inject bubbles below the surface and the negative velocities of the salt water subduct the bubbles to depth (often to the riverbed), forming acoustically significant underwater bubble clouds, as shown in the echosounder image in Figure 8. Fish and suspended sediment were also recorded by echosounder images during the experiment and are a contributor to attenuation due to scattering and absorption. The dense water associated with the TIF, bubble clouds and attenuating features advances first toward NNP at depth under the fresher water. It then continues to fill the water column with the advancing tide (Shen et al. 1999).



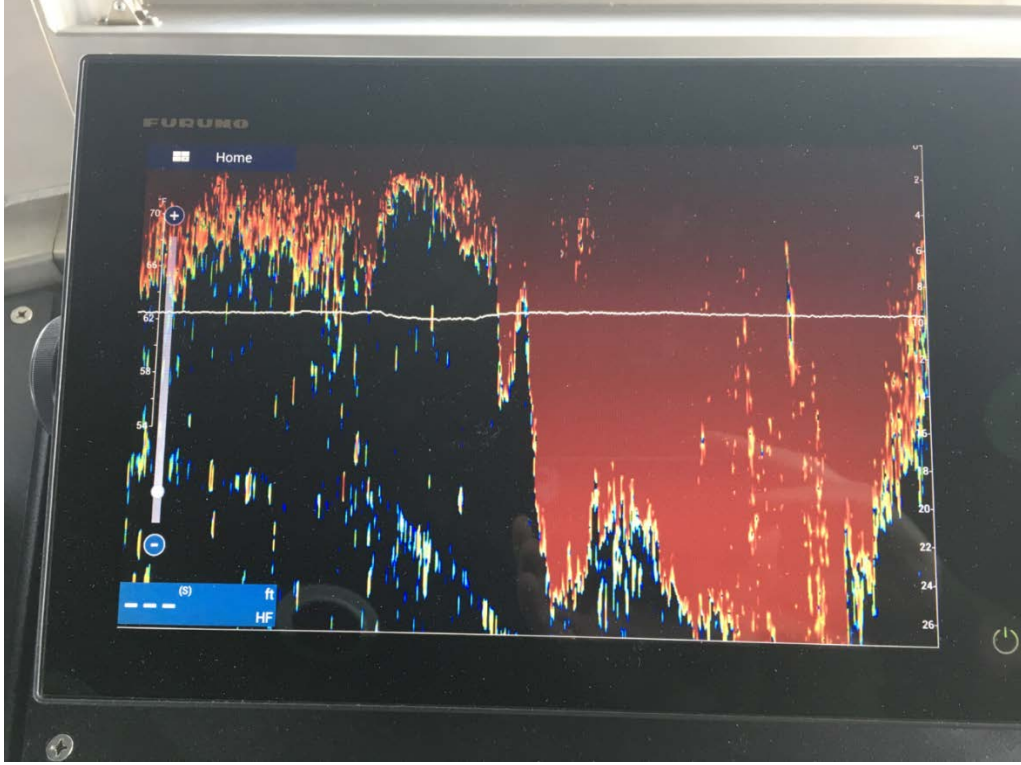
Modeled surface salinity showing the RIF just beginning to advance west of NNP on 19 April 2019 at 1500 Z. Source: Personal Communication, Malcolm Scully, 23 April 2020, Woods Hole Oceanography Institute and adapted from Google Earth Pro.

Figure 6. Modeled Surface Salinity in the James River Estuary



James River Estuary tidal intrusion front between salty and fresh water during flood tide. Bubbles are seen between fresh water on the left and salty water on the right.

Figure 7. James River Estuary Tidal Intrusion Front Surface Expression



Shipboard 200 kHz echosounder data showing the subducted bubbles at the TIF from Figure 7. Negative velocities at the front subduct bubbles to depth

Figure 8. Shipboard 200 kHz Echosounder Data

B. BUBBLES AND SIGNAL PROCESSING

Bubbles in the water column as a result of the TIF are of interest in a dynamic, energetic environment such as the JRE. Bubbles attenuate sound by absorption and scattering (Czerski et al. 2011). A resonance frequency is the natural frequency of vibration determined by the physical parameters of an object, in this case an air bubble. Should the resonance frequency of the bubbles entrained in the TIF become excited by the range of frequencies emitted by the experiment's sound source, transmission loss and acoustic variability through the water column is enhanced (Lurton 2002). Bubble resonance frequency is given by the following equation:

$$\omega_0 = \frac{1}{a} \left(\frac{3\gamma P_{amb}}{\rho_w} \right)^{1/2} \quad (1)$$

where $\Upsilon = c_p/c_v$ is the ratio of the specific heats of the entrained gas, ρ_w is the density of pure water, α is the bubble radius and P_{amb} is the ambient pressure in the bubble (Terrill and Melville 2000). Related studies showed transmission loss due to fish swim bladders through an acoustic transect, and related the transmission loss to the size of fish, size of the swim bladders, and even the location in the water column of the biomass (Diachok 1999, Diachok 2001, Diachok and Wales 2005). These experiments have revealed a modified version of the relationship between the swim bladder “bubble” and resonance frequency due to the shape of the swim bladder and the fact that the swim bladder is surrounded by fish flesh. Diachok and Wales (2005) studied anchovy and jack mackerel in the Yellow Sea. At a depth of 7 m, adult anchovies of about 4 in in length were found to have a resonance frequency of 1.4 kHz, and the juveniles, being slightly smaller, had a resonance frequency of 3.5 kHz (Diachok and Wales 2005). While the effective radii of these fish swim bladders are larger than the expected bubble radii at the JRE, their resonance frequency is within the JRE experiment’s signal band (500 – 5000 Hz). A VIMS fish trawl in the JRE from April 2019 revealed the typical fish species found in the estuary at the time of the experiment. The majority of the fish were Bay Anchovies, and the next numerous species were juvenile Spotted Hake (Personal Communication, Mary Fabrizio, VIMS, 20 September 2019). Adult Bay Anchovies are 4 in. in length and adult Spotted Hake can reach up to 17 cm, or about almost 7 in. in length (VIMS, Chesapeake Bay Program). Juvenile Bay Anchovies and Spotted Hake are comparable in size to the anchovy found in Diachok and Wales (2005) and it is reasonable to expect resonance frequencies of the fish in the JRE to cause TL similar to what was found in the Diachok and Wales (2005) research.

It is expected that resonance frequency of the entire bubble cloud extending along the TIF to be similar to that of a school of swimbladdered fish. Schooling fish show resonance peaks and corresponding relative high TL in accordance with their biological parameters, and their depth and distance from one another. These parameters change throughout the day as do the resonance peaks (Diachok 1999). Patterns of similar resonance peaks and transmission loss throughout the tidal cycle of the JRE will be examined through data

analysis. Excess attenuation due to bubbles, α , is dependent on pressure and signal pathlength. It is determined through the following equation:

$$\alpha = \frac{10}{l} \log \left(\frac{P^2}{P_o^2} \right) \quad (2)$$

and is expressed in units of decibels per meter. The variable l is the signal pathlength, P_o is the received acoustic pressure in bubble-free water, and P is the measured pressure. Filtered frequency band rms acoustic pressure can be used in the equation (Terrill and Melville 2000).

The sound source for JRE2019 was a linearly frequency-modulated (LFM) broad band “chirp” signal in the 500–5000 Hz frequency band. The recorded signals received from the source were match-filtered in the frequency domain. This filters the signal and aids in identifying the known signal amongst the noise of the estuary. The matched-filtered output (MFO) increases temporal resolution, and maximizes the signal-to-noise ratio (SNR). The MFO is used to determine the sound energy level (SEL) which is given by the following equation:

$$SEL = 10 \log \left(\int_0^T P^2(t) dt \right) \text{ dB re } 1 \mu Pa^2 - s \quad (3)$$

where $P(t)$ is the MFO and T is the integration period (Reeder, 2016). This manipulation of data allows for patterns and the arrival structure of the compressed pulse to be identified. In addition to SEL and SNR, the data analysis included a look at the noise energy level (NEL), anomaly and variance across 1/3 octave bands centered on 11 standard frequencies between 500 Hz and 5000 Hz.

III. EXPERIMENT

Experimentation was conducted from 18 April through 25 April 2019 in the James River Estuary. Underway time of the Research Vessel Virginia (R/V Virginia) was dictated by the tidal cycle and the predicted times of high and low tide. The objective was to place the equipment in the water early in the flood tide so that sound transmission began in entirely fresh water and data recorded included acoustic transects of fresh water. Data was subsequently collected during frontal passage as the flood tide entered the sound source transmission path. This ensured that the sound transmission loss and sound propagation differences were recorded and could be studied. All entries from the experiment's log are included in Appendix A.

A. EQUIPMENT

1. Ship and Schedule

Over the course of the experiment all equipment was deployed and recovered from the Virginia Institute of Marine Science's R/V Virginia. The activities detailed in this report focus on the low-to-mid-frequency acoustic propagation portion of the experiment; other principal investigators (PIs) were engaged in other related work. See Figure 9 for a picture of R/V Virginia.



Source: Virginia Institute of Marine Science (2019).

Figure 9. R/V Virginia

2. Bottom Moorings

Three tripods and two small stanchion moorings were deployed on the riverbed. Small, internally recording, omnidirectional hydrophones (Acousondes) and ADCPs were deployed at N1, N2 and N3 for the duration of the experiment. Two of these moorings were called “Spiders,” small fiberglass frames with three legs and weights to resist movement by currents. The Acousonde is a sealed unit containing a hydrophone, along with pressure, attitude and orientation sensors to internally record data to be downloaded later. The ADCPs operated at 1200 kHz and were in 4-Beam Janus configuration with a 20° beam angle.

See Figure 6 for a visual representation of asset locations near the MMMBT (I-664). Tables 2, 3 and 4 list asset latitudes and longitudes, deployment and recovery dates, and times. Spider C2 was deployed with an ADCP at site N1, on the north side of the navigation channel close to the northern tunnel entrance. Spider 24 was deployed at site N3 to the west of the tunnel and south of the navigation channel. Stanchion #1 was deployed at site N4 with an Acousonde, a little less than 1 nm to the west of N5 with another Acousonde. Finally, a tripod from Woods Hole Oceanographic Institute (WHOI) was deployed at site N2, just west of the bridge-tunnel in the center of the navigation channel. This WHOI tripod was of heavier construction for deployment in a deeper area with stronger current. It had an ADCP with the same sampling rate as the others in the experiment and a CTD sensor.

The assets were strategically placed to observe the acoustic signal from source station S3 as a function of time, range and azimuth IVO the estuarine front that was known to twice daily traverse the experimental area. Additionally, hydrophones at N5, N4 and N3 were designed to observe the time and range dependence of the sound radiated by the traffic tunnel.

Table 2. Acousonde Deployments during JRE2019 Project on 18 April 2019

Acousonde	Date and Time (Z) Deployed	Date and Time (Z) Recovered	Location	Depth (m)	Lat (N)	Long (W)
A060	18 April 19 2151Z	1327Z 25 APR	Site N4 (Stanchion #1)	7	36° 57.920'	076° 25.556'
A062	18 April 19 2225Z	1223Z 25 APR	Site N5 (Stanchion #2)	8	36° 57.024'	076° 24.464'
A061	18 April 19 2042Z	1255Z 25 APR	Site N3	11	36° 57.026'	076° 24.746'
WHOI Tripod	18 April 19 2255Z	1146Z 25 APR	Site N2		36° 57.404	076° 24.803'

Table 3. “Spider” Locations with ADCP and/or Acousonde

Spider	Acousonde	ADCP	Date and Time (Z) Deployed	Date and Time (Z) Recovered	Location	Lat (N)	Long (W)
C2	N/A	7290	18 April 19 2024Z	25 April 19 1418Z	N1	36° 57.454'	076° 24.806'
24	A061	2595	18 April 19 2042Z	25 April 1255Z	N3	36° 57.026'	076° 24.746'

Table 4. Site Locations

Site	On Bottom Latitude (N)	On-Bottom Longitude (W)
N1	36° 57.404	76° 24.806
N2	36° 57.324	76° 24.712
N3	36° 57.026	76° 24.746
N4	36° 57.920	76° 25.556
N5	36° 57.084	76° 24.464

3. Vertical Line Array

The Vertical Line Array, or VLA, was used to observe the depth-dependence of the acoustic signal before, during and after the passage of the estuarine front. The mini-cat was anchored for approximately 8 hours at a time during daylight hours. The four-phone VLA

(Cetacean Research Technology C57) was suspended below a small inflatable, one-man fishing pontoon craft (mini-cat); the electronics (Zoom F8n 8-channel recorder, CRT 8-channel pre-amp, MasterClock GPS500 timecode generator and 12v inverter) were contained inside a water-tight box on the top of the mini-cat. The box was covered with aluminum foil to reflect the sun to limit the risk of high internal temperatures. An RBR Solo Temperature sensor (#101610) was placed in the box with the recorder to measure internal temperature. Maximum observed internal temperature was 105° F on 23 and 24 April, with 21 and 22 April logging max temperatures of 81° F and 76° F, respectively.

Figure 10 shows the VLA deployed at site R3, 1.17 nm south of the S1 source station. The VLA phones occupied depths of equal spacing below the mini-cat of approximately 1 m, 3 m, 5 m and 7 m. They were color-coded to ensure identical placement each day. Figure 11 shows the components inside the water-tight case.



Figure 10. The Vertical Line Array (VLA) Deployed in the James River Estuary



The electronics inside the watertight case shown on the mini-cat in Figure 10. The case contained the Zoom F8n 8-channel recorder (blue), the 8-channel pre-amp (gray/white), the GPS time-code generator (cream) and the 12v inverter (red).

Figure 11. VLA Electronics

4. Sound Source

The sound source was a Lubell Lab high-power broadband piezoelectric underwater acoustic transducer (LL1424-HP). It was deployed as part of the apparatus named “the coffin,” a wooden box housing the electronics required to autonomously transmit the acoustic signals. The coffin was deployed on an inflatable mini-cat and contained four 12 vdc marine deep-cycle batteries, a 2 kW DC-AC inverter (AIMS PWRIG200012120S), an uninterruptible power supply (Tripp-Lite UPS), a signal generator (SIGENT SDG1032X), a signal amplifier (Crown CDi2000), a bridge (Lubell AC1424HP), which delivered the amplified acoustic signal to the source suspended below the mini-cat. The source transmitted an LFM broadband signal (“chirp”) in the 500–5000 Hz band. A monitoring hydrophone (Greenridge Sciences Acousonde 3A) was attached to the line from which the source was suspended at a depth of 1.5 m to record the transmitted signal. Additional floatation (foam) was attached to the underside of the coffin for extra

buoyancy. Figure 12 shows the underside of the coffin; Figure 13 shows the equipment inside the coffin.



The underside of the “coffin” (hanging from the ship’s crane) showing the additional floatation, the anchor chain/line and the line from which the acoustic source was suspended.

Figure 12. Coffin Deployment



Electronic equipment inside the coffin which powered and delivered the signal to the source.

Figure 13. Coffin Electronic Equipment

5. Banshee

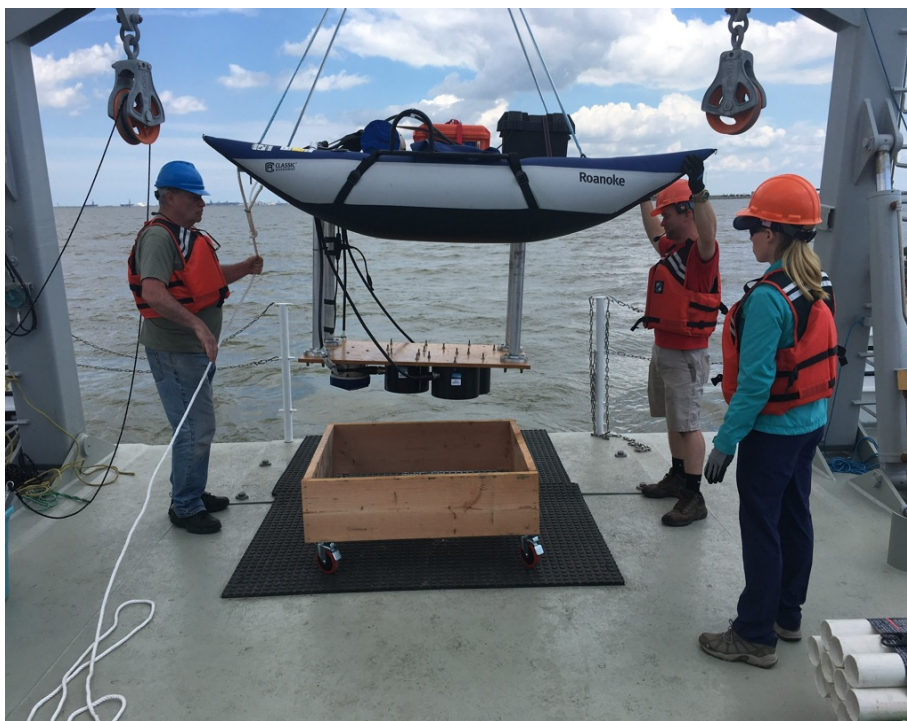
The “Banshee” (named after a comic book superhero whose superpower was emitting powerful sound) consisted of a four channel BioSonics DTXtreme echosounder system deployed on a mini-cat (Figure 14). The echosounder system was powered by a single 12 vdc deep-cycle marine battery, its electronics were housed in an orange watertight box atop the mini-cat, and the four echosounder transducers, along with an ADCP instrument, were mounted on a wooden plate 1 m below the waterline (Figure 15). The echosounder system broadcasts a WIFI signal that allows real-time data visualization and analysis while recording (over short distances), as well as playback and post-processing capabilities. The Banshee was useful in collecting real-time data as the ship passed over the front to visualize bubble entrainment in the vicinity of the front. The Banshee was

designed to be deployed either at anchor to allow autonomous collection of data at one location over periods of hours, or in a towing configuration to collect data along transects. The Banshee was successfully deployed on 24 April 2019 in a towed configuration alongside the ship using the ship's crane. Instead of towing, the ship and Banshee drifted with the wind and current in order to image the flood-tide front along the northern wall of the navigation channel (Figure 16). Effort was made to position the ship north of the channel then drift across the front with the ship's clutch disengaged to minimize bubbles from the ship's propellers ("prop wash") from contaminating the data. The ship drifted across the front several times that day to gather data. The Banshee was lifted out of the water while the ship reset its position.



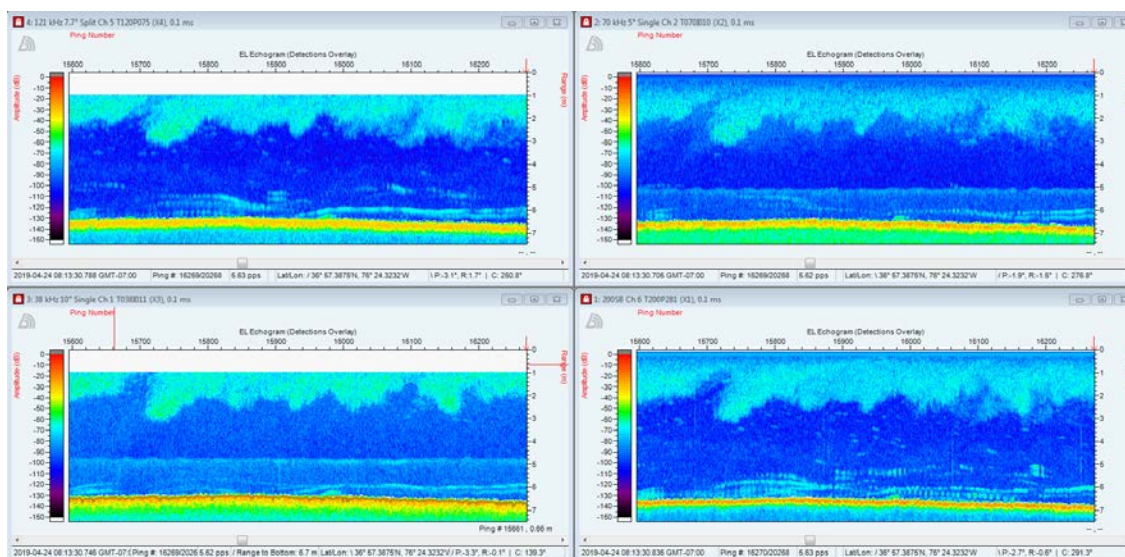
The Banshee deployed from the ship's crane alongside the R/V Virginia on 24 April 2019. The 12 vdc marine battery is in the black box on the left, the BioSonics electronics is housed in the orange watertight case and the excess cable is secured on the right.

Figure 14. The Banshee



The Banshee during deployment from the fantail, showing its underwater substructure; four echosounder transducers and an ADCP were mounted on the wooden plate 1 m below the waterline.

Figure 15. Banshee Deployment off of R/V Virginia



Four channels of BioSonics data as seen on the laptop aboard R/V Virginia while Banshee was deployed on 24 April 2019. The strong scattering (light blue) is from entrained bubbles at the front along the northern wall of the navigation channel to the east of the tunnel ditch.

Figure 16. BioSonics Data on 24 April 2019

6. Mini Mooring

The Mini Mooring (MM) consisted of three Acousondes deployed on a weighted vertical line suspended below an anchored surface buoy. The three hydrophones occupied depths of 2.3 m, 3.5 m and 5.5 m. Weight at the bottom of this line ensured the line remained approximately vertical in the water column— in essence, creating another vertical line array. The MM was deployed at site R4 on 23 and 24 April to observe the acoustic signals propagating to the east from the source at S3a through (and parallel to) the bubble-laden front along the northern wall of the navigation channel. Analysis of these signals will be compared to those observed at N5 which propagated to the south perpendicular to the front.

7. Bubble Device

Another piece of equipment used during the experiment was called the “bubble device.” The bubble device consisted of a Conductivity, Temperature and Depth sensor (RBR CTD #060315), two acoustic projectors (Ocean Sonics icTalkHF and icTalkLF) and a hydrophone (Ocean Sonics icListen) mounted on a makeshift frame and hand-deployed over the side of the ship by line (Figure 17). Foam was fixed between each piece of wood to limit vibration and noise that may be picked up by the hydrophone. An anchor weight was fixed to the bottom of the device to provide some mass to keep the bubble device vertical in the water column. The device was deployed over the side of R/V Virginia primarily during the drift across the front while operating the Banshee and gathering BioSonics data in the vicinity of the Mini Mooring at site R4.

The CTD monitored the environment while the hydrophone collected the signals emitted by the two projectors. The icTalkLF emitted a one second long LFM chirp from 1 to 8 kHz, and the icTalkHF emitted a 1 second long LFM chirp from 10 to 100 kHz. The transmission paths from sources to receiver were approximately 15 cm. The concept is based on Terrill and Melville (2000) and is designed to acoustically observe the frequency-dependent attenuation and travel time through the bubbly mixture in the front in order to extract bubble size distribution.



The bubble device was deployed over the side of R/V Virginia on 24 April 2019 during the same period that the Banshee was in the water. The CTD is the white cylinder at the top of the picture and the two acoustic projectors and hydrophone are attached to the bottom of the wooden frame.

Figure 17. The Bubble Device

B. METHODS

On the first day, 18 April 2019, R/V Virginia was underway at 1102Z for a verified high tide time of 1436Z. The day was used to place equipment that would be on station for the duration of the experiment. The moored stations N1, N2, N3, N4 and N5 were all deployed that day. Tables 2, 3 and 4 describe the stations, equipment at each, their locations and the deployment and recovery times. Due to weather, experimentation was unable proceed on 19 April and R/V Virginia did not go underway. 20 April 2019 was used to master the deployment and recovery process of the gear and reposition Spider C2 slightly from site N1 to site N1a. On 21 April 2019 R/V Virginia was underway at 0909Z for a high tide time of 1518Z. On this day, the VLA and the coffin were used to transmit and collect signal through the front between R1 and S1 west of the bridge-tunnel. The VLA was deployed at location R1 and the source was deployed at S1. In this configuration, sound was transmitted and received in the north to south direction as the estuarine front came from the east. Table 5, gives details on equipment used, deployment and recovery times.

Table 5. Equipment Deployment on 21 April 2019

Equipment	Time and Location Deployed	Time and Location Recovered	Gear Notes	Site
VLA (Receiver)	1042Z 36° 56.927N, 076° 24.744W	1826Z 36° 56.948N, 076° 24.965W	RBR Solo Temp sensor #101610	R1
Coffin (Source)	1250Z 36° 57.363N, 076° 24.274W	1846Z, 36° 57.505N, 076° 24.870W	Lubell hydrophone, Acousonde A065	S1

On 22 April 2019 R/V Virginia was underway at 0939Z, for a high tide time that was verified that day to be at 1600Z. The coffin and VLA were immediately prepared for deployment. The coffin was deployed at S1, and the VLA was deployed at R3. The Banshee was also deployed on 22 April 2019, but experienced complications – the BioSonics cables did not connect to the deck box. It was deployed via crane and remained attached to the ship this way for two short intervals before Banshee operation was suspended for the day. Table 6, gives details on equipment used, deployment and recovery times.

Table 6. Equipment Deployment on 22 April 2019

Equipment	Time and Location Deployed	Time and Location Recovered	Gear Notes	Site
VLA (Receiver)	1135Z 36° 56.924N, 076° 24.947W	1944Z 36° 56.924N 076° 24.947W	RBR Temperature sensor #082173 (platform), #101610 (VLA).	R3
Coffin (Source)	1122Z 36° 57.517N, 076° 24.871W	1922Z 36° 57.153N 076° 24.847W	RBR Temperature sensor #101596, Acousonde A065, Lubell hydrophone	S1
Banshee	1520Z; 1835 36° 57.302N, 076° 26.008W; 36° 57.15N, 076° 24.847W	1527Z; 1845Z	Connectors/cables do not match connections on gear box	

On 23 April 2019 R/V Virginia was underway at 1006Z from Hampton Harbor. Tables 7 and 8 are a summary of equipment deployment. On this day the VLA was deployed again at R3 while the Mini Mooring was deployed at R4 as another asset to measure transmission loss. The sound source, or coffin, was deployed at S3a. S3a is a position south of the I-664 northern bridge in the opening of the river (over the tunnel). This sound source positioning allowed for a more direct path between source and receiver at S3a to R4 across the approaching front and measured through the front in a more east to west transect. In addition, the bubble device was also deployed throughout the day primarily to test its operation.

Table 7. Equipment Deployment on 23 April 2019

Equipment	Time and Location Deployed	Time and Location Recovered	Gear Notes	Depth	Site
VLA (Receiver)	1155Z 36° 86.921N, 076° 24.514W	1921Z 36° 56.913N 076° 24.92W	RBR Temperature sensor #082173 (platform), #101610 (VLA).		R3
Coffin (Source)	1133Z 36° 57.361N, 076° 24.859W; 1241Z 36° 57.362N, 076° 24.865W	1232Z 36° 57.362N 076° 24.865W; 1845Z 36° 57.33N 076° 24.366W	Dragged anchor. RBR Temperature sensor #101596, Acousonde A065, Lubell hydrophone	A065: 1.5 m Source: 4.5 m	S3a
Mini Mooring	1105Z 36° 57.051N, 076° 23.957W	2105Z 36° 57.665N 076° 23.865W	Acousondes A063, A064, A066 (surface to bottom)	A063: 2.3 m A064: 3.5m A066: 5.5m	R4

Table 8. Bubble Device Deployment on 23 April 2019

Time and Location Deployed	Time and Location Recovered
1815Z	1817Z
1821Z	1823Z
2155Z	2155Z
2210Z, In port; 37°01.063N, 076°20.584W Port side aft	2215Z
2216Z, In port; 37°01.063N, 076°20.584W Stbd stern	2221Z
2223Z, In port; 37°01.063N, 076°20.584W Port mid-fantail	2228Z

On 24 April 2019 the Banshee and its instruments were prepared for deployment, as an added instrument for the day's experiment and retry after the problems of the day prior. A goal of this day was also to measure from S3a to R3 and R4 with the VLA and Mini-Mooring.

At 1400Z R/V Virginia was in place east of the tunnel and drifting south across the estuarine front with the Banshee deployed, hanging from the crane with a line to the Banshee's bow. The idea of this drift was to collect CTD, noise and BioSonics data across the front with no interference from the engine of the ship. By 1401Z the ship was drifting to the southwest. The 200kHz fathometer showed bubbles all the way to the bottom of the estuary at 24 feet. After the ship repositioned itself, bubbles were seen in the water column to about 34 feet at 1446Z.

This pattern of resetting to drift across the front continued through the afternoon while the coffin and VLA operated and collected data. At 1740Z while the ship was drifting, it was noticed that the front was receding north back towards the bridge as the flood began to weaken. The experiment moved shortly thereafter to the coal piers to the

northwest of the bridge tunnel to collect data for purposes outside of this technical report, and for the Navy Research Labs (PI onboard). The Banshee continued to collect data near the coal piers and was deployed via its line during southeast transit at 1830Z.

Table 9. Equipment Deployment on 24 April 2019

Equipment	Time and Location Deployed	Time and Location Recovered	Gear Notes	Depth	Site
VLA (Receiver)	1155Z 36°56.927N, 076° 24.945W	2030Z 36°56.927N 076° 24.945W	RBR Temperature sensor #082173 (platform), #101610 (VLA).		R3
Coffin (Source)	1220Z 36°57.370N, 076° 24.833W	1022Z 36°58.359N 076° 24.820W	RBR Temperature sensor #101596, Acousonde A065, Lubell hydrophone	A065: 1.5 m Source: 4.5 m	S3a
Banshee	1347Z drifting across front; 1808Z move to coal piers	1934Z 36°57.870N 076° 25.888W	ADCP #5542 started at 1245Z. Command program: JRE19.whp	Echo-sounder just below surface	Hanging from crane
Mini Mooring	1129Z 36°57.677N, 076° 23.877W	2111Z 36°57.538N 076° 23.628W	Acousondes A063, A064, A066 (surface to bottom), RBR T/P #052170	A063: 2.3 m A064: 3.5m A066: 5.5m	R4

25 April 2019 was a gear recovery day for the experiment. Tables 2, 3, and 4 list equipment recovery locations. Appendix A contains the log from during the experiment. The entirety of the log is included to provide reference and information on the structure of the experiment.

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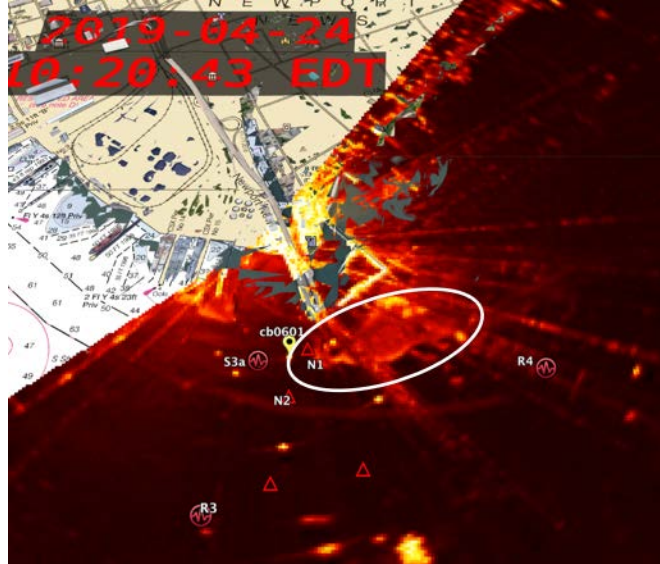
IV. DATA DESCRIPTION

A. OVERVIEW

Signals transmitted by the source at S3a and observed at the mini-mooring (MM) at R4 were recorded on 23 April and 24 April. Instruments were deployed in time to record the transmissions before flood tide, during flood, ebb and afterwards, in order to capture the impact of the entire tidal cycle. Low tide on 23 April occurred at 1108 Z and the high tide occurred at 1648 Z. Low tide on 24 April occurred at 1136 Z, and high tide occurred at 1754 Z. Observed acoustic signal level, BioSonics volume scattering strength (Sv) across the front, modeled salinity and radar images during the observation period are synthesized and analyzed to illuminate the impact of the environment on acoustic propagation in the James River Estuary. This work focuses on data collected on 24 April due to the availability of BioSonics echosounder data and more vivid radar images.

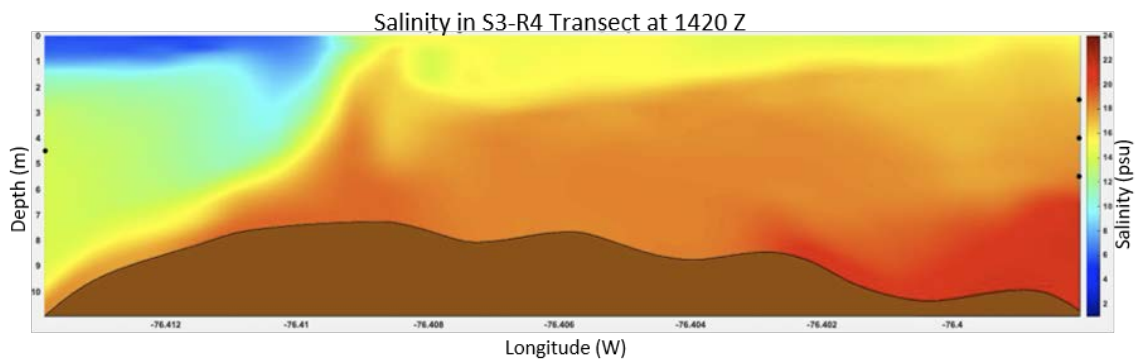
A script was run to process and plot the hydrophone data observed at R4 to provide understanding of the underwater acoustic physics during the tidal cycle. Power spectral density (PSD) of the signal, noise energy and signal-to-noise energy was plotted as a spectrogram from the MFO between 500 Hz and 5000 Hz. The signal captured by the source monitoring phone was used as the correlate for the MFO. Signal energy, noise energy, signal to noise ratio, anomaly and variation was also processed in 1/3 octave bands centered on 500 Hz, 630 Hz, 800 Hz, 1000 Hz, 1250 Hz, 1600 Hz, 2000 Hz, 2500 Hz, 3150 Hz, 4000 Hz and 5000 Hz. The bands around 630 Hz, 2500 Hz and 4000 Hz are analyzed closely for this thesis. These frequencies have the highest signal levels on the source monitoring hydrophone calibration curve and are not too close to the ends of the signal spectrum where the calibration curve showed a drop in energy. On 24 April data was recorded between 1219 Z and 2010 Z. Of interest is the time period of frontal crossing between S3a and R4, a transect across the MMMBT. Because this is a V-shaped front, the underwater foot, or the salt-wedge front, goes across the underwater tunnel before the surface expression. In Figure 18 is the radar image from 1420 Z that shows the surface expression, or TIF, crossing the MMMBT. Figure 19 shows a model depiction of the salinity across the transect at this time. The underwater salt-wedge front is visible at depth

further west than the surface expression. Changes in the acoustic signal level in the transect prior to the TIF entrance is attributable to the salt-wedge front at depth.



Tidal Intrusion Front (TIF) starting to propagate into the S3a-R4 transect at 1420 Z. Circle is around the TIF. Source: Personal Communication, Merrick Haller and Dave Honegger, Oregon State University, 23 April 2020, and adapted from Google Earth Pro.

Figure 18. Tidal Intrusion Front in the Acoustic Transect



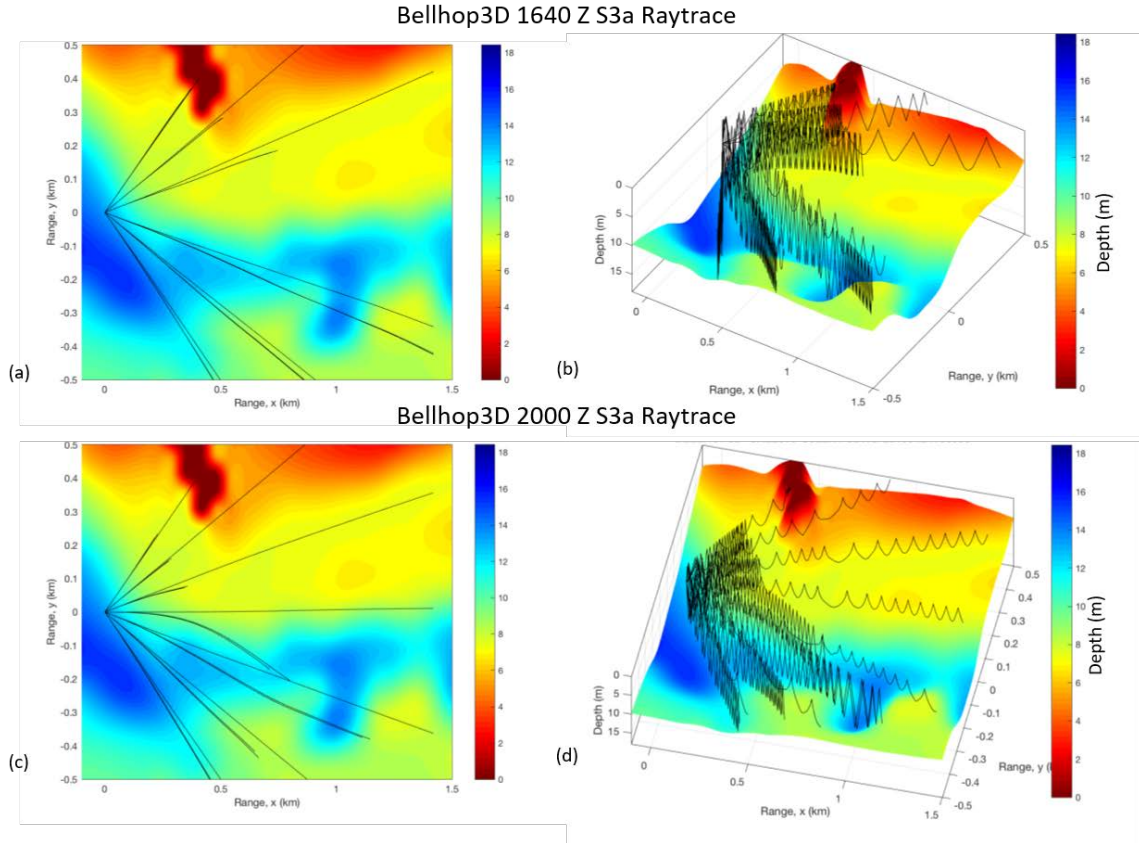
Modeled salinity along the acoustic transect as surface expression begins at 1420 Z. Source: Personal Communication, Malcolm Scully, 23 April 2020, Woods Hole Oceanography Institute.

Figure 19. Modeled Salinity Along the Acoustic Transect

Complex acoustic signal fluctuations occur in the transect during frontal passage. Several TL mechanisms will dominate the environment and complicate interpretation of the data. First, the flow of the incoming tide, starting at depth, increasing in strength until the surface expression is seen, contributes to a decrease in SNR. Secondly, as the front builds, the surface expression comprises bubbles at the frontal boundary. Bubble densities are greatest in shallow depths vs. deeper depths. The V-shape of the salt-water front is the source of the third mechanism of TL considered. In a V-shape the salt water wedges around NNP, at depth at first, so there is fresh water on top of salt water. During this time of frontal propagation, the source is in fresh water. Signals will refract toward the fresh water, as it bends toward regions of slower sound speed. This means the source signal will refract to a surface duct and to the south and southwest, away from the salt-water intrusion. A fourth TL mechanism is out-of-plane bottom scatter. Bottom scattering of the source signal will be from irregularities of the estuarine bottom as well as interaction with the sediment type (Lurton 2002). These four mechanisms - flow noise, excess attenuation (due to scattering and absorption) by bubbles, refraction and out-of-plane bottom scatter - will dominate TL in the acoustic environment. Striations in signal due to vessel noise look like sharp deviations in the acoustic pattern and vary in time scale depending on vessel proximity to the receiver. Overall trends in SNR and the analysis of the one-third octave bands will aid in understanding TL mechanisms. Excess bubble attenuation is greater at higher frequencies, and vessel noise dominates at low frequencies, being the main cause of ambient noise in the 10 - 1,000 Hz frequency band (Lurton 2002). Source signals in the higher frequency range will initially get trapped in the surface duct region more than lower frequency signals (Reeder 2016) and will have a higher susceptibility to bubbles and fish. Thus, the comparison of the top, middle and bottom SNR will aid in understanding TL due to these mechanisms in the estuary.

Modeled salinity in the JRE was provided through correspondence with Malcolm Scully at Woods Hole Oceanography Institute (WHOI). The salinity models shown throughout this thesis are based on a 50 m resolution model of the estuary. As this thesis was being written, the 50 m resolution model was being updated to a 17 m resolution model. A 50 m resolution does not completely capture all of the water column structure on

sufficient time and space scales necessary for acoustic modeling in a highly constrained, variable environment such as the JRE. A 17 m resolution scale is three times finer than resolution used for this thesis. Bottom topography, bottom roughness and water column structure are also accounted for at a low resolution in the environmental and acoustic models used in this thesis. The TL mechanism, excess attenuation due to bubbles and fish, is also not accounted for in this model. However, the salinity models do demonstrate the variability and complexity of this area and are used in this thesis to demonstrate this and show where these intricacies may be complicating the received signal. Dynamic bottom interaction will change the TL of the source signal as the raytraces refract in response to the water column structure (Lurton 2002). To demonstrate the refraction present in the JRE, a Bellhop3D model of sound signal raytraces were produced of the sound source signal propagation from point S3a. This model ingested the range-dependent parameters of the density of the sea bed, attenuation, and the sediment sound speed adjusted for values of a sandy bottom found in the JRE. Parameters were obtained from Hamilton and Bachman (1982), Hamilton (1980) and Zhou and Zhang (2009). Source depth was set to 4.5 m at point S3a and the temperature and salinity model data were used to produce the expected sound raytraces on 24 April 2019. The bathymetry used for this model was the first model version in 50 m resolution and the bathymetry shows known artifacts of false bathymetric features on the southern boundary of the navigation channel. Nevertheless, the model images demonstrate the refraction of sound out of the acoustic transect during propagation of the front. Figure 20 is the Bellhop3D model of the 1640 Z raytrace on the left and 2000 Z raytrace on the right from 24 April. The bathymetry is shaded in blue to denote deeper depths and shallow depths are in red. The raytraces to the north of the channel run into the north bank of the MMMBT. Figure 20 (a) shows the raytrace almost an hour after high tide, when a bubble cloud is known to be present via radar image analysis. No raytraces are modeled in the middle of the channel and it visualizes the contrast to Figure 20 (b). Figure 20 (b) shows the raytrace at 2000 Z when no frontal bubble cloud is visible via radar analysis.

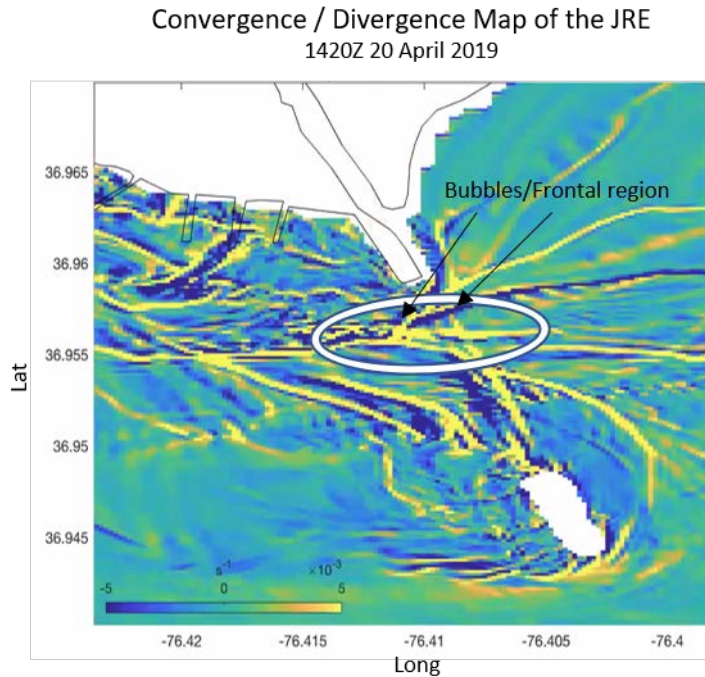


Bellhop3D raytraces of sound source signal from S3a. 1640 Z in the top images show 9 launch beam raytraces from an overhead view (a) and the raytrace model rotated to show propagation through the front during flood tide (b). Images on the bottom show the raytrace during tidal ebb at 2000 Z in the overhead view (c) and rotated to show 3D propagation (d). Adapted from Porter (2016).

Figure 20. Bellhop3D Raytrace from 1630 Z and 2000 Z on 24 April 2019

Figure 21 is a flow divergence and convergence map of the JRE produced with the updated 17 m horizontal resolution. With this second version of the model, more structure of the estuary bottom is captured such as the MMBT trench and the greater detail of the navigation channel. Flow convergence is indicated in yellow and is the location of the TIF and where the bubbles will be subducted. Divergence is indicated in blue. The convergence and divergence regions are dispersed throughout the estuary are indicators of where sound refraction is expected. The figure aids in understanding the complexity of the JRE. It is complicated by the propagating bubble clouds and flow noise previously discussed, and refraction. The acoustic profile from S3a-R4 studied for this thesis is circled in white and

the bubbles and the estuarine front location are notated on the figure. The typical wedge shape of the propagating JRE front is visible in the convergence/divergence map and the strong convergence near the MMMBT is the expected location of bubbles. The frontal pattern visible in Figure 21 is the same shape the TIF is observed in the radar images on 24 April 2019.



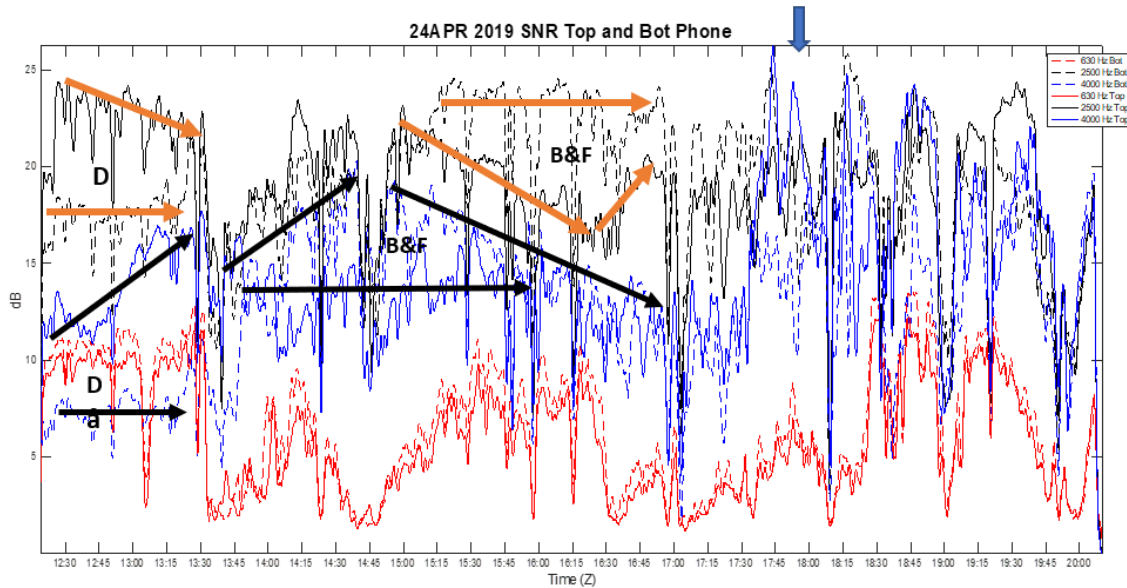
Source: Personal Communication, Malcolm Scully, 23 April 2020, WHOI

Figure 21. Convergence/Divergence of the James River Estuary on 20 April 2019

B. ACOUSTIC SIGNAL

The acoustic signal received at the location of the mini-mooring at R4 was processed with the techniques discussed previously. The one-third octave frequency band center frequencies of 630 Hz, 2500 Hz and 4000 Hz in the top and bottom hydrophone are presented in Figure 22 from 24 April 2019. The high tide is denoted by a blue arrow and structure in the acoustic signal is outlined in black and orange arrows. D is written on the figure to denote where the acoustic structure is responding to possible ducting, and B&F is

printed on the figure to denote where a response to bubbles and fish may be occurring. The low frequency (630 Hz) is about the same between the top and bottom hydrophones over the entire plot. It is less responsive to the changes in the water column and bubbles and fish. It is expected the high frequency is more responsive to bubbles and fish, and it makes sense there is more of a difference between the top and bottom phones in the 2500 Hz and 4000 Hz frequency bands. More energy is also observed on the top phone in comparison to the bottom phone in these mid-frequencies, which suggests ducting. The duct is determined by the gradient via a graph like Figure 22, and the gradient is where the bubbles are expected. Also complicating the signal as the front propagates are the other TL mechanisms that were previously discussed.



Top and bottom hydrophones are compared at 630 Hz, 2500 Hz and 4000 Hz on 24 April 2019 along the acoustic transect. The blue arrow denotes the time of high tide in the data. The black and orange arrows are drawn over notable features in the acoustic structure. Black arrows on the 4000 Hz signal show possible ducting, noted with a D, and possible bubbles and fish interference noted with a B&F. The orange arrows do the same for the 2500 Hz.

Figure 22. Top and Bottom Hydrophone Comparison at 630 Hz, 2500 Hz and 4000 Hz

To further the analysis, Figure 23 provides a comparison of three plots that demonstrate the complications of the received signal. Figure 23a is top hydrophone SNR

that was plotted in Figure 22 with solid lines. The middle plot (b) is a comparison of the broadband Signal Noise Energy (SNE) and Noise Energy (NE). Striations in the NE and any time the NE overtakes the SNE are periods in the data that have been overrun with vessel noise. Black vertical lines through the plots indicate areas where a striation is noticeable. The SNR spectrogram at the 11 1/3-octave band center frequencies is on the bottom, part (c). Shaded boxes on the figure indicate where signal noise has been swamped by passing vessel noise. When vessel noise interferes only with the lower frequencies, the shading extends only to the 630 Hz on the SNR plot, (a). Vessel noise dominates at the lower frequencies more than at the higher frequencies, but when the noise overruns all of the frequency bands due to vessels at very short ranges, the entire plot, (a) through (c), are shaded in blue. Any time the 630 Hz frequency band drops below about 6 dB in Figure 23(a) the signal has been overrun by vessel noise. The 4000 Hz frequency band is useful for analysis purposes throughout most of the data with small interferences in this signal. 4000 Hz is largely above the range of interference from the vessel noise and trends are discernable through the striations.

Before the front comes across the transect, the low frequency is steady at about 10 dB in the 630 Hz frequency band until about 1330 Z where the signal is drowned out by vessel noise. The high frequency, 4000 Hz band, is increasing in energy during this time, which shows potential ducting. Higher frequencies are more readily ducted above the salt wedge and it is expected this would be seen on the top phone first as the front crosses the transect. The 2500 Hz and decreases around the time the front moves in, from about 1445 Z to 1630 Z. There is large increase in the 4000 Hz signal outside the vessel interference from about 1345 Z to 1500 Z. A decrease in the 4000 Hz signal then follows in the bottom phone of 9 dB from 1500 Z to about 1700 Z and a drop of 3 dB is seen in the top phone from 1600 Z to 1700 Z. The decreases are significant, and are an indication of attenuation due to bubbles and fish. The dotted line traces the suggestion the 630 Hz frequency band spectrography through vessel interference. Signal strength suggests an increase through the experimental timeframe signifying a deepening waveguide through the frequency bands.

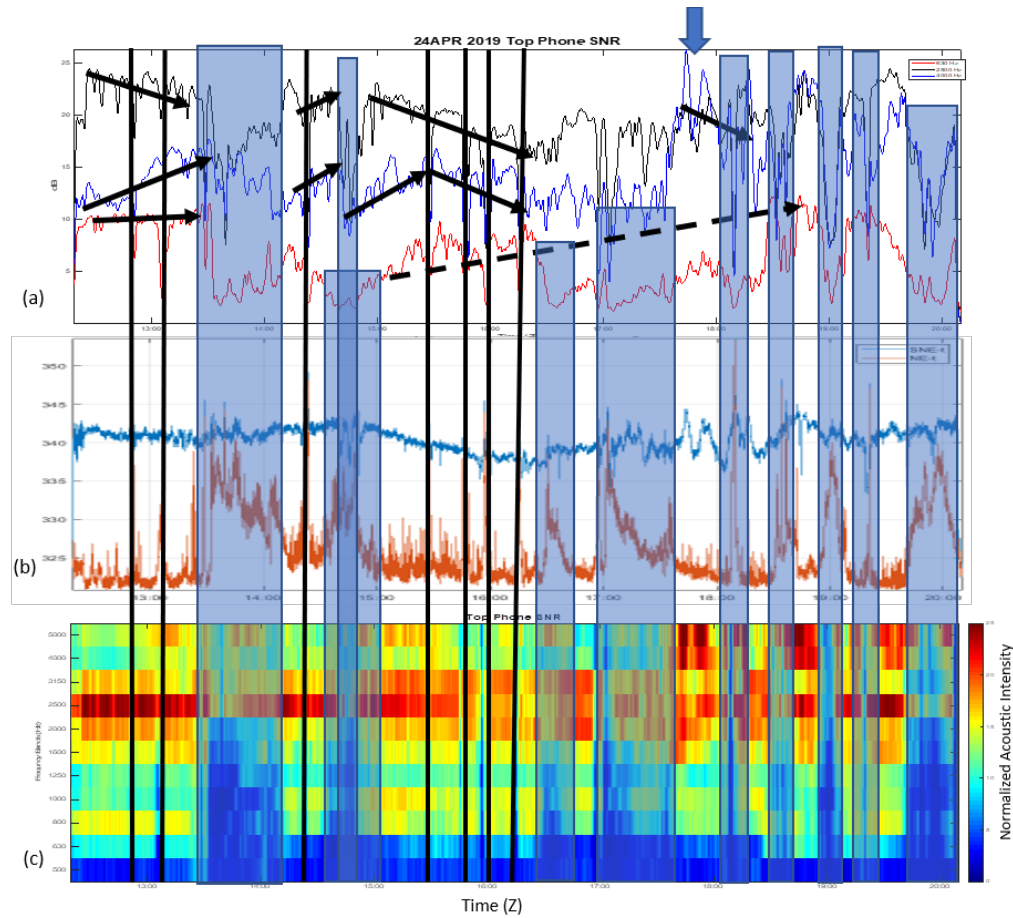
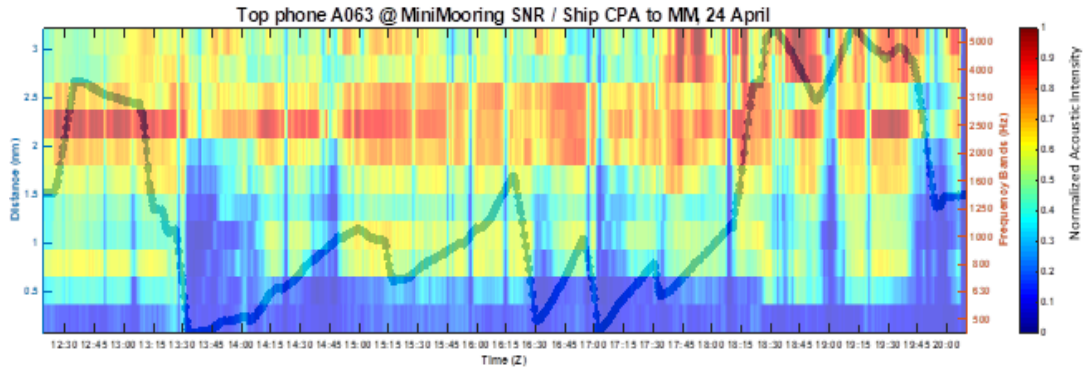


Figure 23 (a) is the top hydrophone SNR on 24 April 2019 in the 630 Hz, 2500 and 4000 Hz frequency bands. Trends in the signal are traced with black arrows. The dotted arrow is suggested trend through vessel interference. Top hydrophone broadband SNE and NE is plotted on (b), and the top hydrophone SNR spectrogram is on the bottom (c). Time periods of vessel interference are highlighted in the blue boxes that extend through the figure to affected frequency bands in (a). Striations in the signal due to passing vessels are traced with a straight black line in (a) - (c). The blue arrow indicates the time of high tide (1754 Z).

Figure 23. Top Phone SNR (a), Top Phone SNE and NE (b), and Top Phone SNR Spectrogram

Figure 22 and 23 show striations throughout the data collection that are traced with a black line on Figure 23. As discussed, the James River Estuary is located in a high-trafficked region of the Chesapeake Bay and as expected, and the striations are strongest in the top of the water column, or in the top hydrophone signal recordings. R/V Virginia was in the vicinity of R4 on 24 April collecting BioSonics data while drifting across the front. Closest point of approach (CPA) to R4 was plotted on top of the top hydrophone power spectral density (PSD) in Figure 24.



Distance from R4 is on the left y-axis, signal-to-noise-energy ratio in the bands of interest on the right y-axis.

Figure 24. Ship CPA to Source vs. SNR PSD on 24 April 2019

Figure 24 shows an R/V Virginia CPA to the MM at R4, which is the cause of the sharp decrease in TL at time 1330Z. Other vessels in the time period of frontal passage came close to R4 and are detectable as highlights in the radar imagery. One or two other vessels passed R4 in the radar images between 1415–1500 Z where the SNE decreases.

Analysis of the variance between the hydrophones in the one-third octave band frequencies was analyzed for signs of frontal passage and TL mechanism interference. The plotted variance was largely useless due to vessel interference. Overall, the variance was more elevated in the top phone than the bottom phone, as expected. Surface duct propagation and bubble cloud attenuation affect the top of the water column more than shallower depths. Regions of frontal passage such as on ebb tide at 1815 show top phone of 2.6 dB at 1815 Z while the variance on the bottom phone reaches 1.9 dB at that time. The variance at 1700 Z is about 1.3 dB on the bottom phone while it is 1 dB on the top phone indicating possible refraction as the front builds. Both these times are within the timeframe highlighted in Figure 22 showing large top phone decrease in signal energy. Elevated variance at flood tide between 1430 Z and 1500 Z also exists.

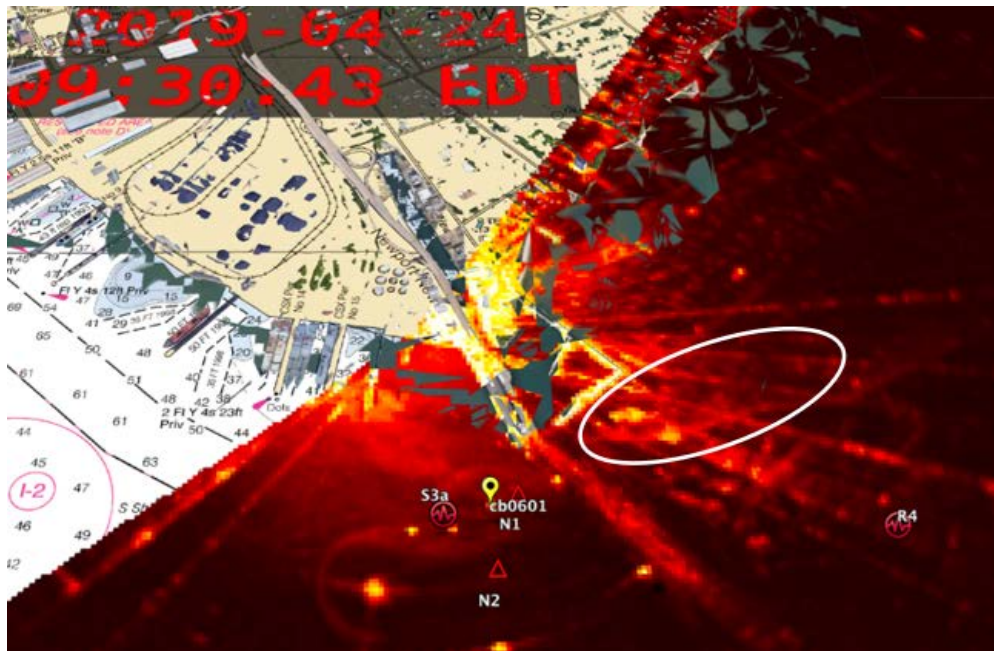
The top and bottom hydrophones are only 3 m apart, therefore, the large amount of fluctuation and difference in the received signal between the top and bottom hydrophones presented in this section indicates significant dynamical processes and mechanisms affecting the oceanographic acoustics. In the following sections the signal patterns outlined

in Figures 22 and 23 will be analyzed with corroborating environmental models and real-time radar and BioSonics data from the time of frontal passage.

C. ENTRANCE OF THE FRONT: DISCUSSION ON SOUND INTENSITY LEVEL BETWEEN 1300 Z AND 1430 Z

Through vessel interference figures 22 and 23 highlighted interesting trends in the received signal from the beginning of data collection to 1430 Z. In this timeframe the front is setting up to the east and north of the transect and begins to propagate toward the MMMBT. Figure 22 annotated a steady 630 Hz frequency band signal from beginning at time 1219 Z to about 1330 Z, and a possible ducting pattern in the signal in the top phone at 2500 Hz. R/V Virginia travels extremely close to R4 and interferes with the signal from about 1330 Z to 1415 Z.

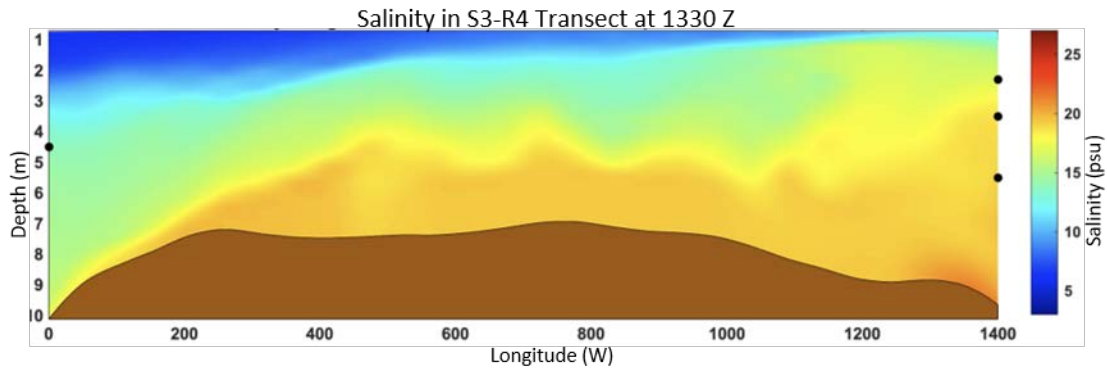
Figure 25 shows the radar image at 1330 Z. The surface expression of the front (TIF) is circled but is not yet in the acoustic transect. However, the 2500 Hz frequency band has dropped by 4 dB from 1219 Z to the time of vessel interference (1330 Z).



Source: Personal Communication, Merrick Haller and Dave Honegger, Oregon State University, 23 April 2020, and adapted from Google Earth Pro.

Figure 25. Radar Image of the acoustic transect at 1330 Z

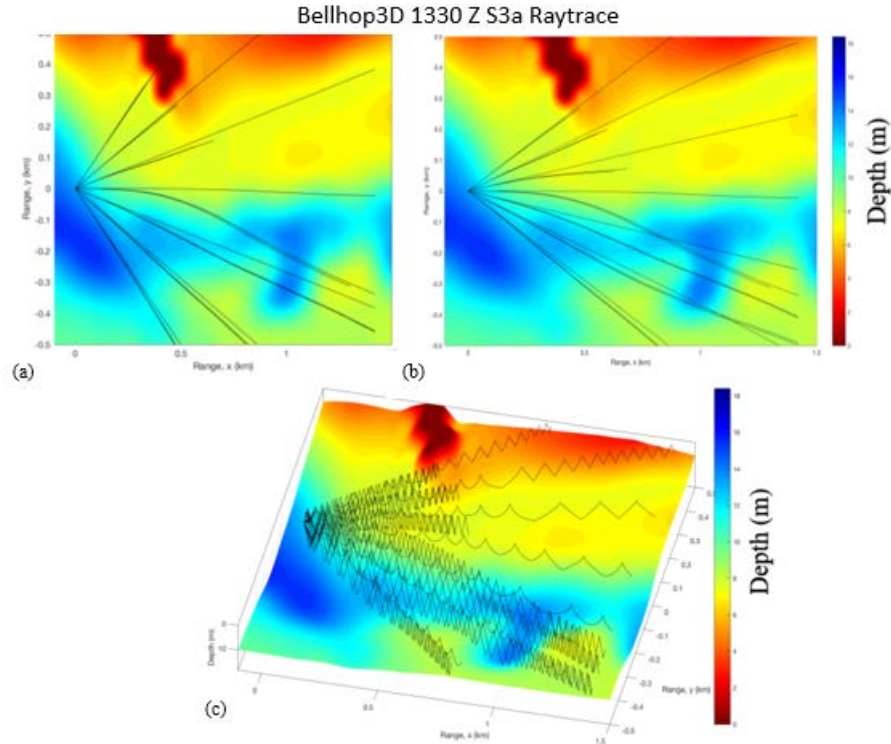
The cause of the drop in SNR in the 2500 Hz frequency band is likely related to the propagating tidal front at depth. This hypothesis is substantiated with the WHOI model data in Figure 26. This model shows that the source is at a depth of relatively fresher water compared to the receivers. The TIF is lagging the salt-wedge front at depth.



The sound source and hydrophone receivers are denoted as black dots on the left and right axis, respectively. Source: Personal Communication, Malcolm Scully, WHOI, 20 April 2020.

Figure 26. Modeled Salinity at 1330 Z in the Acoustic Transect

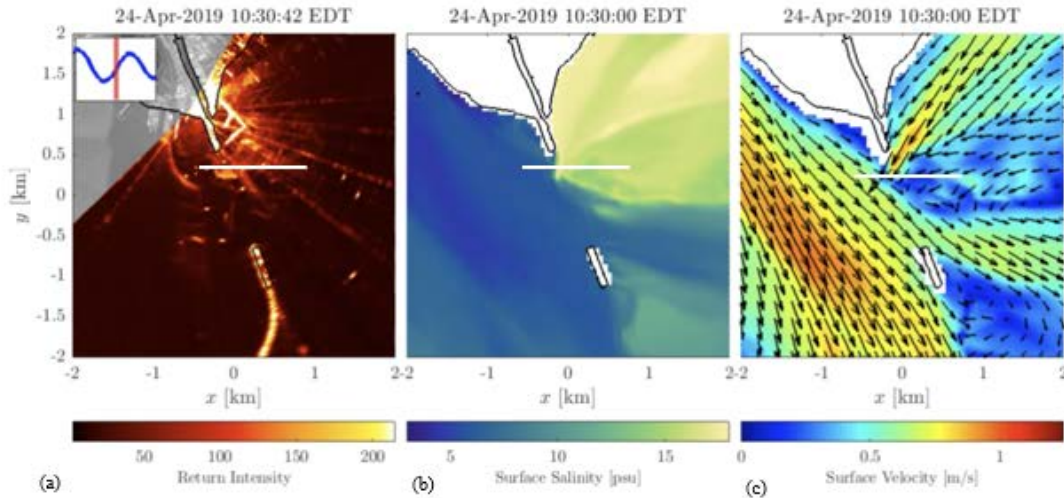
The Bellhop3D raytrace also supports another hypothesis for decreased SNR at 1330 Z. The model shows bending in the signal to the south, away from the receiver at this time in Figure 27(a) - (c). Figure 27(a) is the sound source modeled at a launch angle of 45° and (b) and (c) are modeled at 30° . Figure 27(c) is (b) rotated to show propagation through the channel. These figures demonstrate how the rays refract toward the south of the transect.



Bellhop3D Raytrace models at 45° launch angle (a), and 30° launch angle in (b) and (c). Subplot (c) is the 3D model rotated to show propagation of the signal through the transect. Adapted from Porter (2016).

Figure 27. Bellhop3D Model of Acoustic Transect on 24 April 2019 at 1330Z

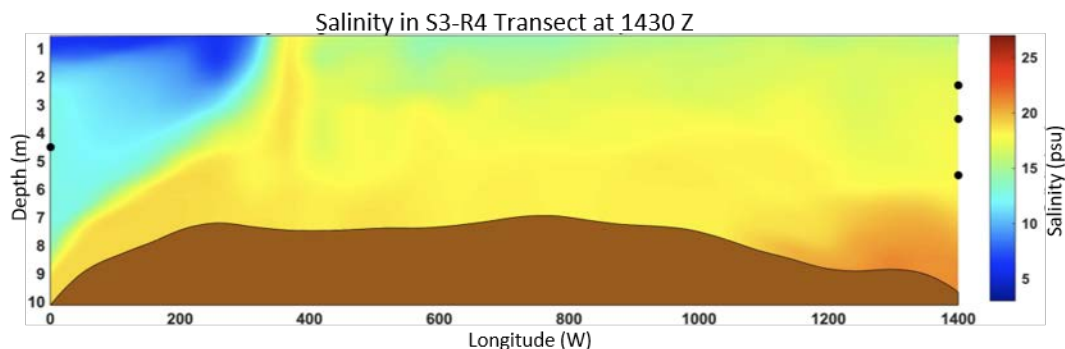
At 1430 Z the TIF is visible just north of the transect, seen in Figure 28 in the left panel. In the middle panel is modeled surface salinity, and the third panel is modeled surface velocity. These figures clearly show that the surface expression is beginning to interact with the transect, while Figures 24 and 26 offer evidence of acoustic variability due to the salt-wedge front at depth prior to 1430 Z. Analysis of the radar images show that the TIF intersects the S3a-R4 transect at about 1420 Z.



The radar image of the transect is highlighted in white at 1430 Z on the left panel (a). In the middle panel is modeled surface salinity (b), and the third panel is modeled surface velocity (c). The acoustic transect is drawn in as a white line on (a) - (c). Location in the tidal cycle is indicated in the upper-left corner of (a). Source: Personal Communication, Malcolm Scully, WHOI, 20 April 2019. Source: Personal Communication, Merrick Haller and Dave Honegger, Oregon State University, 23 April 2020, and adapted from Google Earth Pro.

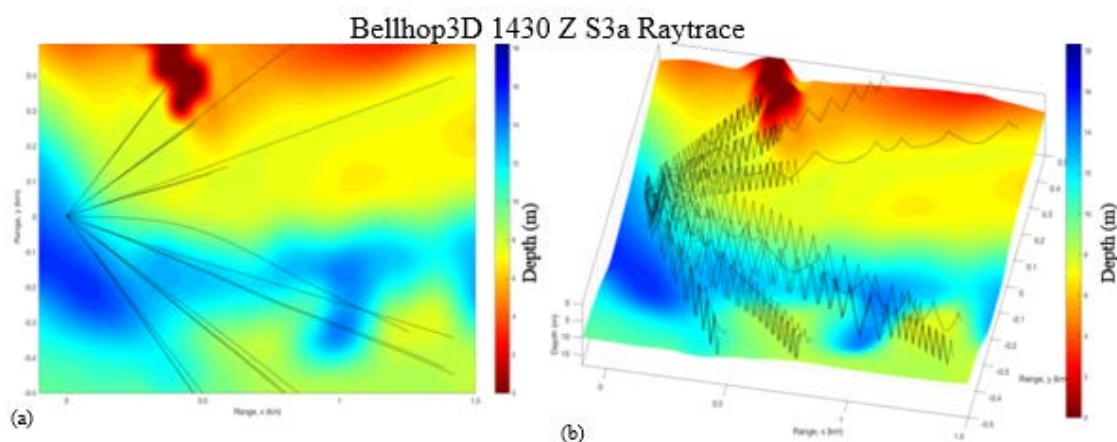
Figure 28. Radar, Modeled Surface Salinity and Modeled Surface Velocity at 1430 Z

For comparison, the acoustic transect salinity is modeled in Figure 29 at 1430 Z to show the underwater salinity structure as the TIF propagates. There is a marked difference between 1330 Z in Figure 26 compared to Figure 29. Figure 30 is the raytrace Bellhop3D model at 1430 Z to compare the difference this salinity propagation makes in the refraction. Figure 30 is modeled at a 45° launch angle. This model shows even less signal propagation through the center of the navigation channel and more refraction of the signal in comparison to the 45° launch angle in Figure 27. This is due to the continued propagation of the front and the increase in the salinity gradient between the propagating front and the area of the estuary to the south of the transect where rays are refracting toward.



The sound source and hydrophone receivers are denoted as black dots on the left and right axis, respectively. Source: Personal Communication, Malcolm Scully, WHOI, 20 April 2020.

Figure 29. Modeled Salinity at 1430 Z at the S3a-R4 Transect at 1430 Z on 24 April 2019

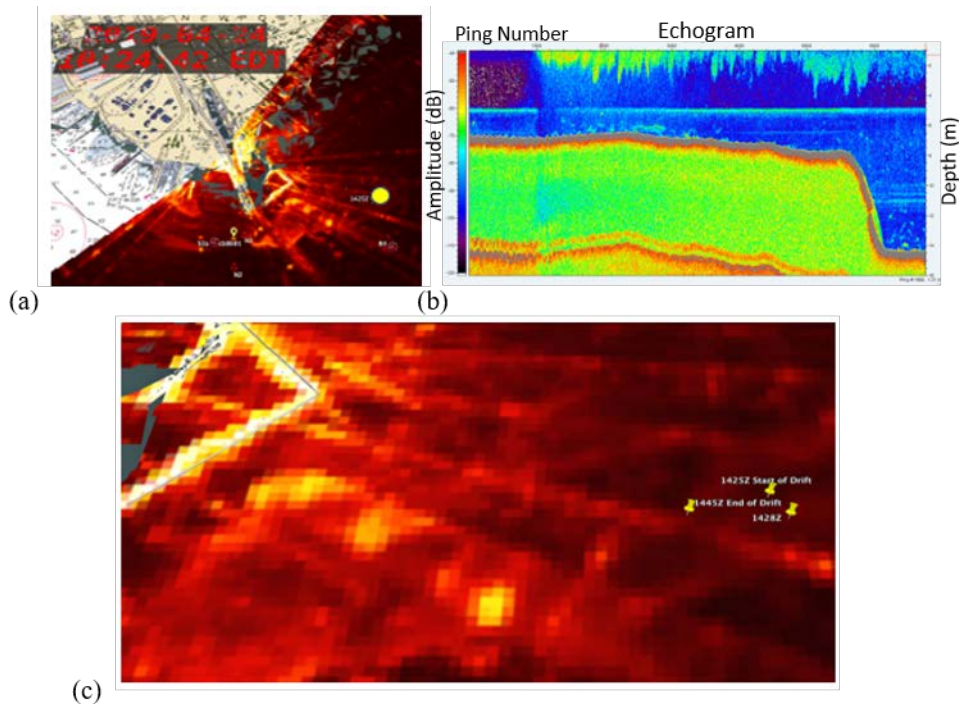


Bellhop3D Raytrace models at 45° launch angle in an overhead view in (a), and in (b) rotated to show propagation of the signal through the transect. Adapted from Porter (2016).

Figure 30. Bellhop3D Model of Acoustic Transect on 24 April 2019 at 1430Z

During this time on 24 April 2019 real-time echosounder BioSonics data was collected east and south of the acoustic transect as R/V Virginia drifted across the front. The ship began drifting across the front shortly after 1400 Z. This data is useful in substantiating model data, radar images, determining placement and depth of the tidal bubble cloud and movement of the salt-wedge front at depth. Several drifts were completed between 1400 Z and 1800 Z. In the BioSonics data presented in this thesis a yellow marker indicates the position of the R/V Virginia on the radar image with each BioSonics picture.

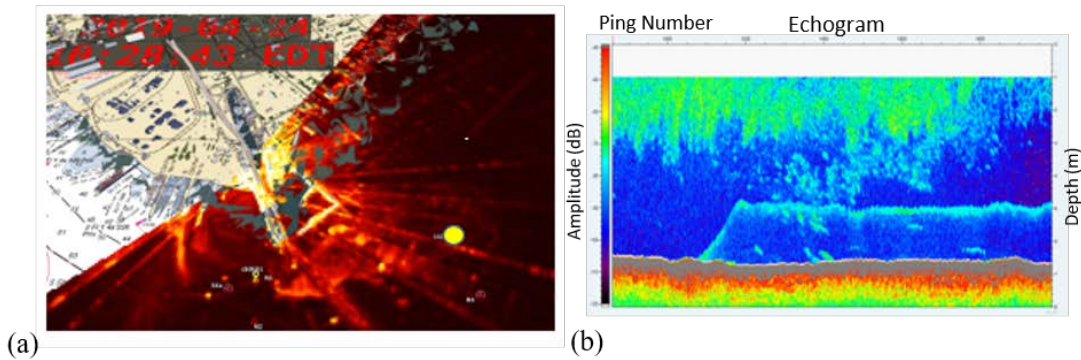
Figure 31 shows an interesting picture the echosounder caught at 1425 Z. The location of R/V Virginia on the radar image at 1425 Z overlaid on Google Earth is in the left panel, and the BioSonics image is in the right panel. At this time the R/V Virginia is floating over frontal bubble clouds, layers of stratified water in the water column and is also capturing the deeper portion of the navigation channel. All of these elements have effect on transmission loss and help explain any signal loss and variability around this time.



R/V Virginia position indicated with a yellow dot on the left (a) and BioSonics data from 1425 Z on the right (b). The positions of R/V Virginia at 1425 Z, 1428 Z and at the end of the drift, 1445 Z, are shown in (c). Source: Personal Communication, Merrick Haller and Dave Honegger, Oregon State University, 23 April 2020, and adapted from Google Earth Pro.

Figure 31. BioSonics Data and R/V Virginia Location on a Drift on 24 April 2019

The image just a few minutes later at 1428 Z displays the transect as the R/V moves just to the south of the yellow indicator in Figure 31 (a). Figure 33 shows a transect in water less than 8 m and a wedge of sediment or bottom layer moving in the direction of the front.



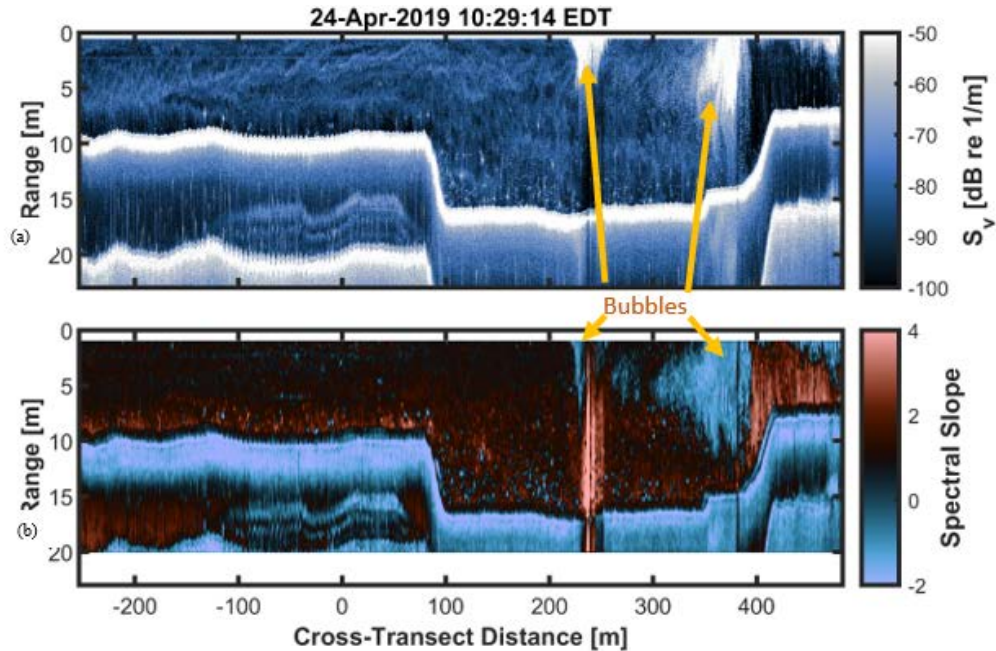
R/V Virginia position indicated with a yellow dot on the left (a) and BioSonics data from 1428 Z on the right (b). Refer to Figure 31(c) for the drift trajectory R/V Virginia was on at this time from 1425 Z to 1445 Z. Source: Personal Communication, Merrick Haller and Dave Honegger, Oregon State University, 23 April 2020, and adapted from Google Earth Pro.

Figure 32. BioSonics Data and Location on 24 April 2019 at 1428 Z

The data presented in Figure 32 is from a position to the north of the S3-R4 transect. Figure 32 (b) shows bubbles subducted to depth that were also noted onboard the ship 200 kHz echosounder and recorded in the experimental log at this time. A wedge of possibly suspended sediment is visible as the salinity front pushes through the estuary. This layer is clearly visible for the next hour in the BioSonics Data. Sediment transport mostly affects the sound levels above 1 kHz according to findings from Bassett et al. (2013). Therefore, it can be reasoned that sediment transport is contributing to the SNR drop in the higher frequencies during frontal transport on 24 April 2019. It also correlates the steady 630 Hz frequency band SNR from 1530 Z to 1630 Z, while the 4000 Hz frequency band and bottom phone 2500 Hz frequency band drops in signal strength.

Figure 33 is more real-time data collected in the JRE of the transect during the week of the experiment by researchers from WHOI on the R/V Tidewater. Figure 33 was taken at 1430 Z. It is a cross-channel transect east of the tunnel trench and crossed the acoustic transect, S3a - R4. The navigation channel is between 100 m and 400 m. This image provides more evidence of bubbles in the TIF, and fish throughout the water column affecting acoustic propagation loss. It is valuable in analysis of the received signal since excess attenuation bubbles and fish cause are not accounted for in the environmental models used in this thesis. Patterns and structure of the bubbles and fish are seen in the

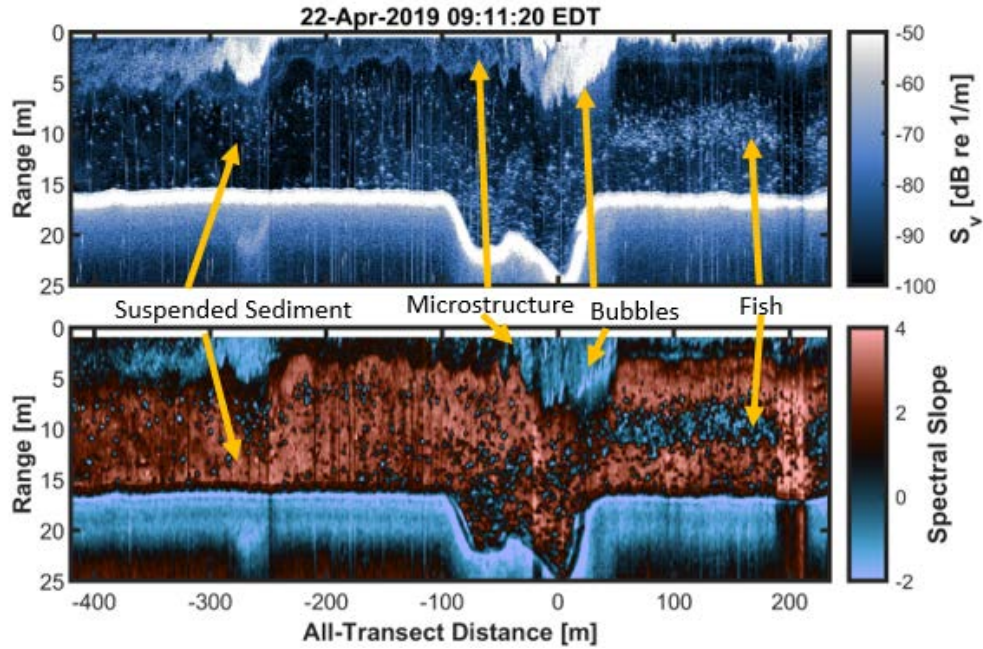
undulating pattern at the surface that is also in the echosounder data on this day. This helps to explain the variability in the received signal at R4.



The top panel (a) is the image produced by the 70 kHz echogram. The bottom panel (b) is produced via spectral fitting. The tunnel ditch is visible between 100 m and 400 m in Cross-Transect Distance. Bubble clouds are visible at the top of the profile. White dots through the water column are fish. Source: Personal Communication, Chris Bassett, WHOI, April 22, 2020.

Figure 33. Cross-Transect High-Frequency Acoustic Backscatter in the JRE at 1430 Z on 24 April 2019

Further evidence was collected during the week via echosounder of sediment transport. The image in Figure 34 from 22 April 2019 depicts a similar structure to Figure 31 and 32, providing evidence to the commonality of suspended sediment and deeply entrained bubble clouds. Figure 34 is an along-channel transect of the R/V Tidewater with the tunnel trench between -100 and 0 m. It is representative of 23 and 24 April 2019.



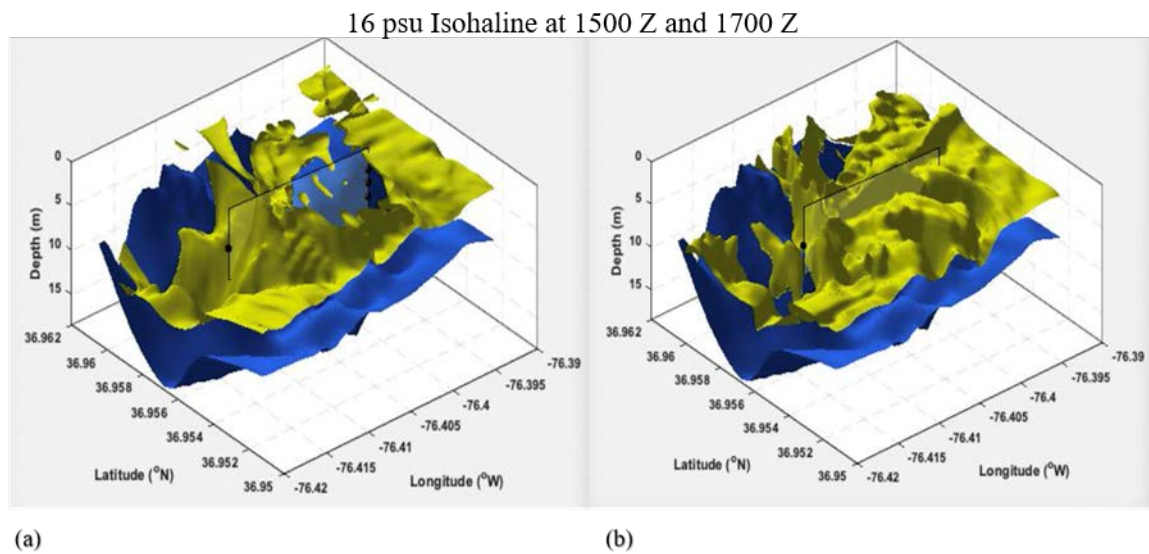
The top panel (a) is the image produced by the 70 kHz echogram. The bottom panel (b) is the produced via spectral fitting. Suspended sediment, microstructure of the water column and bubbles and fish are noted and are visible at the top of the profile. Source: Personal Communication, Chris Bassett, WHOI, April 22, 2020.

Figure 34. Cross-Transect High-Frequency Acoustic Backscatter in the JRE at 1411 Z on 22 April 2019

D. FRONTAL PROPAGATION: DISCUSSION OF SIGNAL BETWEEN 1500Z – 1700Z

Between 1500 Z and 1700 Z the frontal structure continues to propagate through the James River Estuary and north up the James River. The top and bottom phones react to continual oscillations through this period in the isohaline layers, the continuation of rising salinity levels in the transect and a changing environment as the tidal cycle approaches high tide at 1754 Z when the currents relax. There is no such thing as slack water in an estuary as water is always moving at all times in the tidal cycle in this environment. Figures 23 and 24 show the 2500 Hz and 4000 Hz frequency band decrease in top phone signal strength and energy dramatically at this time. The 2500 Hz frequency band decreases by about 8 dB between 1500 Z and 1615 Z. The 4000 Hz frequency band also decreases by almost 7 dB from 19 dB at 1515 Z to 12.4 dB at 1630 Z.

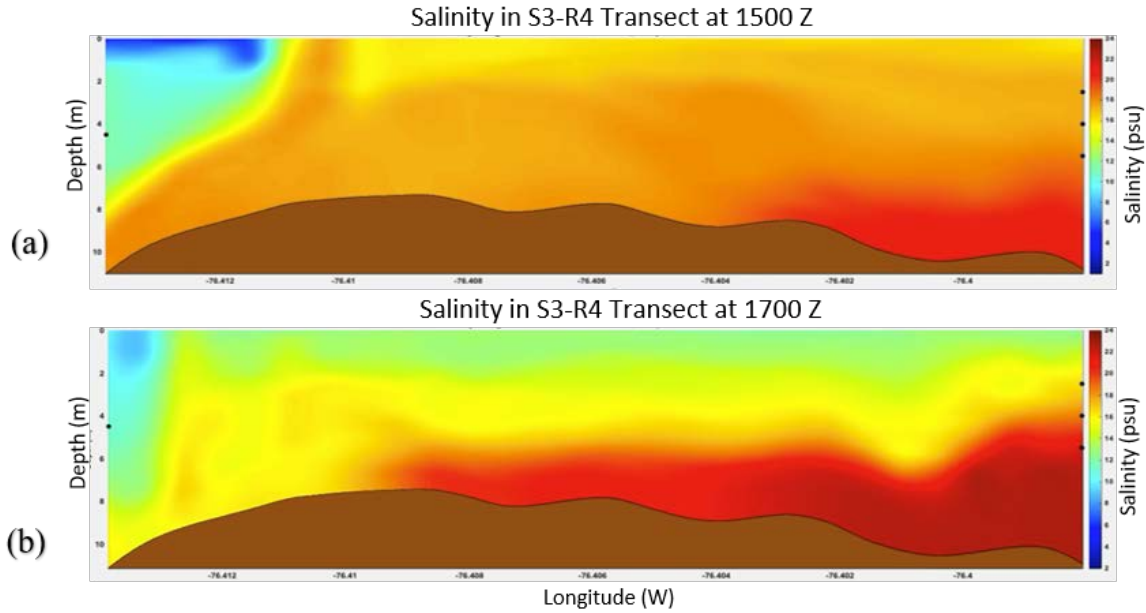
Figure 35 is the 16 psu isohaline layer modeled in the JRE with the WHOI salinity model at times 1500 Z and 1700 Z. The 16 psu halocline layer is modeled in green and the blue contours are the bathymetry of the estuary. The 16 psu isohaline layer was chosen because it is a layer that is representative of the strongest salinity gradient in the water column. The acoustic transect is shown as a clear box in the model. The variability of the 16 psu isohaline layer increases in this time period and fills a large amount of the transect by 1700 Z.



The 16 psu isohaline layer modeled at 1500 Z (a) and 1700 Z (b). The acoustic transect is the clear box and the black dot indicates the position of the source. Source: Personal Communication, Malcolm Scully, WHOI, 20 April 2020.

Figure 35. 16 PSU Isohaline Layer in the Acoustic Transect at 1500 Z and 1700 Z on 24 April 2019

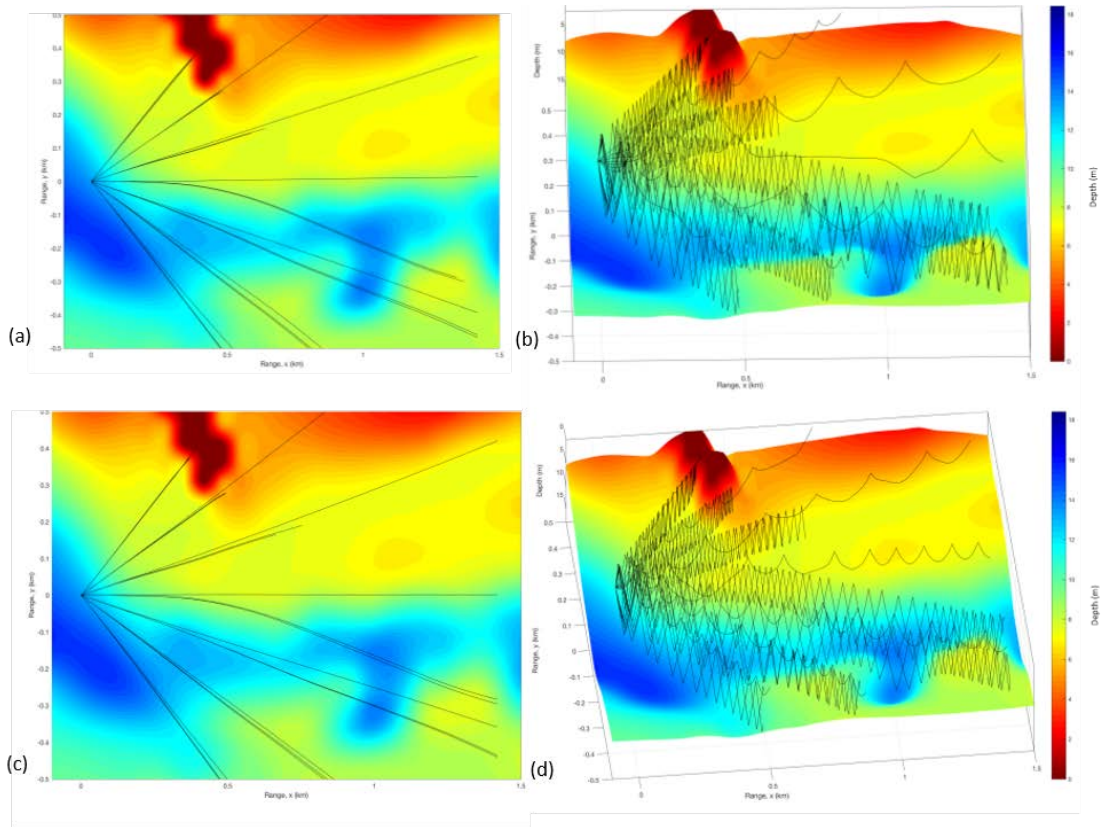
Figure 36 is the modeled salinity of the acoustic transect at 1500 Z and 1700 Z. The source remains in relatively fresh water as the higher salinity propagates through the transect within this timeframe.



Source: Personal Communication, Malcolm Scully, WHOI, 20 April 2020.

Figure 36. Modeled Salinity of the Acoustic Transect at 1500 Z and 1700 Z on 24 April 2019

The layers of salinity support the theory of refraction and ducting as mechanisms of TL from 1500 Z to 1700 Z. Figure 37 is included to show Bellhop3D raytrace images of the transect at 1500 Z and 1700 Z. The overhead views are shown in (a) and (b) while (c) and (d) are rotated to show propagation in a 3D view. The ray in the middle of the transect in Figure 37(d) does not touch the bottom of the navigation channel. This ray is being ducted in the surface layer of lower salinity. Although the ray paths are largely modeled on the same transects at both times, the transect is much more stratified at 1700 Z than 1300 Z, and different ducting patterns are modeled.

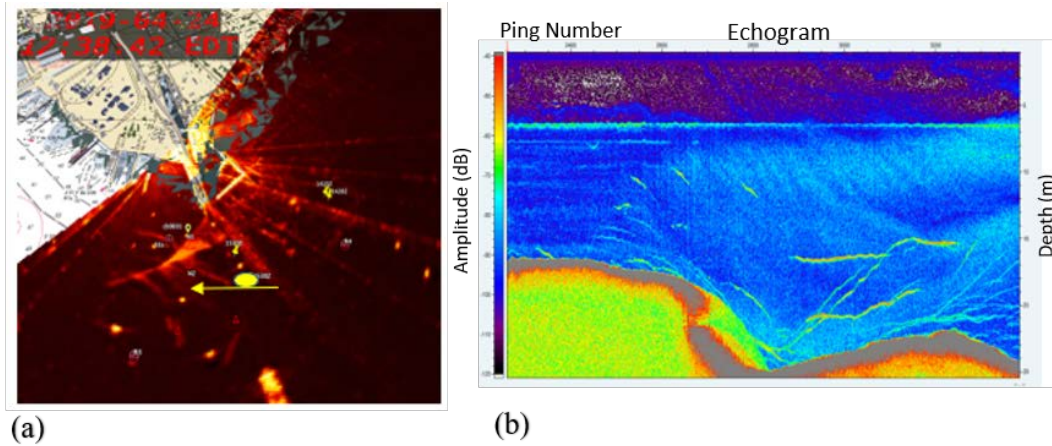


Bellhop3D Raytrace models at 45° launch angle in an overhead view in (a) at 1500 Z, and in (b) at 1700 Z. Subplot (c) and (d) are rotated to show propagation of the signal through the transect at 1500 Z and 1700 Z, respectively. Adapted from Porter (2016).

Figure 37. Bellhop3D Model of Acoustic Transect on 24 April 2019 at 1500 Z and 1700 Z

Flow noise is also occurring. To verify more of the water column structure, Figures 38 and 38 are included. Pictures of the echosounder data clearly display indications of large bubble propagation at this time.

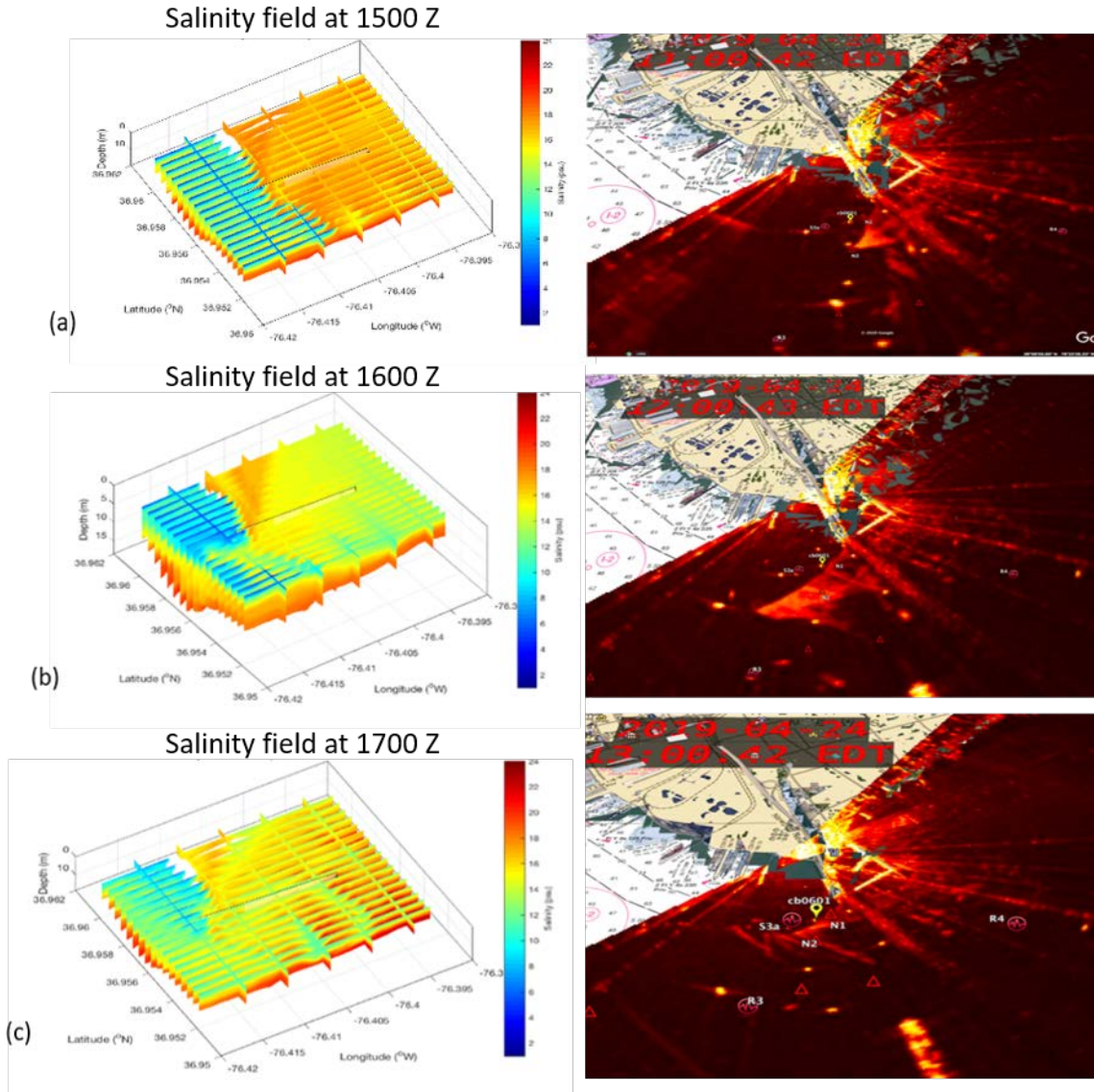
Figure 38 is the BioSonics data at 1638 Z with the radar image from 1638 Z. Stratification in the salinity layers and the visible line between layers is still visible in the echosounder image. There are no bubbles in the BioSonics data but a line of frontal bubble clouds is in the transect and shown via the radar image.



R/V Virginia position indicated with a yellow dot on the radar image on the left (a) and BioSonics data from 1638 Z on the right (b). The yellow arrow is the drift R/V Virginia took from 1631 Z to 1651 Z. Personal Communication, Merrick Haller and Dave Honegger, Oregon State University, 23 April 2020, and adapted from Google Earth Pro.

Figure 38. BioSonics Data and Location on 24 April 2019 at 1638 Z

Figure 39 is a three-panel figure of the radar and modeled salinity of the transect at 1500 Z, 1600 Z and 1700 Z. The salinity models on the right are made of cross and length-wise sections of depicted salinity for a 3D look at the V-shaped front.



The modeled salinity of the acoustic transect at 1500 Z (a), 1600 Z (b) and 1700 Z (c) on the left and associated radar image on the right. Source: Personal Communication, Malcolm Scully, WHOI, 20 April 2020, Personal Communication, Merrick Haller and Dave Honegger, Oregon State University, 23 April 2020, and adapted from Google Earth Pro.

Figure 39. Modeled Salinity and Radar Image from 1500 Z, 1600 Z and 1700 Z on 24 April 2019

At about 1630 Z the frontal expression at the surface begins to weaken as high tide with weakened currents approaches. This is seen through analysis of Figure 38 and radar images between 1600 Z and 1700 Z. This weakening gives reason to the increase in signal energy in the 2500 Hz band due to decreased flow noise. At 1630 Z the signal was at 16.1

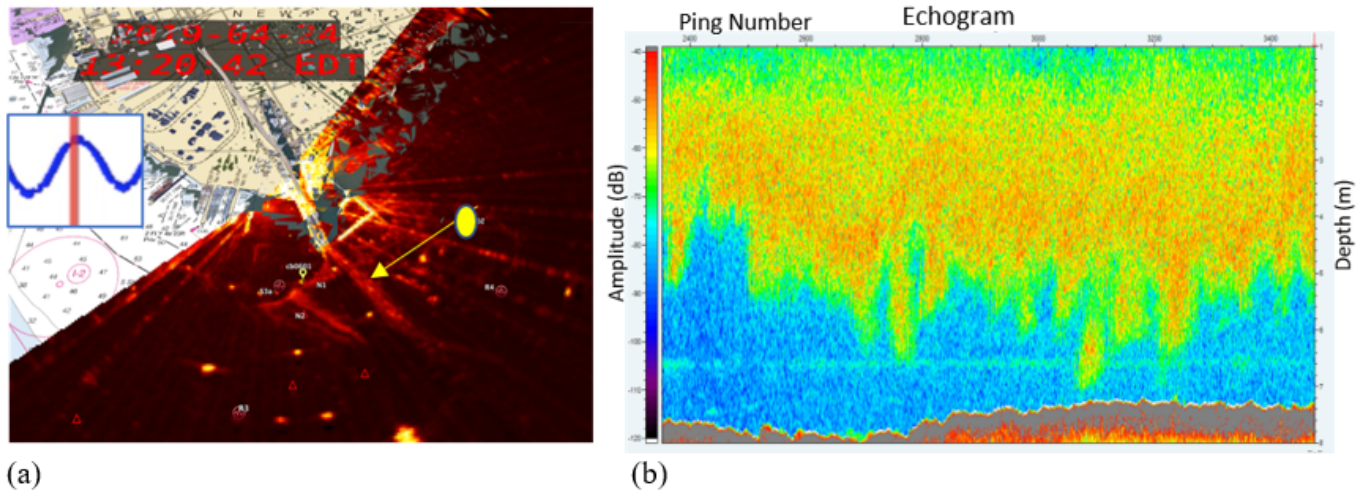
dB and at 1655 Z signal is at 20.4 dB. The decreasing 4000 Hz frequency band signal may still be affected by the remaining bubble cloud as the 2500 Hz band experiences the beginning of a slackening tide.

At 1700Z, the R/V Virginia came within 0.2 nm of the receiver according to the GPS data and radar, accounting for the striation in the SNE spectrogram and the start of mixed signal readings.

E. 1700 Z TO EBB TIDE

At 1700 Z a striation is visible in the data (see Figures 22 and 23), and elevated noise levels interfere with the received signal from about 1700 Z to 1740 Z. Elevated noise above the SNE is a problem from 1830 Z to 1845 Z and again at about 1920 Z. Looking in between these interferences a pattern of oscillating SNR marks the period of time from 1700 Z to the end of the experiment on 24 April 2019. Other than the oscillations, the SNR shows a possible trend of decreasing SNR in the 4000 Hz and 2500 Hz frequency bands, denoted by the arrow on Figure 23 from 1745 Z to about 1820 Z. Other possible signal trends analyzed is the possible increase in SNR in the 630 Hz frequency band denoted by the dotted line on Figure 23 from 1500 Z to 1845 Z. The 630 Hz frequency band signal is muddled by vessel interference through the experimental period but these clear signals are discernable before and after frontal passage. The 630 Hz signal is at 6 dB right after 1500 Z in the top phone, and at 13.4 dB at 1845 Z, a significant increase in energy.

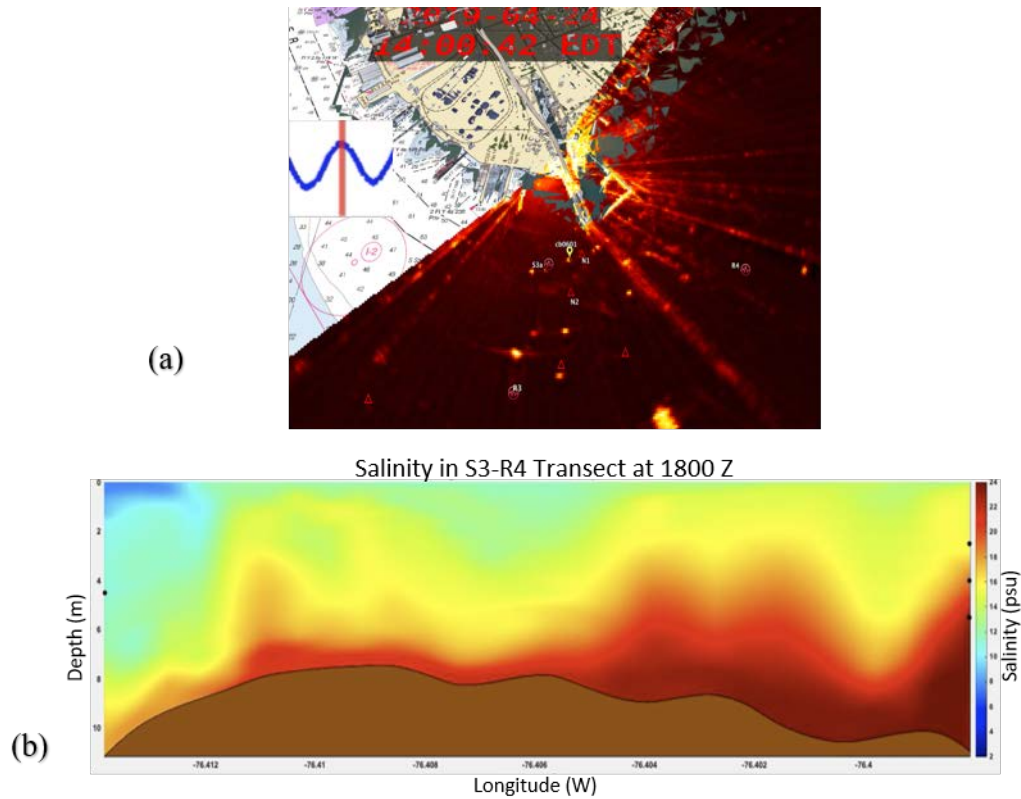
Figure 40(b) is the BioSonics image taken at 1720 Z on the right, and the corresponding position on the radar image at 1720 Z on the left. R/V Virginia's position is marked with a yellow circle and the inset on (a) shows the placement in the tidal cycle. A large bubble cloud is still visible in the water column at 1720 Z, extending almost to the bottom in the area ensonified just to the north of the acoustic transect. In the experimental log it is recorded that R/V Virginia was drifting over bubbles greater than 20' in depth according to the ship sonar. Figure 39(b) validates this with the BioSonics echosounder.



R/V Virginia position indicated with a yellow dot on the radar image on the left (a) and BioSonics data from 1720 Z on the right (b). The inset in (a) shows the 1720 Z tidal cycle position. The yellow arrow shows the drift trajectory the R/V Virginia was on at this time drifting from 1708 Z to 1728 Z. Source: Personal Communication, Merrick Haller and Dave Honegger, Oregon State University, 23 April 2020, and adapted from Google Earth Pro.

Figure 40. BioSonics Data and Location on 24 April 2019 at 1720 Z

A front was recorded at high tide for the day (1754 Z), and over the next 40 minutes the frontal bubble cloud almost disappears from the radar images. The mixed received signal level marked by ups and downs in signal energy strength is reflected in the modeled underwater environment. Distinct salinity layers are modeled in Figure 40 (b) at 1800 Z. The 1800 Z radar image is included for context in (a), with an inset to show the point in the tidal cycle 1800 Z lies.



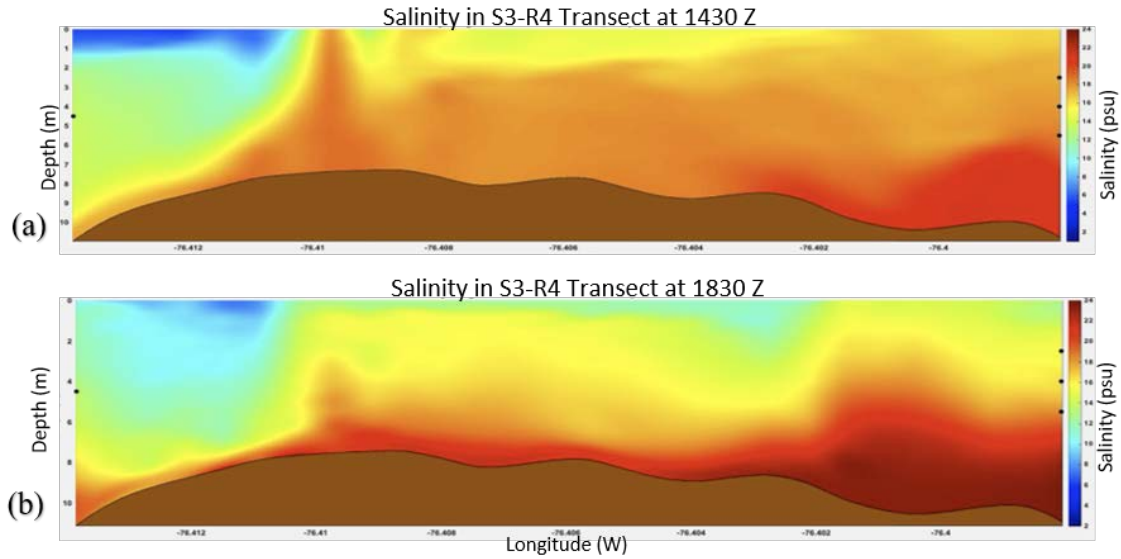
Radar image from 1800 Z in (a) with an inset for tidal cycle reference. Modeled salinity in (b). Source: Personal Communication, Malcolm Scully, WHOI, 20 April 2020, Personal Communication, Merrick Haller and Dave Honegger, Oregon State University, 23 April 2020, and adapted from Google Earth Pro.

Figure 41. Radar and Modeled Salinity on 24 April 2019 at 1800 Z

F. TIDAL FLOOD AND EBB COMPARISON

Figures 22 and 23 show a significant amount of structure in the acoustic signal on tidal flood than compared to the structure of the signal during ebb tide. Figure 42(a) is a comparison of the salinity model in the flood tide at 1430 Z and during the ebb tide at 1830 Z. The leading edge of the front moving west during flood tide is more stratified than the western edge of the front on tidal ebb. Horizontal stratification is greater during tidal ebb than tidal flood. This is expected because the depth-dependent mixing along the salt-wedge front occurs along the western side during flood tide. The portion of the tide that came in behind the front is more stratified, as can be seen in the eastern (right) side of Figure 42 (a) and (b). As the tide relaxes and ebbs, the mixed, less dense water from the western side of the transect rides on top of the more saline, denser water on the bottom. The sharper

horizontal salinity gradients are modeled underwater moving constantly in a wave-like pattern, and this is reflected in the variable sound signal in Figures 22 and 23 at high tide and afterward.

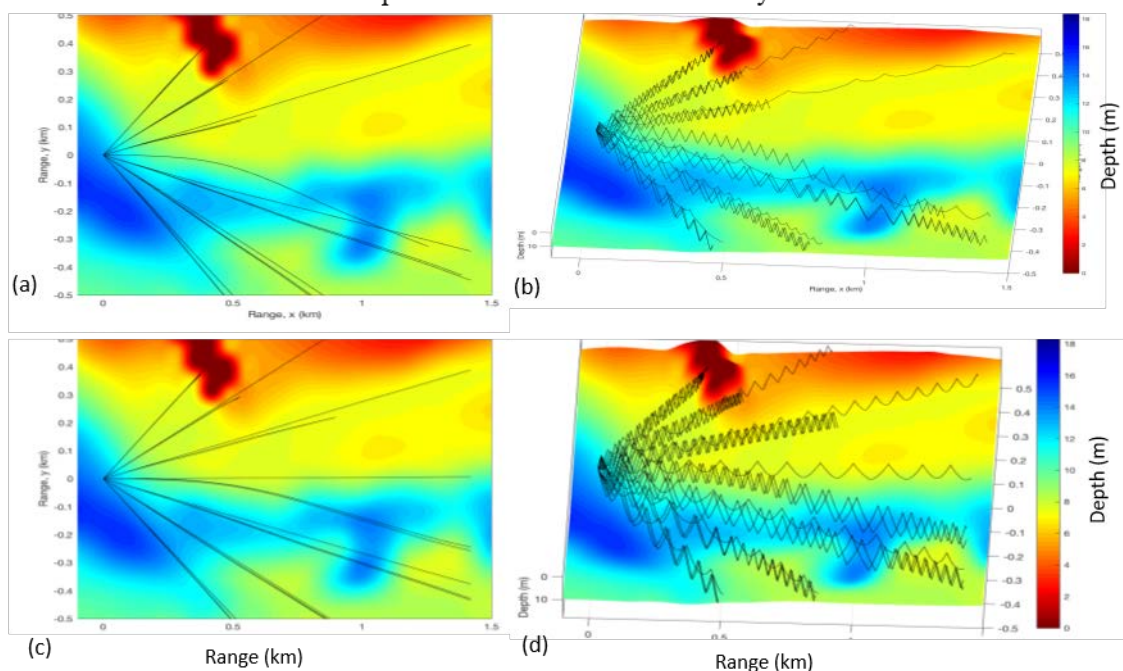


Modeled salinity of the acoustic transect at 1430 Z (a) and 1830 Z (b) representing flood and ebb tide. Source: Personal Communication, Malcolm Scully, WHOI, 20 April 2020.

Figure 42. Modeled Salinity in the Acoustic Transect at 1430 Z and 1830 Z on 24 April 2019

Modeled raytraces of the acoustic transect at 1430 Z and 1830 Z show a difference in the refraction of the source signal. The varying salinity structure at these times will affect the horizontal refraction and out-of-plane bottom scatter, two mechanisms of TL. Also visible in Figure 43 is evidence of ducting to different degrees in the channel depending on propagation and salinity structure. The raytraces at 1830 Z show a little less refraction than at 1430 Z, indicating that greater refraction is present during flood tide. This helps explain greater acoustic signal TL during flood tide in comparison to ebb tide during the experiment.

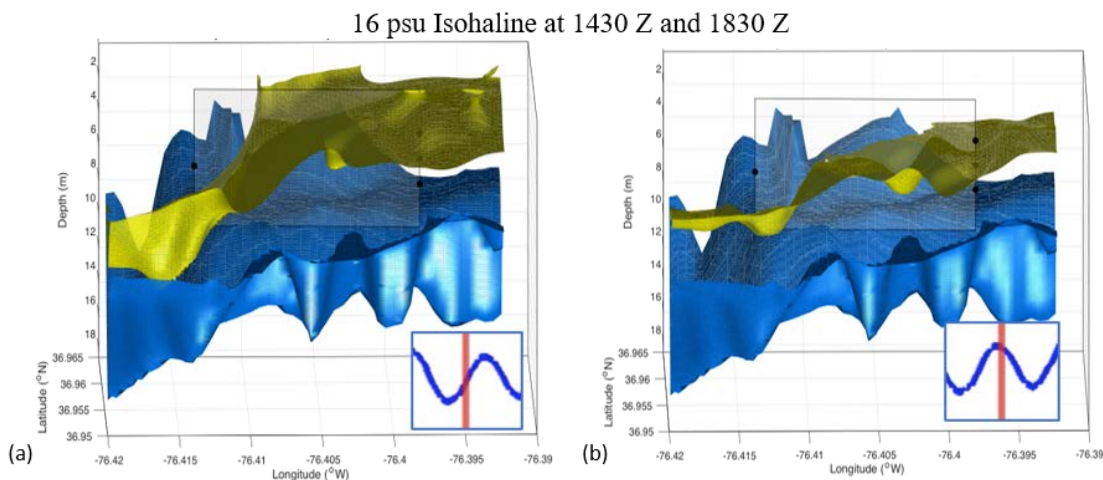
Bellhop3D 1430 Z and 1830 Z S3a Raytrace



Bellhop3D raytraces of sound source signal from S3a. 1430 Z on the top (a) and (b) as an example during flood tide in the overhead and 3D view, respectively. The raytrace model from 1830 Z on the bottom, (c) and (d) are included as an example of ebb tide in the overhead and 3D view, respectively. Adapted from Porter (2016).

Figure 43. Bellhop3D Raytrace from 1430 Z and 1830 Z on 24 April 2019

The 3D structure of the front will affect the refraction of the sound refracts to areas of slower sound speed and lower salinity. The 16 psu isohaline is modeled in Figure 44. This figure shows the lower depth level of the 16 psu isohaline on ebb tide as the fresher river water is allowed to move toward the east toward the Chesapeake Bay. In Figure 44(a) the transect shows greater levels of salinity extending to the north and south of the transect higher in the water column.



16 psu isohaline models of the acoustic transect. The left panel (a) is the model at 1430 Z at flood tide and the model on the right is at 1830 Z (b) at ebb tide. The yellow layer is the 16 psu isohalocline and the blue is the estuarine bathymetry. The insets in both (a) and (b) show the location of the respective figures in the tidal cycle. Source: Personal Communication, Malcolm Scully, WHOI, 20 April 2020

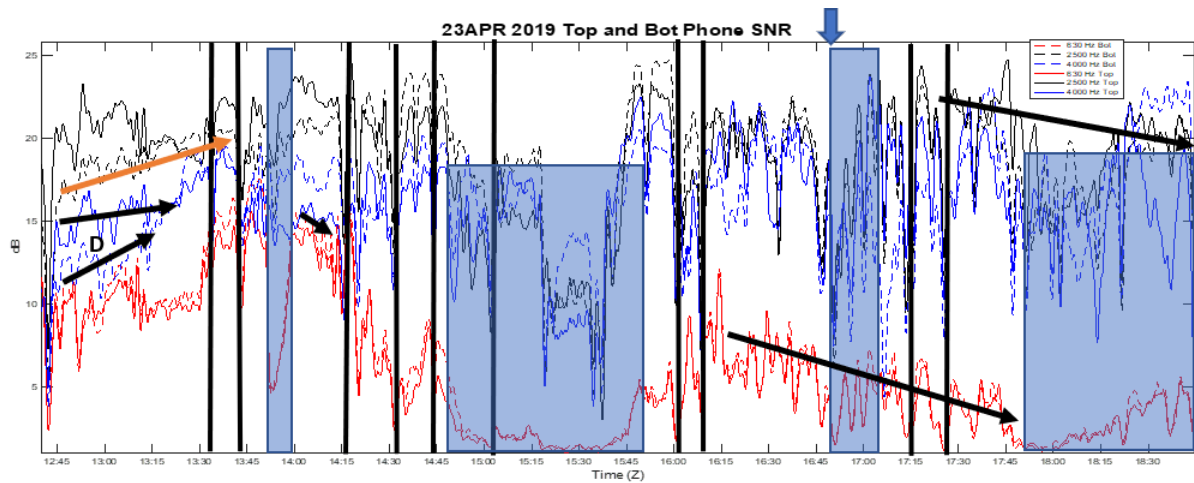
Figure 44. 16 psu Isohaline Salinity Model of the Acoustic Transect at 1430 Z and 1830 Z on 24 April 2019

Shortly after 1800 Z the surface expression of the front is gone from the transect, causing the increase in signal strength. On the spectrogram in Figure 24 (c) there is an overall increase in SNR from roughly 1750 Z to 2000 Z. Signal strength is getting stronger as there is less bubble scattering and absorption in the transect as the front dissipates and the TIF recedes back to the Chesapeake Bay. SNR in Figures 22 and 23 show striations from 1815–2000 Z. SNR remains fairly high, between 18–24 dB in the upper frequencies during this time-frame, with oscillations of about 3–5 dB.

G. COMPARISON OF TRANSMISSION LOSS ON 23 APRIL AND 24 APRIL

A comparison for similarities in the frequency bands on 23 and 24 April follows to demonstrate diurnal trends in the acoustic profile during the tidal cycle. On the 23rd the low tide was at 1108 Z and the high tide was at 1648 Z in comparison to April 24th when the low tide occurred at 1135 Z and the high tide occurred at 1754 Z. Disturbances to the signal strength are notable from about 1515 Z to 1540 Z when the R/V Virginia ran close to the receiver, and again from about 1745 Z to almost the end of the data collection. From the start of data collection to 1500 Z, the SNR increases as the flood tide builds, similar to

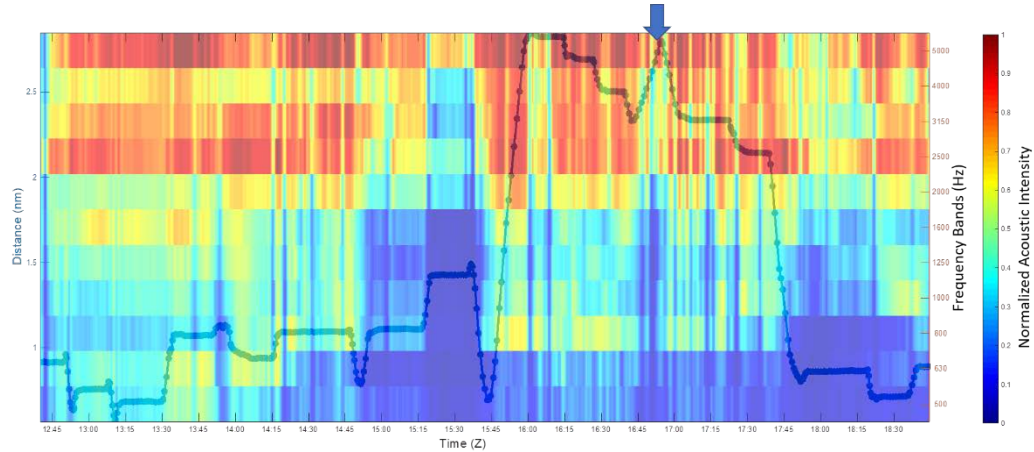
what was seen on the 24th. There is a decrease within this time from 1330 Z to 1415 Z, especially in the lower frequencies, and some interference to blame. Interference decreases SNR from passing vessels with striations, but around 1600 Z, SNR rises and oscillates with the slack tide. Following slack tide there is a decrease in SNR from 1730 Z to 1800 Z in the upper frequencies, and from about 1600 Z to 1800 Z in the 630 Hz frequency band. Figure 45 outlines the patterns and interference on 23 April 2019 found in the SNR data.



The 630 Hz, 2500 and 4000 Hz frequency bands from the bottom phone (dashed line) and top phone. Trends in the signal are traced with black arrows. D annotates possible ducting. The blue boxes and black vertical lines highlight vessel interference and striations in the data, respectively. The blue arrow indicates high tide at 1648 Z.

Figure 45. Top and Bottom Hydrophone SNR in the 630 Hz, 2500 Hz and 4000 Hz Frequency Bands on 23 April 2019

Figure 46 shows where the R/V Virginia CPAs occur in relation to top phone SNR PSD on 23 April 2019. Interference is unfortunately affecting the signal at areas of interest in the flood and ebb tide.



R/V Virginia CPA distance plotted on the top hydrophone SNR. CPA is plotted on the left y-axis and frequency bands on the right y-axis.

Figure 46. Ship CPA to Source vs. SNR PSD on 23 April 2019

Radar images on 23 April 2019 are less informative about the location of the TIF than on 24 April 2019. However, the data is still helpful in analyzing similarities to 24 April in SNR patterns through the tidal cycle. Just as on 24 April, source signal ducting patterns are evident as the front begins propagation. Both 23 April and 24 April 2019 exhibit an initial increase in SNR in the experimental period in the upper frequencies and show evidence of ducting. Although hard to read through vessel interference, there is some evidence of a decrease in signal strength between 1400 Z and 1500 Z on 23 April as was seen on 24 April due to bubbles and fish. On both days a mixed acoustic signal after high tide is evident as a result of fluctuations in the ebbing salinity layers of the water column.

V. CONCLUSIONS

An acoustic field experiment was conducted in the James River Estuary during April 18–25, 2019 to measure the transmission loss patterns in the estuary through an advancing and retreating tidal front. During the experiment, an LFM acoustic signal in the 500 - 5000 Hz band was transmitted by an acoustic source deployed west of NNP and the MMBT at station S3a. The sound signal was observed and recorded at a receiver 1.4 km to the east at station R4. The impact of environmental factors on acoustic propagation was examined through analysis of the received signal, modeled salinity fields, 3D acoustic modeling of raytraces, BioSonics volume scattering (S_v) through the front, and low-angle surface-backscatter radar images.

Environmental characteristics, such as the structure of the underwater bubble clouds, the suspended sediment, stratification of the water column and the presence of fish were captured in the BioSonics echosounder data and throughout the week in echosounder images collected by WHOI researchers on the JRE. This data establishes typical patterns of the JRE throughout the week and corroborates the structures and features the experiment captured on 24 April 2019. Environmental models used for this thesis revealed stratification differences between flood and ebb tide. The leading edge of the front moving west during flood tide is more stratified than this western edge of the front on tidal ebb. During tidal ebb, the mixed, less dense water from the western edge of the front rides on top of the denser water on the bottom. 3D acoustic modeling of raytraces verified refraction of the signal to lower salinity regions during frontal propagation.

Three 1/3 octave frequency bands centered on 630 Hz, 2500 Hz and 4000 Hz were chosen due to their placement at the peaks of the hydrophone calibration curve. Structure of the received acoustic signal is evident on a tidal timescale. The propagation of the V-shaped salt-wedge front begins at depth and the received signal starts to show signs representative of refraction and acoustic ducting into the fresher water near the surface. Significant differences developed between the received signal at the top hydrophone versus the hydrophone at depth. Bellhop3D acoustic modeling was utilized to show the vertical and horizontal refraction of sound energy from the source at S3a. The modeling shows

greater refraction away from the acoustic transect during flood tide than ebb tide. In addition, bubble clouds, fish and suspended sediment are all evident in echosounder images of the propagating front. The received signal shows lower energy level when the front occupies the acoustic transect and higher signal levels with no clear trends as the front moves away from the acoustic transect. A decrease in signal level of about 8 dB was recorded during flood tide from over an hour and 15 minutes; based on analysis of environmental data from radar, echosounder and environmental models, this 8 dB fluctuation was found to be due to attenuation from scattering and absorption by extensive bubble clouds and fish, horizontal sound refraction, ducting, bottom scatter and flow noise.

Future work in the acoustic estuarine environment should continue to quantify each of the TL mechanisms studied in this thesis in relation to a propagating front. Vessel interference complicated received signal data in this experiment. A stronger source signal due to the highly energetic and complex estuarine environment should be considered future studies. The placement of hydrophones throughout the water column at greater separation will aid in the study of ducting and refracting signal. Comparison of these thesis results with the received signal at station R3, where the VLA was measuring received signal, will aid in further characterizing the estuarine environment.

APPENDIX. EXPERIMENTAL LOG

Log entries from 18 April 2019 are as follows:

0229Z – ADCP 2595 tests OK. Downloaded program JRE19.whp.
0242Z – ADCP 7290 tests OK. Downloaded program JRE19.whp.
0257Z – ADCP 5542 tests OK. Downloaded program JRE19.whp.
1159Z – Depart Weems, on the Rappahannock River for the James River.
1835Z – Finished preparing the four moorings. ADCP 2595 on Spider 24, ADCP 7290 on Spider C2.
1845Z – First line out in Bluewater Yachting Center to pick up passenger.
1850Z – Underway
1907Z – Start ADCP 7290 on Spider C2.
1920A – Start ADCP 2595 on Spider 24. Both ADCPs respond correctly; unable to hear over engine noise.
2024Z – Deploy Spider C2 with ADCP 7290 at site N1(on bottom time).
2030Z – Anchors away at N1.
2040Z – Deploy Spider 24 with ADCP 2595 and Acousonde A061 at site N3 (on bottom time).
2057Z – Anchors away at N3.
2151Z – Deploy Station #1 with Acousonde A060 at site N4 (on bottom time).
2158Z – Anchors away at N4.
2225Z – Deploy Station #2 with Acousonde A062 at site N5 (on bottom time).
2230Z – Anchors away at N5.
2255Z – Deploy WHOI Tripod at site N2 (on bottom time).
2301Z – Anchors away at N2.
0004Z (19 April 2019) – First line over at Bluewater Yachting Center.
19 April – Weather conditions prevented the underway of R/V Virginia.

Log entries from 20 April are as follows:

1102Z – R/V Virginia underway.
1153Z – Reupload batteries in Castaway 5002.
1628Z – Coffin deployed.
1641Z – Anchors away at coffin location 36° 58.17N, 076° 26.23W.
1700Z – Coffin Recovered.
1725Z – Coffin deployed with weights and four batteries at 36° 58.061N, 076° 26.506W.
1739Z – Coffin recovered.
1905Z-1910Z – VLA deployed and recovered. Weight too far forward.
1912-1917Z – VLA deployed and recovered. Weight more aft.
2213Z – N1 on deck at 36° 57.404N, 076° 24.819W.
2231Z – N1 in water at 36° 57.418N, 076° 24.662W.
2238Z – Anchors away at N1a at 36° 57.433N, 076° 24.675W.
2340Z – R/V Virginia in port at Bluewater Yachting Center.
Log entries from 21 April are as follows:
0909Z – R/V Virginia underway from Bluewater Yachting Center.

0946Z – Program RBR Solo Temperature #101610 to start at 0955Z, 5 second sampling rate. Estimated logging ends on 12/1/2023.
 1042Z – VLA platform deployed; anchors away (includes RBR Solo Temp #101610). 36° 56.927N, 076 ° 24.944W = R1.
 1239Z – Program RBR Solo Temperature #101596. Set to start at 1250Z. Five second sampling rate. Estimated logging ends on 9/1/2023.
 1250Z – Lubell source in water, broadcast driven by electronics in coffin (on fantail) at 36° 57.363N, 076 ° 24.274W
 1340Z – Fully outfitted coffin anchored and is broadcasting with Acousonde A065 and RBR Solo Temp #101596. 36° 57.518N, 076° 24.855W. A065 depth is 1.5 m.
 1826Z – VLA platform aboard. 36° 56.948N, 076° 24.965W.
 1846Z – Coffin aboard. 36° 57.505N, 076° 24.870W.
 1938Z – In port Bluewater Yachting Center.

Log entries from 22 April are as follows:

0939Z – R/V Virginia underway. “Green” GPS is running.
 0945Z – Preparing coffin for deployment. Replaced signal generator. RBR T sensor #101596: start at 1000Z on 22 April at 5 second sampling rate. Included Acousonde A065.
 1006Z – Preparing RBR T/P for VLA platform. Sensor #082173. Start at 1030Z on 22 April at 2 Hz sampling rate (good until 5/24/2019). Attached 6 in above yellow hydrophone.
 1037Z – RBR T sensor #101610 set for VLA: Start at 1045Z with a 5 second sampling rate (good until 8/2/2023).
 1122Z – Coffin deployed at 36° 57.517N, 076° 24.81W.
 1135Z – VLA deployed at 36° 56.924N, 076° 24.947W.
 1520Z – Banshee deployed; tethered. 36° 57.302N, 076° 26.008W.
 1527Z – Banshee recovered.
 1739Z – Complications with Banshee; the BioSonics connector/cables do not match the connections on the deck box.
 1835Z-1845Z – Second test of Banshee: rearranged weight balance works. However, line got caught on lower deck during deployment.
 1922Z – Coffin recovered at 36° 56.517N, 076° 24.871W.
 1944Z – Recover VLA at 36° 56.924N, 076° 24.947W. Complication: anchor line wrapped around the rudder
 2004Z – After cutting the anchor line near the top (having grappled for the line below the mag) able to pull the line in and clear.
 2107Z – In port Bluewater Yachting Center.

Log entries from 23 April are as follows:

1006Z – R/V Virginia underway from Bluewater Yachting Center.
 1009Z – Prepare RBR Temperature sensor #101596 for the coffin. Starts at 1030Z, sampling rate of 5 seconds, good until 2023.
 1013Z – Prepare RBR Temperature sensor #101610 for the VLA box. Start at 1045Z, sampling rate of 5 seconds, good until 2023.
 1018Z – Prepare RBR Temperature/Pressure sensor #082173 for the Mini Mooring (Acousonde mooring). Start at 1045Z, sampling at 2 Hz, good until 2023.

1105Z – Deploy Acousonde Mini Mooring at 36° 57.057N, 076° 23.951W. Includes Acousondes A063, A064, A066 (surface to bottom) at 2.3 m, 3.5 m, 5.5 m depth.

1133Z – Coffin deployed at 36° 57.361N, 076° 24.859W. Includes Acousonde A065 at 1.5 m depth.

1155Z – VLA deployed at 36° 56.921N, 076° 24.954W.

1232Z – Coffin dragged anchor. Recover coffin at 36° 57.250N, 076° 24.514W.

1241Z – Coffin redeployed 36° 57.362N, 076° 24.865N.

1506Z – Preparing RBR CTD #060315 for bubble contraption. Start at 1530Z on 23 April, end at 1530Z on 25 April. Sample rate 1 Hz. Deployed bubble contraption. See Table 8.

1845Z – Recovered Coffin.

1905Z – Recovered anchor for coffin at 36° 57.33N, 076° 24.866W.

1921Z – Recovered VLA – 36° 56.913N, 076° 24.927W.

2105Z – Recovered Acousonde Mini Mooring – 36° 57.665N, 076° 23.865W.

2208Z – In port Bluewater Yachting Center.

2210Z-2228Z – Deployed and recovered bubble contraption for readings off starboard and port side of ship. See Table 8.

Log entries from 24 April are as follows:

1011Z – Prepare RBR T/P sensor #082173 for VLA. Start at 1030Z. Sampling rate of 2 Hz. Good until 5/24/2019.

1012Z – R/V Virginia underway.

1026Z – Prepare RBR Temperature sensor #101610 for VLA. Start at 1045Z, sampling at 5 seconds. Good until 9/4/2023.

1030Z – Prepare RBR T#101596 for coffin. Start at 1045Z. Five second sampling rate. Good until 9/4/2023.

1034Z – Acousondes on Mini Mooring: A063, A064, A066 (surface to bottom order) at 2.3 m, 3.5 m, 5.5 m. Acousonde on coffin (source): A065. 1.5 m depth

1048Z – Prepare RBR T/P #052170 for Mini Mooring. Start at 1100Z, sampling at 2 Hz. Good until 9/5/2023.

1129Z – Deploy Mini Mooring at R4: 36° 57.677N, 076° 23.877W.

1155Z – Deploy VLA at R3: 36° 56.927N, 076° 24.945W.

1220Z – Deploy coffin at S3a: 36° 57.370N, 076° 24.833W.

1245Z – Started ADCP #5542 on Banshee command program JRE19.whp. All command responses are correct when test (cannot hear audible signals.)

1307Z – ADCP heard pinging.

1347Z – Banshee deployed, hanging from crane, with tether from Banshee bow to ship. Deployed at 36° 57.589N 076° 23.961W.

1400Z – Plan is to drift south; reposition to north, drift across front east of tunnel. Now drifting.

1408Z – Prepare RBR Concerto CTD #60315 for Bubble Contraption. Start at 1415Z, sample rate at 1 Hz. Nominal end time 1415Z on 10/25/19.

1401Z – Turn engine on to move across front doing CTD and dBRD profiles while drifting Banshee nose down in water.

1410Z – Drifting to SW. 200 kHz fathometer shows bubbles to bottom at 24 ft. Picture taken.

1417Z – Turns on engine; picture.

1423Z – Drifting WSW in front of nonlinear current.
 1448Z – Turns on; picture.
 1454Z – Tidewater passed close by; prop wash/wake.
 1456Z – Bubbles to ≥ 34 ft. Picture.
 1459Z – Turns on; Navy ship passed; picture.
 1513Z – Resetting east to sample.
 1520Z – Drifting; set/drift; 246° at 1 kt.
 1527Z – Bubbles to 18 ft.
 1532Z – Resetting.
 1535Z – Drifting, bubbles > 18 ft.
 1546Z – Picture taken.
 1550Z – Resetting.
 1554Z – Drifting; put Banshee in on top of bubbles
 1559Z – Turns on; Resetting.
 1601Z – Drifting.
 1605Z – Bubbles > 20 ft; picture.
 1620Z – Resetting.
 1630Z – Drifting.
 1634Z – Bubbles > 20 ft, just south of 7 ft ledge. Good that there exists bubbles along (northern) wall (of navigation channel); it correlates to S3-R4 acoustic transect.
 1638Z – Bubbles to bottom at 28 ft; picture.
 1645Z – Picture.
 1655Z? – Resetting.
 1603Z – Drifting; dBRd at 14 ft; was 9 ft.
 1715Z – Picture. Bubbles to 20 ft.
 1726Z – Picture.
 1728Z – Resetting.
 1740Z – Drifting. Note: Looks like front recedes north back towards bridge as flood weakens.
 1751Z – Bubbles; picture.
 1755Z – Picture. Bubbles to 18 ft.
 1808Z – Moving to coal piers; picture.
 1811Z – Castaway: as we passed over the I-64 bridge-tunnel into the convergence zone (and deeper water), the tend of the line changed.
 1830Z – Survey tracks next to coal piers; moving SE making way/let Banshee going backwards thru water 180° ; picture.
 1853Z – Turning to NW track.
 1925Z – Finished 2.5 tracks; moving to recover source at S3.
 1934Z – Recovered Banshee at $36^\circ 57.870\text{N}$, $076^\circ 25.888\text{W}$.
 2022Z – Recover the coffin at $36^\circ 57.359\text{N}$, $076^\circ 240820\text{W}$.
 2030Z – Recover VLA at $36^\circ 56.927\text{N}$, $076^\circ 24.945\text{W}$.
 2111Z – Recover Mini Mooring – at $36^\circ 57.538\text{N}$, $076^\circ 23.628\text{W}$.
 2208Z – In port at Bluewater Yachting Center.
 Log entries from 25 April are as follows:
 0958Z – R/V Virginia underway from Bluewater Yachting Center.

1146Z – WHOI tripod aboard at 36° 57.210N, 076° 24.387W.
1223Z – N5 aboard at 36° 57.054N, 076° 24.524W.
1255Z – Spider 25 at N3 aboard at 36° 57.024N, 076° 24.754W.
1327Z – Stanchion #1 at N4 aboard at 36° 56.864N, 076° 25.395W.
1418Z – Spider C2 at N1 aboard at 36° 57.434N, 076° 24.785W.
1543Z – Lines out at Hampton Harbor fish market piers at 37° 01.406N, 076° 20.555W.

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LIST OF REFERENCES

- Bassett, C., J. Thomson, and B. Polagye, 2013: Sediment-generated noise and bed stress in a tidal channel, *J. Geophys. Res. Oceans*, 118(4), <https://doi.org/10.1002/jgrc.20169>.
- Chesapeake Bay Program: Fish Field Guide, 2020: Bay Anchovy. Accessed 15 May 2020, www.chesapeakebay.net/S=0/fieldguide/critter/bay_anchovy#.
- Czerski, H., M. Twardowski, X. Zhang, and S. Vagle, 2011: Resolving size distributions of bubbles with radii less than 30 μm with optical and acoustical methods, *J. Geophys. Res.*, 116, C00H11, <https://doi.org/10.1029/2011JC007177>.
- Diachok, O., 1999: Effects of Absorptivity due to fish on transmission loss in shallow water, *J. Acoust. Soc. Am.*, 105(4), 2107–2128, <https://doi.org/10.1121/1.426816>.
- Diachok, O., 2001: Interpretation of the spectra of energy scattered by dispersed anchovies, *J. Acoust. Soc. Am.*, 110(6), 2917–2923, <https://doi.org/10.1121/1.1413996>.
- Diachok, O., and S. Wales, 2005: Concurrent inversion of geo- and bio-acoustic parameters from transmission loss measurements in the Yellow Sea, *J. Acoust. Soc. Am.*, 117(4), 1965–1976, <https://doi.org/10.1121/1.1862093>.
- Dong, L., D. Wang, K. Wang, S. Li, S. Dong, X. Zhao, T. Akamatsu, and S. Kimura, 2011: Passive acoustic survey of Yangtze finless porpoises using a cargo ship as a moving platform, *J. Acoust. Soc. Am.*, 130(4), 2285–2292.
- Fillinger, L., A. Sutin, and A. Sedunov, 2011: Acoustic ship signature measurements by cross-correlation method, *J. Acoust. Soc. Am.*, 129(2), 774–778.
- Hamilton, E., 1980: Geoacoustic modeling of the sea floor: *J. Acoust. Soc. Am.*, 68(5), 1313–1340.
- Hamilton, E. and R. Bachman, 1982: Sound velocity and related properties of marine sediments: *J. Acoust. Soc. Am.*, 72(6), 1891–1904.
- Haviland-Howell, G., A. Frankel, C. Powell, A. Bocconcelli, R. Herman, and L. Sayigh, 2007: Recreational boating traffic: A chronic source of anthropogenic noise in the Wilmington, North Carolina Intracoastal Waterway, *J. Acoust. Soc. Am.*, 122(1), 151–160.
- Kuo, A.Y, R.J. Byrn, P.V. Hyer, E.P. Ruzecki, and J.M. Brubaker, 1990: Practical application of theory for tidal-intrusion fronts, *J. Waterway, Port, Coastal and Oc. Eng.*, 116(3), 341–361.

- Lavery, A., W. Geyer, and M. Scully, 2013: Broadband acoustic quantification of stratified turbulence, *J. Acoust. Soc. Am.*, 134(1), 40–54.
- Li, M., W. Liu, R. Chant, A. Valle-Levinson, 2017: Flood-ebb and spring-neap variations of lateral circulation in the James River estuary, *Cont. Shelf. Res.*, 148, 9–18.
- Lurton, X., 2002, *An Introduction to Underwater Acoustics*, Praxis Publishing, 302 pp.
- MacLennon, D., 1990: Acoustical measurement of fish abundance, *J. Acoust. Soc. Am.*, 87(1), 1–15, <https://doi.org/10.1121/1.399285>.
- McConnell, S., M. Schilt, and J. Dworski, 1992: Ambient noise measurements from 100 Hz to 80 kHz in an Alaskan fjord, *J. Acoust. Soc. Am.*, 91(4), 1990–2003.
- Military.com Network, 2020: Naval Station Norfolk Base Guide. Accessed 26 April 2020, <https://www.military.com/base-guide/naval-station-norfolk>.
- Nichols, M.M., G.H. Johnson and P.C. Peebles, 1991: Modern sediments and facies model of a microtidal coastal plain estuary, the James Estuary, Virginia, *J. Sed. Petro.*, 61(6), 883–899.
- NOAA NCEI, 2020: Bathymetric Data Viewer. Accessed 01 May 2020, <https://maps.ngdc.noaa.gov/viewers/bathymetry>.
- NOAA, National Ocean Service, Center for Operational Oceanographic Products and Services. Accessed 25 October 2019, <https://co-ops.nos.noaa.gov/waterlevels.html?id=8638610&type=Tide+Data&name=Sewells%20Point&state=VA>.
- Poikonen, A., 2010: High-frequency wind-driven ambient noise in shallow brackish water: Measurements and spectra, *J. Acoust. Soc. Am.*, 128(5), EL242–EL247, <https://doi.org/10.1121/1.3488589>.
- Porter, M., 2019: Beam tracing for two- and three-dimensional problems in ocean acoustics, *J. Acoust. Soc. Am.*, 146(3), 2016–2029.
- Radhakrishnan, S., 2009: Acoustic propagation in the Hudson River Estuary: Analysis of experimental measurements and numerical modeling results, Ph.D. dissertation, Stevens Institute of Technology, 162 pp.
- Reeder, D., 2016: Field observation of low-to-mid-frequency acoustic propagation characteristics of an estuarine salt wedge, *J. Acoust. Soc. Am.*, 139(1), 21–29, <https://doi.org/10.1121/1.4939108>.

- Reeder, D., D. Honnegger, J. Joseph, C. McNeil, T. Rago, and D. Ralston, 2018: Acoustic propagation at low-to-mid-frequencies in the Connecticut River. *Proc. Meet. Acoust.*, Minneapolis, MN, Acoust. Soc. Am., <https://doi.org/10.1121/2.0000811>.
- Roh, H.-S., A. Sutin, and B. Bunin, 2008: Determination of acoustic attenuation in the Hudson River Estuary by means of ship noise observations, *J. Acoust. Soc. Am.*, 123(6), EL139–EL143, <https://doi-org.libproxy.nps.edu/10.1121/1.2908404>.
- Shen, J., J.D. Boon and A.Y. Kuo, 1999: A Modeling Study of a Tidal Intrusion Front and Its Impact on Larval Dispersion in the James River Estuary, Virginia, *Estuaries*, 22(3A), 681–692.
- Stolkin, R., A. Sutin, S. Radhakrishnan, M. Bruno, B. Fullerton, A. Ekimov, and M. Raftery, 2006: Feature based passive acoustic detection of underwater threats, *Proc. SPIE*, Photonics for Port and Harbor Security II, Orlando, FL, Vol. 6204, p. 620408.
- Terrill, E.J. and W.K. Melville, 2000: A broadband acoustic technique for measuring bubble size distributions: Laboratory and shallow water measurements, *J. Atm. Oc. Tech.*, 17, 220–239.
- Virginia Department of Transportation, 2019: Virginia Department of Transportation Flickr. Accessed 14 October 2019, <https://www.flickr.com/photos/vadot>.
- Virginia Institute of Maritime Science, 2020: VIMS Research and Services. Accessed 14 October 2019, https://www.vims.edu/research/facilities/vessels/rv_virginia/index.php.
- Virginia Institute of Maritime Science, 2019: VIMS Research and Services, R/V Virginia. Accessed 15 May 2020, https://www.vims.edu/research/departments/fisheries/programs/multispecies_fisheries_research/species_data/spotted_hake/index.php.
- Vracar, M., and M. Mijic, 2011: Ambient noise in large rivers (L), *J. Acoust. Soc. Am.*, 130(4), 1787–1791, <https://doi.org/10.1121/1.3628666>.
- Wysocki, L., S. Amoser, and F. Ladich, 2007: Diversity of ambient noise in European freshwater habitats: Noise levels, spectral profiles, and impact on fishes, *J. Acoust. Soc. Am.*, 121(5), 2559–2566, <https://doi.org/10.1121/1.2713661>.
- Zhou, J., and X. Zhang, 2009: Low-frequency geoacoustic model for the effective properties of sandy seabottoms, *J. Ac. Soc. Am.*, 125(5), 2847–2866.
- Zhu, X.-H., C. Zhang, Q. Wu, X. Fan, and B. Li, 2010: Acoustic measurement of tidal bores in the Qiantang River, China, *Proc. CISP*, 2010 3rd International Congress on Image and Signal Processing, Yantai, China, CISP, pp. 3839–3843.

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