Configurable UUV Electric and Magnetic Field Sensor Network

Final Report

11/1/2021

Grant Number: N00014-17-1-2152

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coPI's: Michael Anderson, James Frenzel, Eric Wolbrecht, Terrance Soule

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Distribution Statement

Project Summary

Copies of the annual RPPRs for the project are attached for reference.

The major goal for the project was to develop and demonstrate the sensors, data acquisition and other equipment needed to conduct Underwater Electric Potential (UEP) and magnetic signature measurements with a commercial off the shelf (COTS) Unmanned Underwater Vehicle (UUV).

ONR ordered a UUV from Riptide Inc. as the COTS UUV for conducting UEP and magnetic signature measurements in conjunction with this research project. The completed vehicle was not delivered to ONR and Riptide Inc. filed for Chapter 7 bankruptcy on July 5th, 2019. BAE Systems acquired Riptide and stated their intention to fulfill the original order to ONR. But the vehicle was not delivered to ONR and was subsequently unavailable for use. In order to acquire a COTS UUV for this project the decision was made to use unspent travel/testing funds to purchase a nose and tail cone from BAE Systems to combine with the sensor and battery sections purchased in 2018. After receiving permission from ONR, a nose and tail cone were ordered from BAE Systems with the down payment being received on September 3rd, 2019. The sections were delivered to the UI on February 24th, 2020. These sections were combined to make a complete Riptide 1MP, see Figure 1.3 in the 2019 RPPR, for use in field testing.

The project was successful in demonstrating the use of UI research UUVs to make UEP and magnetic signature measurements in an ocean environment. Field testing at SFOMF successfully demonstrated the UUVs could make magnetic field measurements with a noise floor in the 5 n-Tesla range. The UI research team developed an electric field sensor for making the UEP measurements. After several design iterations and tests the final version of the electric field sensor is a 3” diameter ball sensor with 3-axis Ag/AgCl electrode pairs featuring an UI designed embedded low-noise pre-amplifier. The UI team also investigated and developed a prototype packed bed carbon electrode sensor.

The approach taken for measuring magnetic and electric field data with the Riptide UUV has primarily focused on the development of the Stand Alone Sensor Module (SASM) which could be mounted to any COTS UUV and a NI-DAQ based system housed in the instrumentation payload section as a back-up should the SASM prove ineffective. The waterproof SASM has been constructed and tested both in the UI laboratory setting and in-water at ARD mounted to a UI AUV. The SASM is capable of recording six channels of 24-bit data at 5K SPS allowing simultaneous recording of the internal Billingsley triaxial fluxgate magnetometer and the UI developed three axis electric field sensor. In addition, the SASM includes a Memsense IMU with a recording rate of 100 SPS. This system is powered by a minimum of four standard 9V batteries and can be mounted onto almost any COTS UUV. The SASM is 30 inches in length and 2.5 inches in diameter.

The final version of the SASM successfully demonstrated a noise floor of less than 1 uV_{rms}/m with Ag/AgCl electrodes in tank tests at the UI.

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2017 RPPR Report

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Accomplishments

What were the major goals and objectives of the project?

- Assemble UUVs (Unmanned Underwater Vehicle) capable of performing electric and magnetic field surveys of naval vessels.
- Perform electric field survey of surface vessel in salt water environment at the South Florida Ocean Test Facility (SFOMF).
- Assess the feasibility of UUV underwater electric potential (UEP) survey by comparing UUV-acquired measurements to equivalent measurements with a static array.

What was accomplished towards achieving these goals?

1. Development of Spherical UEP (Underwater Electric Potential) Sensors.
   a. Two new 3" diameter UEP sensor have been fabricated. A photograph of one of the sensors is shown in Figure 1. The sensors consist of three Ag/AgCl electrode pairs, embedded on orthogonal axes on the surface of a polymer sphere. Also embedded in the sphere is a

Figure 1. New 3" ball electric field transducer. In this photo, the transducer is suspended in a salt-water tank for performance measurements.

three-channel pre-amplifier with an adjustable gain.

b. Noise-floor tests of one of the new UEP sensor was conducted in a salt-water tank at UI. The results of one of these tests is shown in Figure 2. In the upper three plots, the time-series of raw voltage at the pre-amplifier output has been adjusted with the pre-amplifier gain, electrode separation, and sensor shape-factor to take units of UEP (μV/m), and has been low-pass filtered at a frequency of 20 Hz. The lower plot in Figure 2 shows that amplitude spectral density of each channel. From the time-series, and the amplitude spectral density, a noise floor of ~0.5 μV/m was observed.

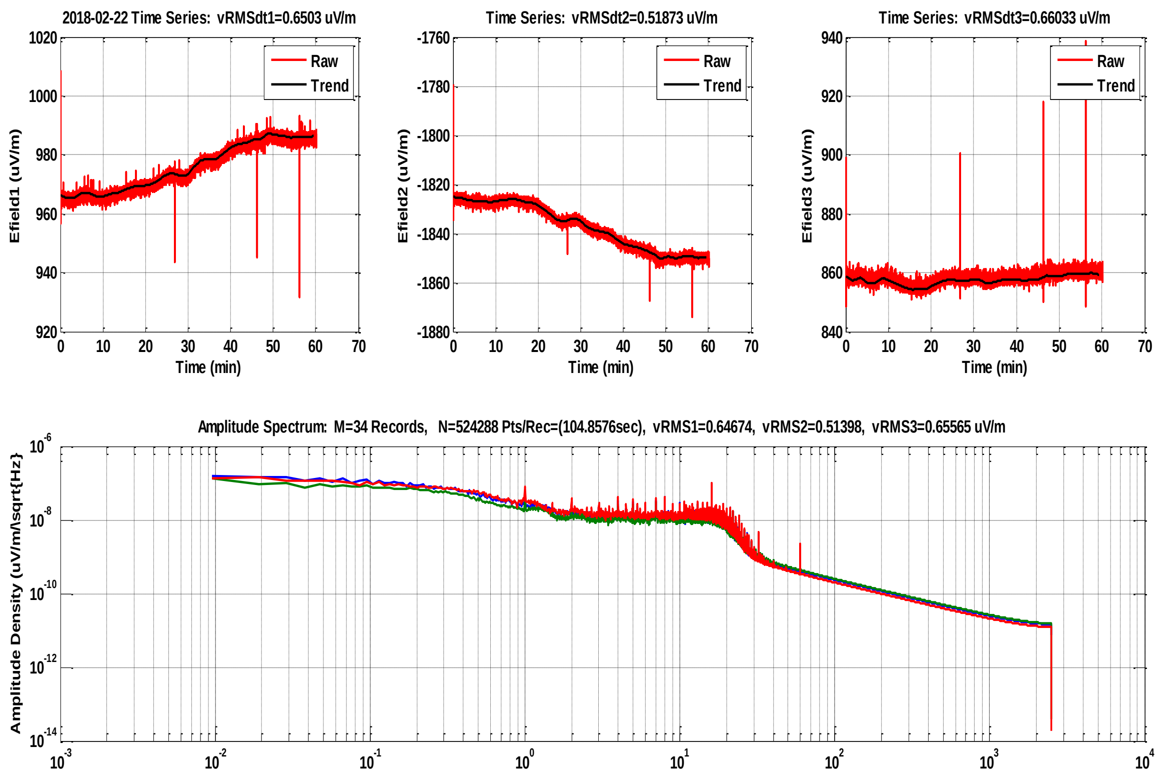

Figure 2. Noise-floor measurements with 3" diameter spherical electric field sensor. (Upper)- Raw voltage from each channel, adjusted to units of electric field, and low-pass filtered at 20 Hz, (Lower)- Amplitude spectral density for each channel.

2. <u>Development of DAQ (Data Acquisition System) for Riptide UUV.</u>
   a. A design for a system that will acquire magnetic and UEP measurement, and angular orientation on a Riptide UUV has been completed. The Riptide UUV is a 7.5" diameter vehicle sold and manufactured by Riptide Autonomous Solutions. A diagram of the Riptide vehicle with UI (University of Idaho) modifications is shown in Figure 3. UI modifications include the 25.5" long Payload Section, a 12" long Battery Section, an ultra-short baseline (USBL) acoustic transponder, and a spherically-shaped UEP sensor. Based upon this design, procurement of the Riptide components is in process through UI Purchasing. Our understanding is that delivery will take place mid-June 2018.

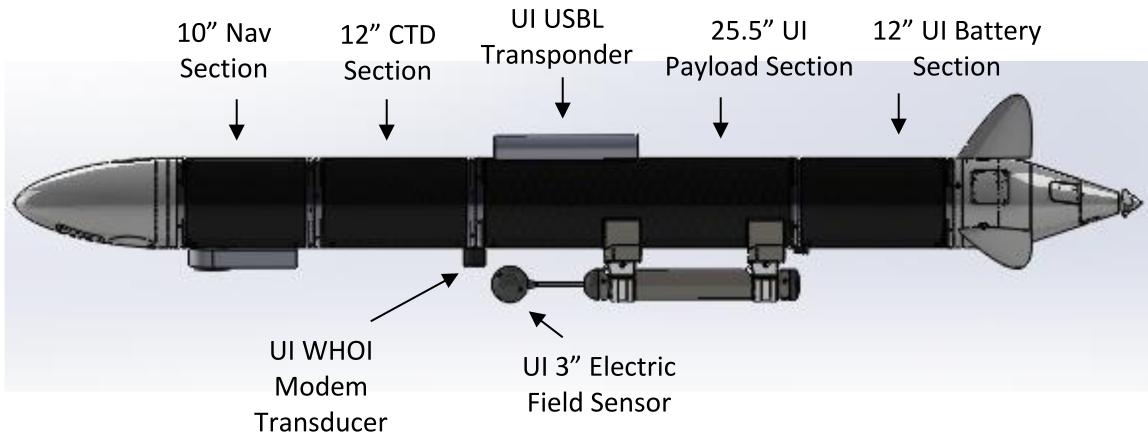

Figure 3. Riptide vehicle with UI modifications.

b. The UI modifications to the Riptide include the presence of UEP and magnetic field sensors, an IMU to measure sensor orientation, an acoustic modem, microcontrollers, miniature computer, and a National Instruments data acquisition system. The purpose of these components is to record data and facilitate testing. A photograph of the components that are to be placed in the 25.5” long UI Payload Section is shown in Figure 4 with a 7” ID PVC tube used for mockup purposes.

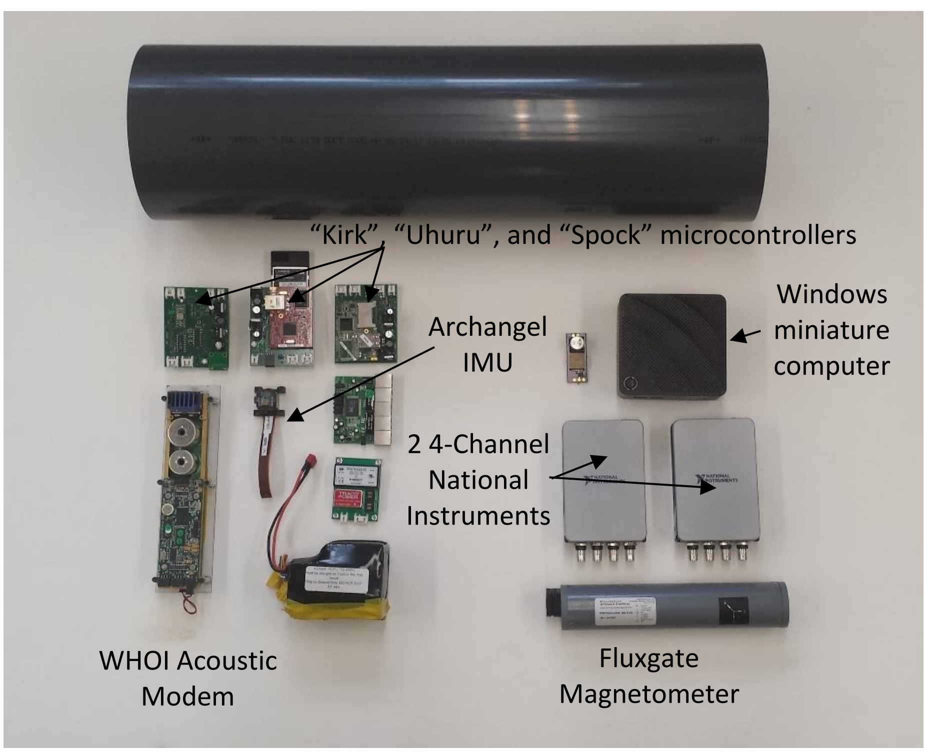

Figure 4. Components in UI Payload Section. Black tube above is used for mockup purposes.

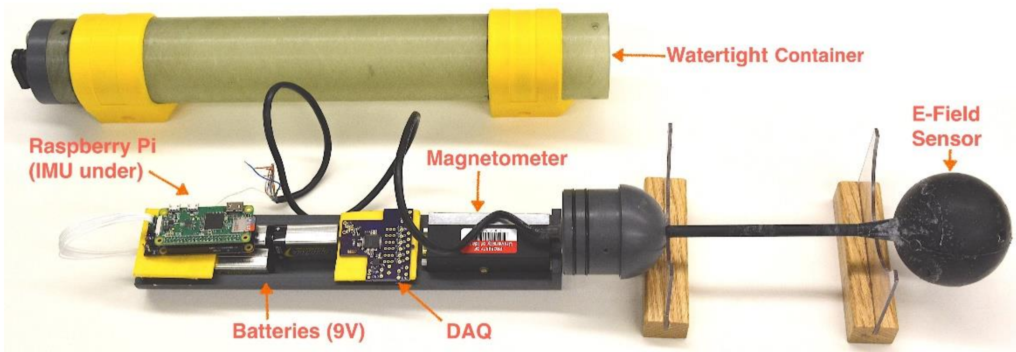

Figure 5. Stand-alone electric- and magnetic-field measurement unit. The water-tight container is 2.5" diameter and ~18" long. The entire unit, including E-field sensor, is 27" long.

3. Development of a Stand-Alone Sensor Module.
   a. A stand-alone unit capable of measuring electric and magnetic field, intended to be installed onto any UUV, is almost complete. The stand-alone system is designed to operate without any electronic connection to the UUV, although provision is made to communicate with an UUV with a serial interface if available.
   b. Components of the system in the water-tight container are shown in Figure 5. This system is capable of digitizing pseudo-differential 8-channels with 24-bit resolution at speeds up to 2kSamp/sec. The electronic components have been successfully tested on the bench with UEP and magnetic sensors. An example measurement of electric and magnetic field is shown in Figures 6 and 7. These measurements were performed to check the function of the DAQ unit, and have as-yet not been quantified as to accuracy or precision. Presently, bench testing and mechanical assembly continues.
4. Development of a GUITAR Carbon Sensor for Measurement of UEP
   a. GUITAR, an allotrope of carbon discovered at the UI by Dr. Frank Chen and his research team, is being evaluated as a UEP sensor. The sensor consists of a GUITAR-coated halloysite powder contained within a polylactic acid (PLA) polymer perforated tube via a nylon mesh screen. The active material surrounds a graphite collector rod which is mechanically and electrically attached to a SEACON connector via silver epoxy. The SEACON connector is mechanically and chemically bonded to a polymer cap which fits over the top of the perforated tube. Another cap fits over the bottom of the tube. The caps are bonded to the tube with epoxy and a polyurethane filler occupies the interior space of both caps, thus retaining the active material in place within the tube (Figures 8 and 9).
   b. The noise floor of the GUITAR electrode was measured in a salt water testing tank and found to be comparable to that of the Ag/AgCl electrodes, the alternate UEP sensor being examined. While the GUITAR electrode has a higher noise floor than the Ag/AgCl, it is within an order of magnitude of the Ag/AgCl noise floor (Figure 10). The UEP frequency response of the GUITAR electrode was also tested at 0.1, 1, 10, 100, and 1000 Hz. The UEP was generated using an AC current generator passing a

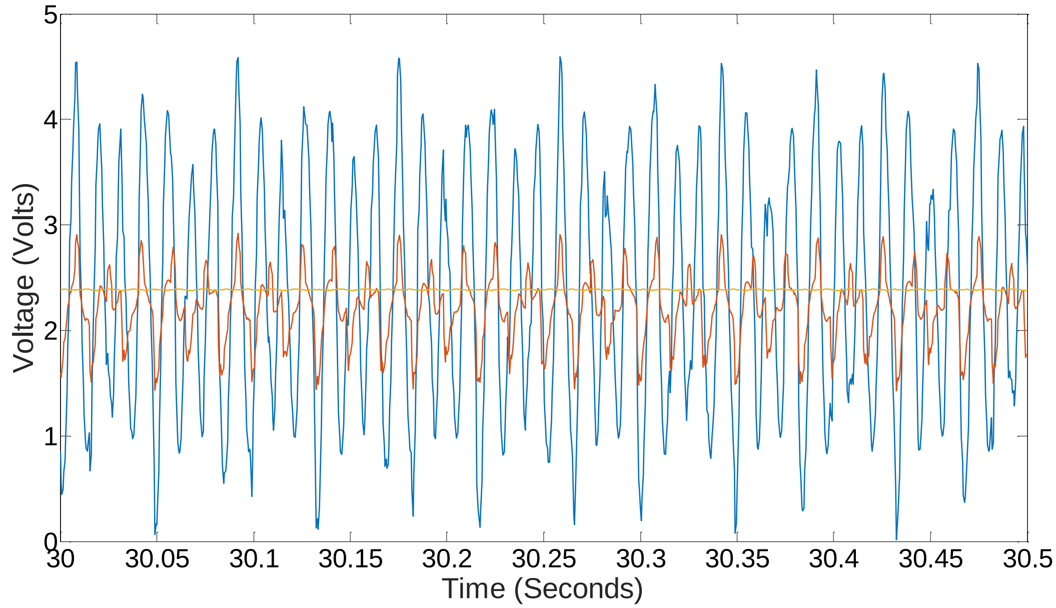

Figure 6. Sample measurements of signal from electric field sensor acquired by the UI DAQ unit.

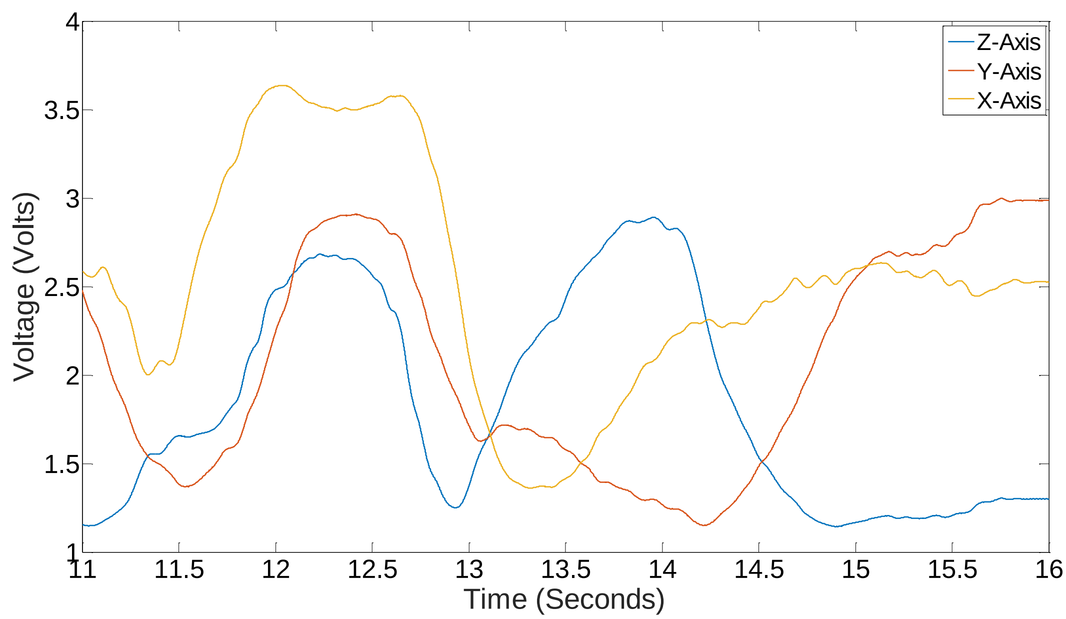

Figure 7. Example measurements of signal from flux-gate magnetometer acquired with UI DAQ unit.

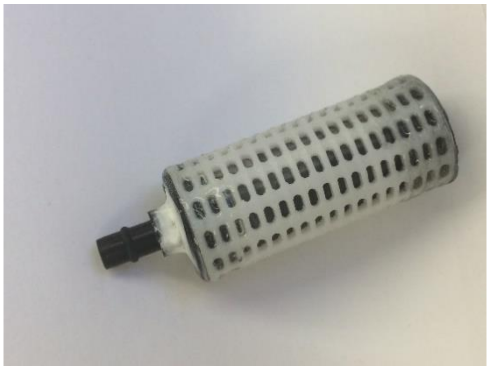

Figure 8. Photograph of current GUITAR electrode prototype.

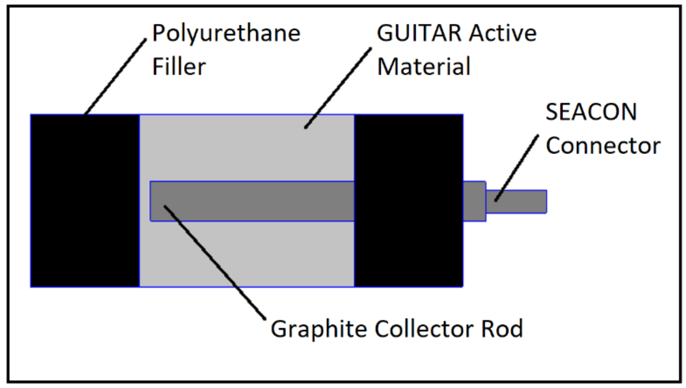

Figure 9. Cross-sectional drawing showing the interior features of the current GUITAR electrode prototype.

signal to two opposed plates submerged within a salt water testing tank. The test showed good frequency response at all frequencies tested except at 0.1 Hz (Figure 11). These results are preliminary and further testing is required to fully characterize the properties of the electrodes.

5. UUV Navigation and Tracking
   a. Analysis of UUV navigation during tests conducted at SFOMF August 15-19 2016 shows that the UUVs were able to successfully navigate in the presence of currents. Evidence to support this conclusion is shown in Figure 12 where estimates of North and East current were observed to be statistically the same for UUV navigation in the north and south directions. In addition, a separate analysis shows that the surveyed location of one of the transponders may have been incorrect. This fact

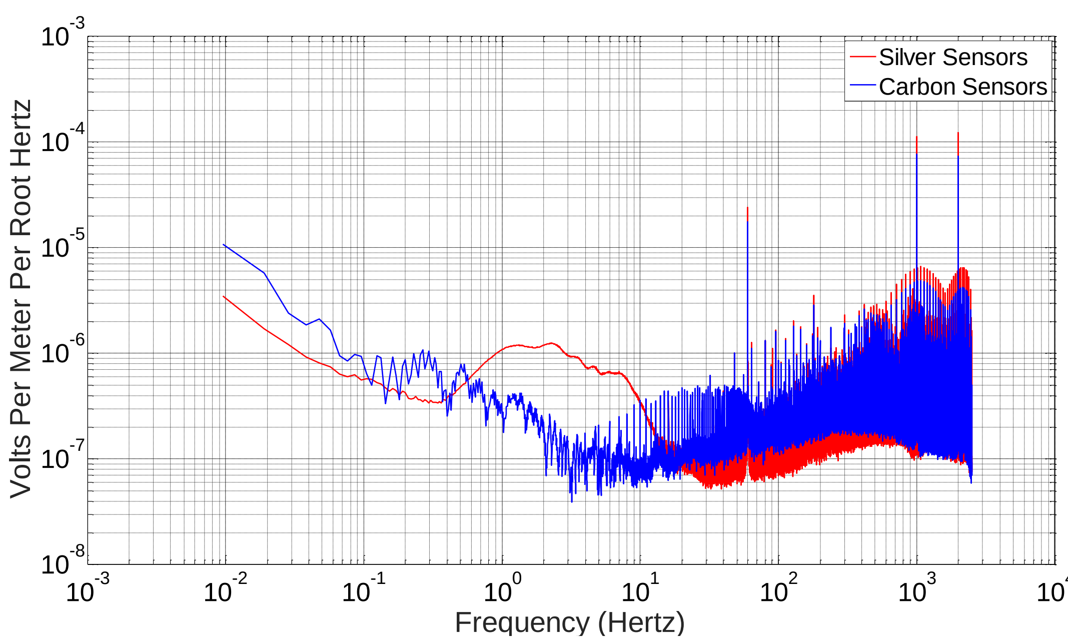

Figure 10. Graph comparing the respective noise floors of Ag/AgCl and GUITAR electrodes.

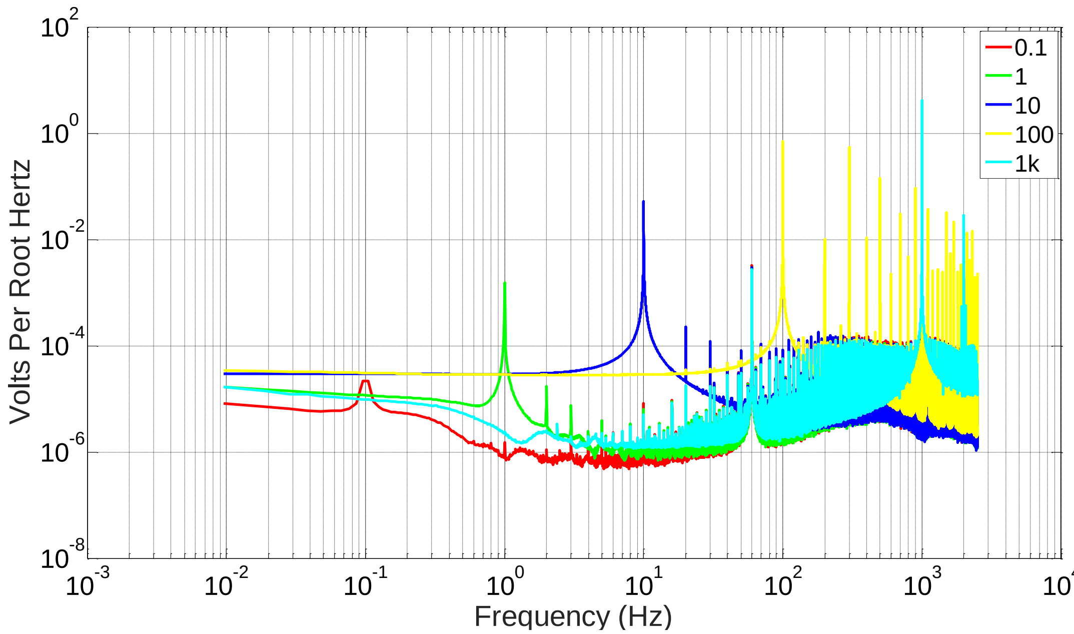

Figure 11. Frequency-response of current GUITAR electrodes.

indicates that the navigation is relatively robust.

b. Acoustic tracking techniques that will allow measurement of UUV position to an accuracy of ~10 cm is now being explored using a Monte Carlo analysis. The plan involves the use of a commercially available acoustic receiver array which can measure the range and angle to an UUV equipped with an acoustic transponder. To achieve accuracy in tracking a UUV, it will be proposed to mount a receiver array on one or more (ASVs) Autonomous Surface Vehicles. One measurement scenario is shown in Figure 13. The autonomous surface vehicle(s) would maneuver in a loose formation with the UUV to achieve a highly accurate measurement of UUV position relative to the ASVs. In this scenario, it is assumed that the Target Ship is equipped with position a measurement system equivalent to DGPS.

6. <u>Testing at Acoustic Research Detachment</u>

Tests of UI UUV with stand-alone mockup were conducted at ARD June 6th, 2017. The mockup replicated the geometry of the new stand-alone Sensor Module with 3” diameter EF sensor was attached to one of the UI’s UUVs and it was tested in-water. The tests demonstrate the UI UUV could still dive and maneuver with the larger external payload. In addition, the field testing was used to verify a new text-to-speech feature on AVcommander, the base station software for the UI UUVs. The text-to-speech helps reduce operator workload and allows them to focus on other aspects of testing. We also conducted tests of mission patterns suitable for ship surveys. The two patterns tested were a lawn-mower pattern with a five-meter offset to each leg, and a zig-zag pattern with a five-meter offset to each side.

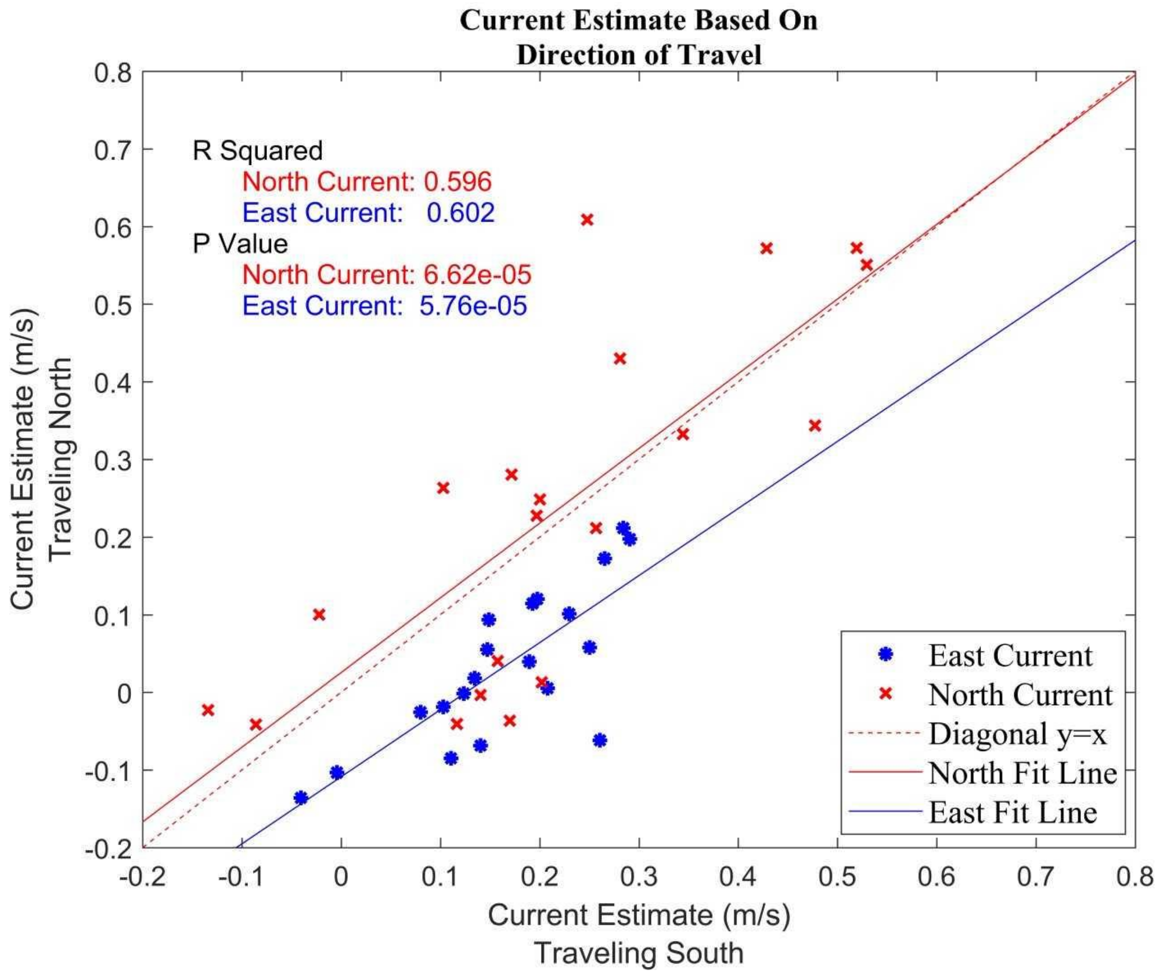

Figure 12. Estimates of East and West components of ocean current for AUVs travelling north and south.

Range measurement tests were conducted at ARD April 19th, 2018. The purpose of the test was to collect data to establish the accuracy of acoustic range measurements used to estimate UUV position. This data is now being analyzed.

What opportunities for training and professional development did the project provide?

Attended IEEE/MTS OCEANS 17 ANCHORAGE September 18-21.

How were the results disseminated to communities of interest?

Ronnie Ross, Richard Oare, Michael Anderson, Eric Wolbrecht, John Canning, Jim Frenzel, Terry Soule, Juan Arias, Dean Edwards, “Underwater electric field measurement and analysis”, *IEEE/MTS Proceedings of Oceans 2017*, Anchorage Alaska, September 18-21, 2017.

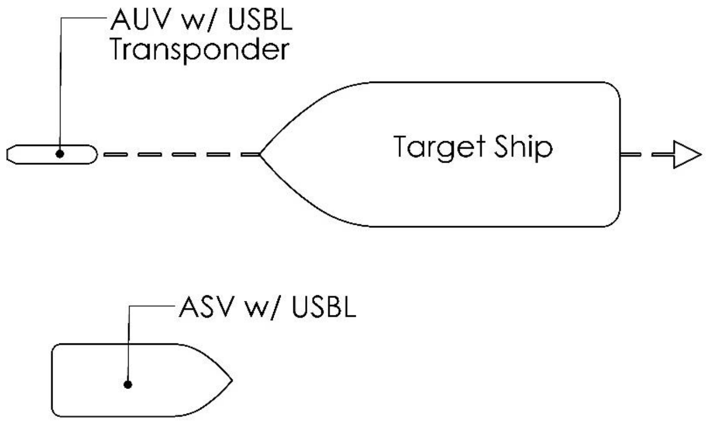

Figure 13. Scenario for tracking AUV.

Pick II, D., Wolbrecht, E., Anderson, M., Edwards, D., Canning, J. , "Comparison of USBL Configurations for Deployable AUV Navigation." Abstract submitted for presentation at *Proceedings of IEEE/MTS Oceans 2018*, Charleston SC, October 22-25, 2018.

E. Wolbrecht, J. Gergen, R. Ross, J. Osborn, J. Canning, M. Anderson, E. Edwards, "Estimating and Compensating for Water Currents in AUV Navigation: Field Testing", in preparation, to be submitted to the Journal of Advanced Robotics Systems.

What do you plan to do during the next reporting period to accomplish the goals and objectives?

We plan to

- Prepare the modified Riptide commercial AUV for possible ocean measurements in Fall 2018.
- Perform electric- and magnetic-field measurements for an ocean-going naval vessel.
- Complete development of the stand-alone electric- and magnetic-field measurement system.
- Investigate acoustic tracking of AUVs performing electric- and magnetic-field measurements

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- Perform electric field survey of surface vessel in salt water environment at the South Florida Ocean Test Facility (SFOMF).
- Assess the feasibility of UUV underwater electric potential (UEP) survey by comparing UUV-acquired measurements to equivalent measurements with a static array.

What was accomplished towards achieving these goals?

1. <u>Development of UEP (Underwater Electric Potential) Sensors.</u>
    a. Additional 3" diameter Ag/AgCl electrode UEP sensors have been fabricated. Figure 1.1 shows a 3-axis UEP sensor and a 1-axis carbon sensor. Figure 1.2 shows salt-water test tank data for the Ag/AgCl and carbon electrodes. The Ag/AgCl noise floor was 0.64, 0.68, and 0.58 uV/m and the carbon was 1.6 uV/m after 20 Hz low-pass filtering.

Figure 1.1 3-axis, 3" diameter Ag/AgCl ball in a salt-water test tank and 1-axis carbon electric field sensors.

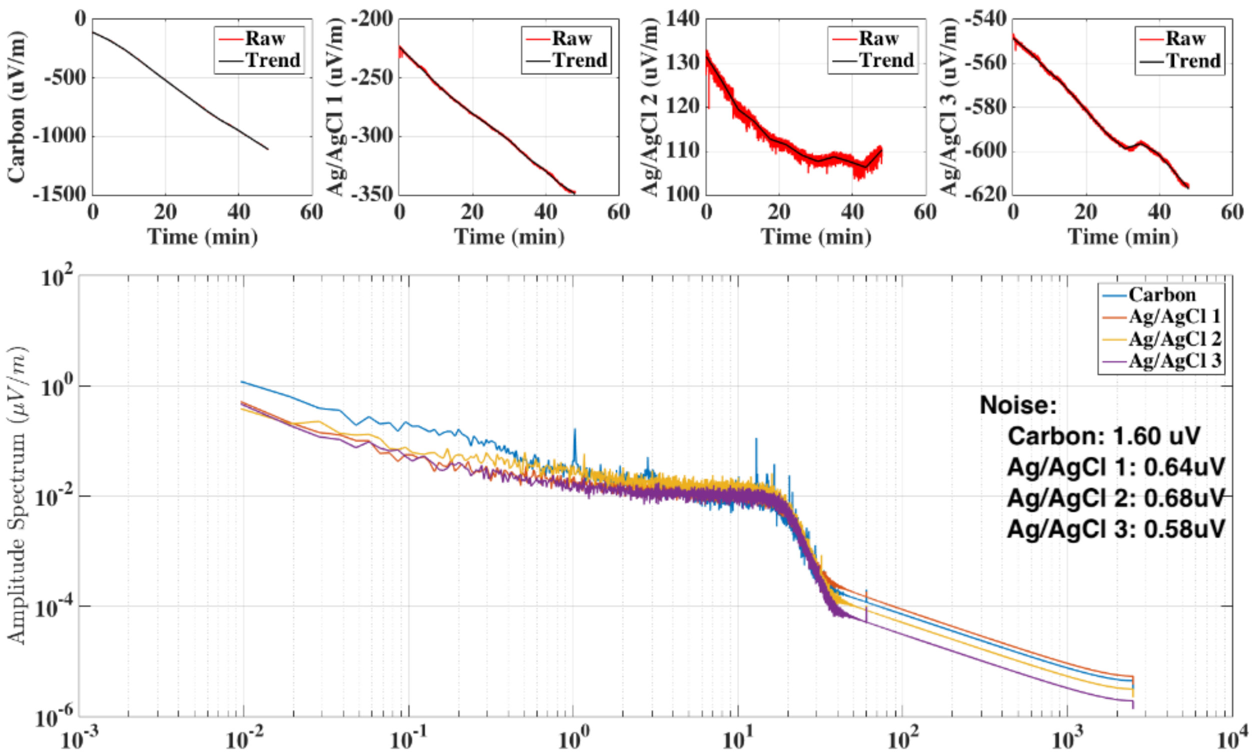

Figure 1.2 Three axis, 3" diameter Ag/AgCl ball electric field sensor and 1-axis carbon electric field sensor salt-water test tank performance measurements. The 1-axis carbon electric field and the Ag/AgCl sensors had pre-amplifier gains of 250x and 500x respectively.

2. Development of NIDAQ (Data Acquisition System) for Riptide UUV.
   a. ONR has ordered a UUV from Riptide Inc., shown in Figure 2.1, as a UUV for conducting UEP and magnetic signature measurements in conjunction with this research project. The UI worked with Riptide Inc. in selecting the appropriate components needed for a test section which could house the National Instruments based data acquisition system (NIDAQ) designed in 2017. An order for the following sections fabricated by Riptide were placed on April 19, 2018 and are shown in Figure 2.2: (A) WHOI transducer section, (B) instrumentation section, (C) Seacon connectors section, (D) UI battery section and (F) battery holder, and (G) two water tight end caps for tank testing. The sections arrived in mid-December 2018.

Figure 2.1 ONR Riptide (7.5"dia. and 8' long)

   b. The instrumentation hardware for the NIDAQ has been mounted to a tray, labeled E in Figure 2.2, and preliminary bench testing with the system has been conducted.
   c. Code has been developed for the mini-PC connected to the two NI-

9239 voltage input modules. This program is compatible with both the Riptide and the UI-AUVs and runs three main processes:

i. A TCP/UDP server that connects to the internal local network inside the Riptide and uses the same communication protocol that runs on the UI-AUVs. Its objective is to identify command packages to control and synchronize the recording of log information.
ii. An NI-DAQ controller that runs as a thread compatible with the TCP/UDP server. This module uses an API offered by National Instruments to control its NI-DAQ devices programmatically.
iii. A log recording process that takes the UEP and magnetic signals from the NI-DAQ devices and telemetry from UI boards stores it in a file with a GPS timestamp.

d. The NIDAQ software can identify emergency abort conditions in the UI payload section or from the Beagle-bone processor on the RIPTIDE.
e. The UI payload section can now receive a start mission command or abort as well as broadcast mission progress messages via the onboard WHOI modem.

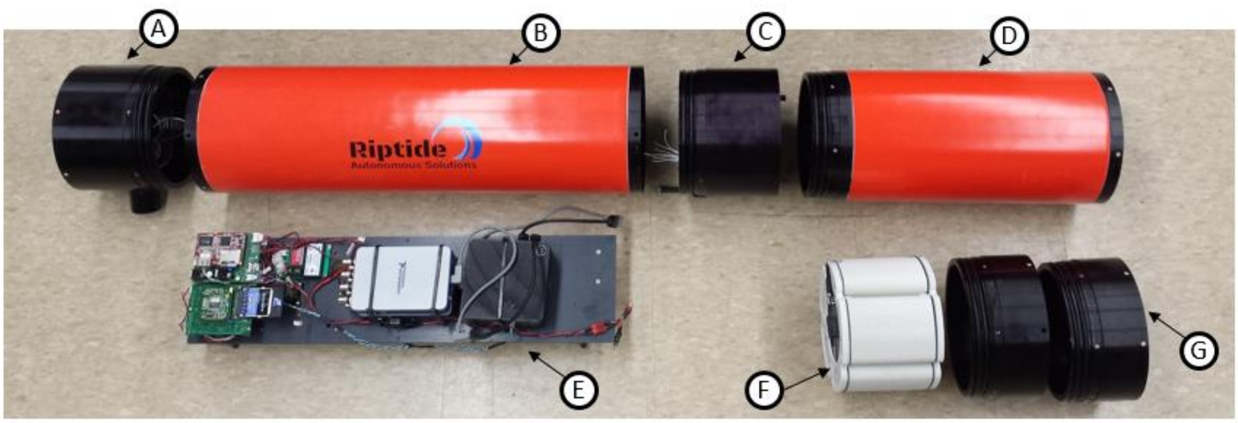

Figure 2.2 UI Riptide hull sections and UI instrumentation payload.

A. WHOI Transducer Section
B. Instrumentation Section (24” long)
C. Seacon Connectors (2) Section
D. UI Battery Section (12” long)
E. Instrumentation Payload
F. Battery Holder (1)
G. End Caps for Tank Testing (2)

3. <u>Development of a Stand-Alone Sensor Module (SASM).</u>
   a. The waterproof stand-alone sensor module has been constructed and tested both in the UI laboratory setting as well as at ARD. The SASM is capable of recording six channels of 24-bit data at 2K SPS allowing simultaneous recording of a three axis magnetometer and three axis electric field sensor data. In addition, the SASM includes a Memsense IMU with a recording rate of 100 SPS. This system is powered by a minimum of four standard 9V batteries and can be installed on almost any UUV. The SASM is shown partially disassembled in Figure 3.1 and fully assembled and submerged in a test tank in Figure 3.2. The SASM measures 30 inches in length and 2.5 inches in diameter.

Figure 3.1 Stand Alone Sensor Module (2.5" dia. by 30") with 1-axis carbon EF sensor probe.

b. Data taken at ARD in Bayview is shown in Figures 3.3 and 3.4 for the single axis carbon electric field probe and the three-axis magnetometer total field respectively. Both data sets were taken simultaneously while being moved with the UI AUV vehicles. Data is low-pass filtered at 10Hz for both the electric and magnetic sensors. Recording is done at 2K SPS for 30 minutes.

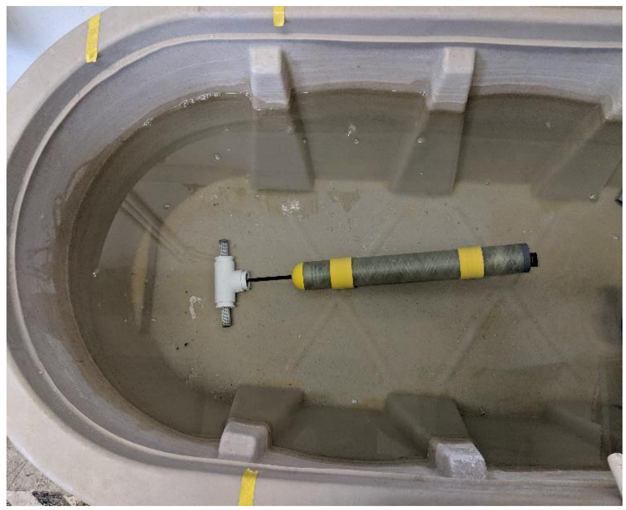

Figure 3.2 Stand Alone Sensor Module, SASM, with 1-axis carbon EF sensor.

4. <u>Development of a GUITAR Carbon Sensor for Measurement of UEP</u>
    a. Tank testing at the UI and field testing at ARD has shown the carbon electric field sensors, see Figures 1.2 and 3.3, to be operational in both fresh and salt water.
    b. The pseudo-graphite carbon material (formerly called GUITAR) used in the carbon electric field sensors is hydrophobic. In order to prepare the electrodes for use in water, they are subjected to a one-time treatment where they are soaked in 100% methanol for a brief time and subsequently soaked in a 50% methanol and water solution. After this treatment, the electrodes readily accept water even after repeated uses and drying for storage.
    c. It was found that the polylactic acid (PLA) used to form the rigid perforated housing for the sensors is not suitable for long term saltwater use and degrades prematurely. New housings made with nylon 12 have been acquired and will be used in producing new electrodes.
    d. The graphite collector rod was previously impregnated with paraffin to prevent corrosion of the interface between the rod and the SEACON connector. In the newest electrodes, a low-viscosity epoxy product known as Petropoxy 154 is vacuum

impregnated into the collector rod. This will ensure a fixed impregnation of the rod which will not be degraded by repeated pressurization and depressurization cycles resulting from diving and surfacing of the AUV.

e. A three axis test fixture is being prepared to accommodate the carbon sensors.

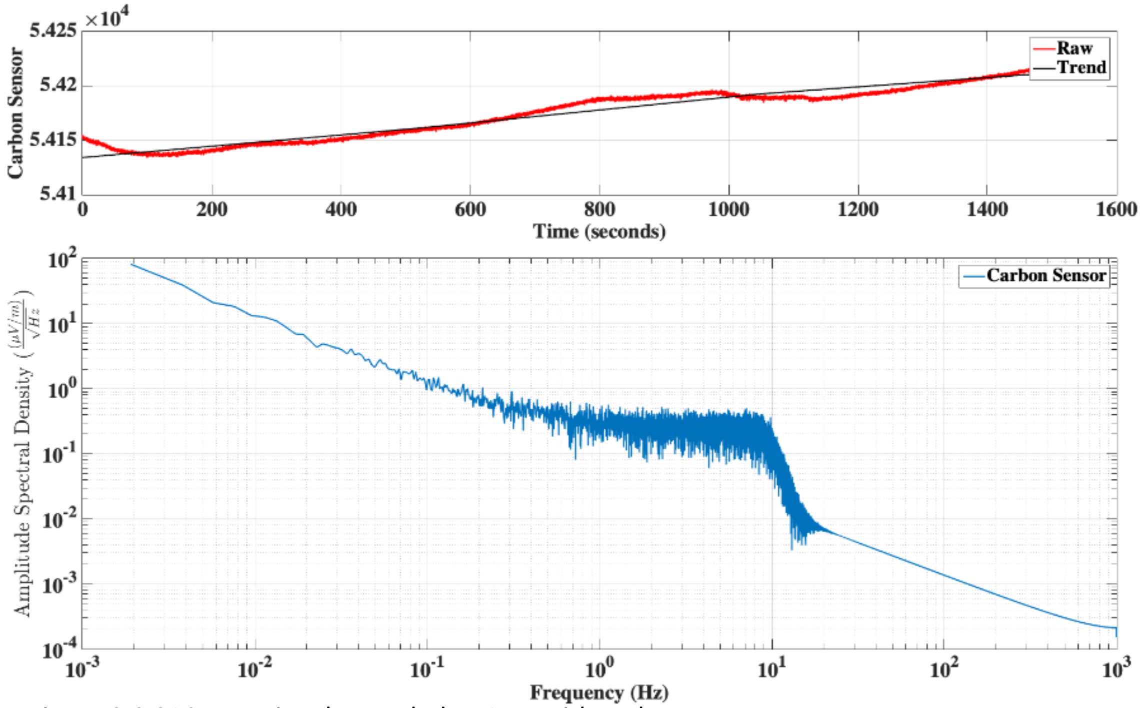

Figure 3.3 SASM EF signal recorded at ARD with carbon sensor.

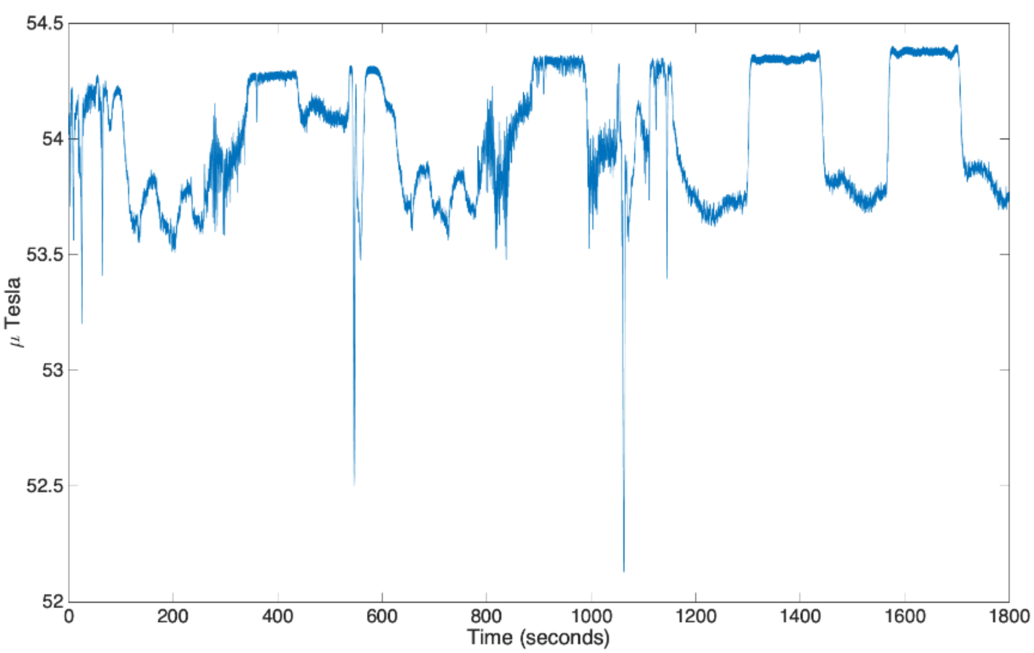

Figure 3.4 SASM un-calibrated magnetic signal recorded at ARD.

5. <u>UUV Navigation and Tracking</u>
   a. Acoustic tracking techniques that will allow measurement of UUV position to an accuracy of ~20 cm was investigated using a Monte Carlo analysis. Commercially available USBL and LBL measurement systems were modeled in simulation to compare the position uncertainty of the two navigation systems. It was found that the typical LBL localization, shown in Figure 5.1, was less accurate than the USBL, shown in Figure 5.2. The total position accuracy of the LBL system is approximately ~25cm, while the USBL system has a total position accuracy of ~20cm but in a

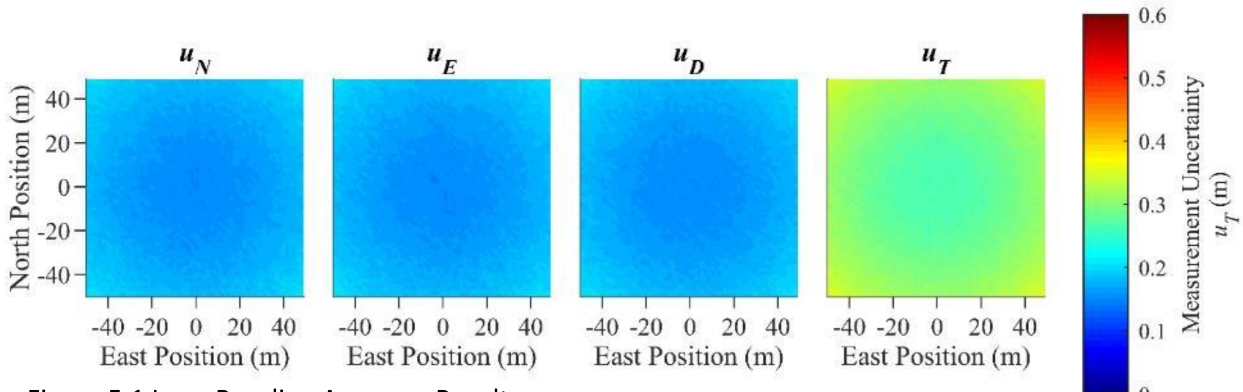

Figure 5.1 Long Baseline Accuracy Results.

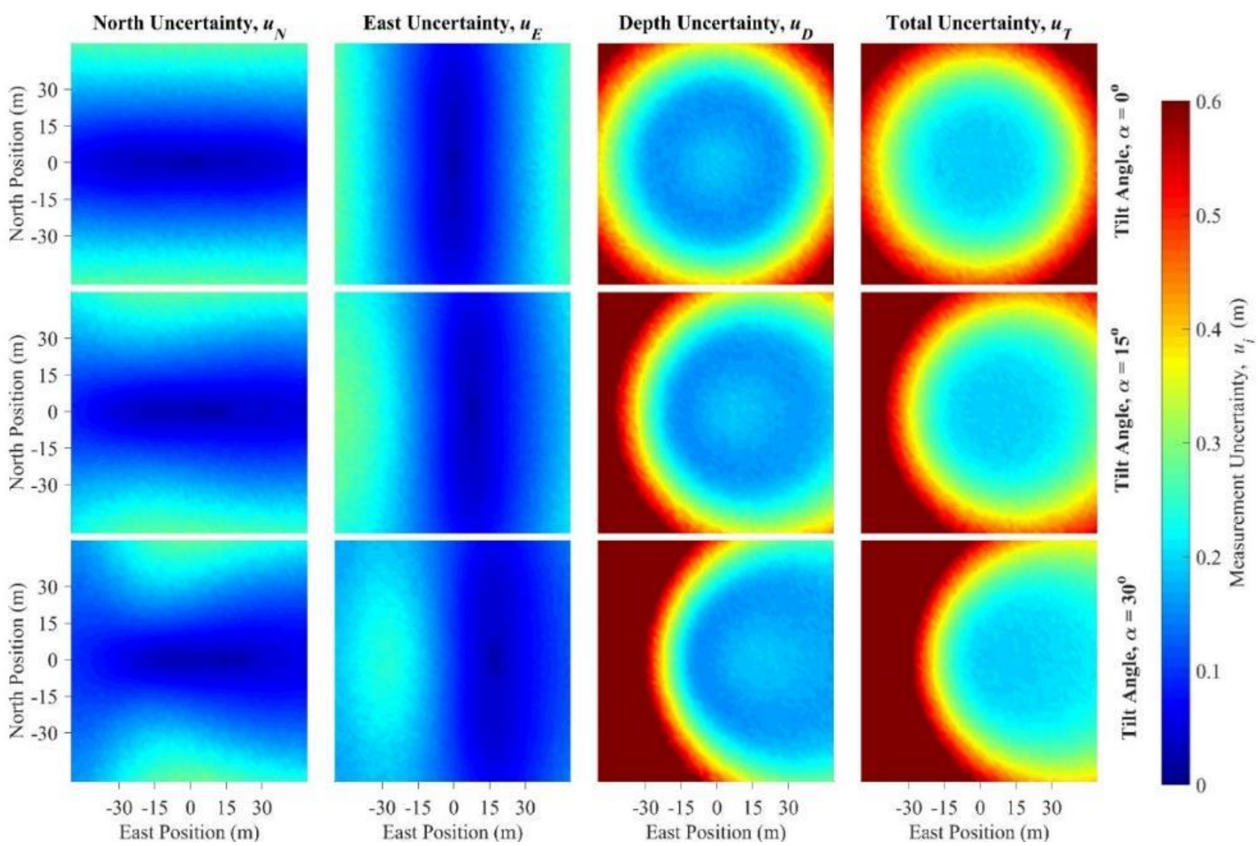

Figure 5.2 Ultra-Short Baseline Accuracy.

smaller region than the lowest uncertainty of the LBL system. Additionally, it was found that accurate position and orientation measurements of the USBL-equipped ship is essential if it is not the same ship being surveyed. This would be comparable to having the USBL transceiver mounted to an Autonomous Surface Vehicle (ASV). Accurate GPS positioning, with an accuracy on the order of ≤0.1m, and an accurate motion reference unit (MRU), e.g., the Kongsberg MRU 5+, are essential to accurately determine AUV position in the desired reference frame.

b. Current UI UUV navigation utilizes an extended Kalman filter (EKF) to combine a kinematic model, LBL ranges, and sensor measurements to navigate. An expansion of current EKF implementation was investigated in post-processing. This expansion included USBL position measurements within a post-process EKF using UI UUV field test data collected at SFOMF, August 15-19, 2016. The simulation results, see Figure 5.3, suggest that AUV localization can be greatly improved in post-processing through the inclusion of USBL position measurements in the EKF.

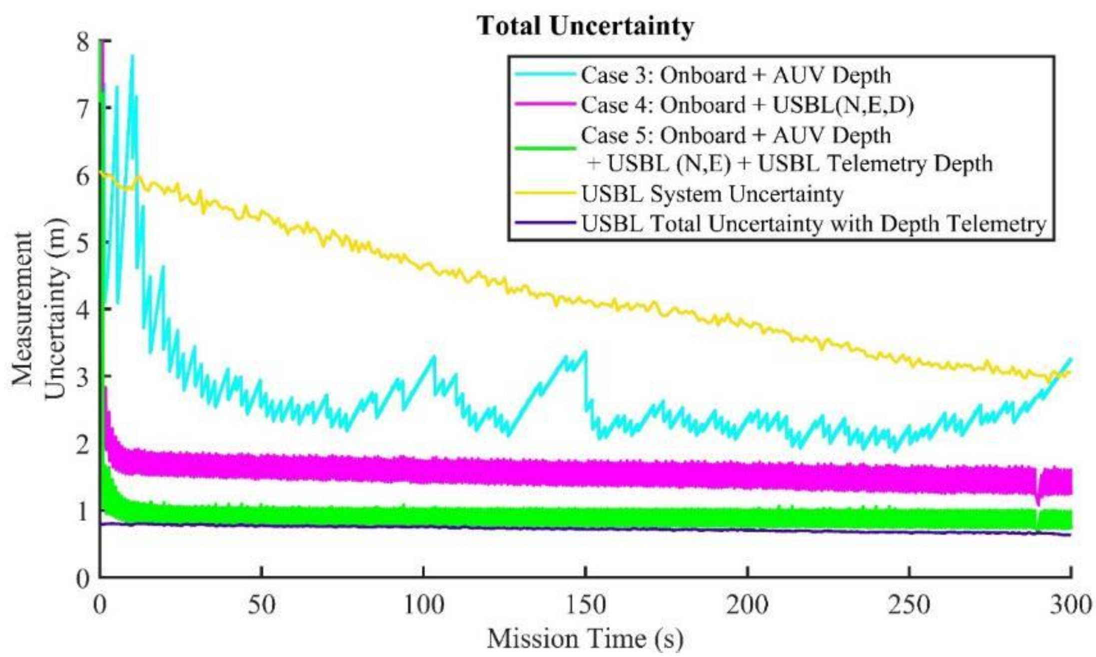

Figure 5.3 Simulated Extended Kalman Filter and USBL Results.

6. <u>Testing at Acoustic Research Detachment</u>

a. Trips for field testing at ARD were conducted on April 19th and November 20th, 2018. The purpose of the tests were to verify navigation and tracking software, in-water testing of the SASM, and to evaluate the UI AUVs ability to navigate and maneuver with the larger sensor module attached to the vehicle. The tests demonstrate the UI UUV could still dive and maneuver with the larger external payload. In addition, the field testing was used to verify a new text-to-speech feature on AVCommander, the base station software for the UI UUVs. The text-to-speech helps reduce operator workload and allows them to focus on other aspects of testing. We also conducted tests of mission patterns suitable for ship surveys.

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Marulanda, Juan F., Dean B. Edwards, Robert B. Heckendorn, and Terence Soule, "Learned Anticipation Strategy on Complex Behaviors and as an Approach to Generalization Behavior for the Coordination of an AUV Fleet." In OCEANS 2018 MTS/IEEE Charleston, pp. 1-9. IEEE, 2018.

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Distribution Statement

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Accomplishments

What were the major goals and objectives of the project?

- Prepare the modified Riptide commercial AUV for possible ocean measurements in Fall 2019.
- Perform electric- and magnetic-field measurements for an ocean-going naval vessel.
- Complete development of the stand-alone electric- and magnetic-field measurement system.
- Investigate acoustic tracking of AUVs performing electric- and magnetic-field measurements.

What was accomplished towards achieving these goals?

1. Prepare Riptide commercial UUV for ocean measurements.

ONR ordered a UUV from Riptide Inc., shown in Figure 1.1, as a commercial off-the-shelf (COTS) UUV for conducting UEP and magnetic signature measurements in conjunction with this research project. The completed vehicle was not delivered to ONR and Riptide Inc. filed for Chapter 7 bankruptcy on July 5th, 2019. BAE Systems acquired Riptide and has stated their intention to fulfill the original order to ONR. But the vehicle was not delivered to

Figure 1.1 ONR Riptide (7.5”dia. and 8’ long)

ONR and was subsequently unavailable for use in this reporting period. In order to acquire a COTS UUV for this project the decision was made to use unspent travel/testing funds to purchase a nose and tail cone from BAE Systems to combine with the sensor and battery sections purchased in 2018, see Figure 1.2. After informing our ONR contacts of the planned purchase, and receiving permission to proceed, a nose and tail cone were ordered from BAE Systems with the down payment being received on September 3rd, 2019. The sections were delivered to the UI on February 24th, 2020. These sections were combined to make a complete Riptide 1MP, see Figure 1.3, for use in field testing.

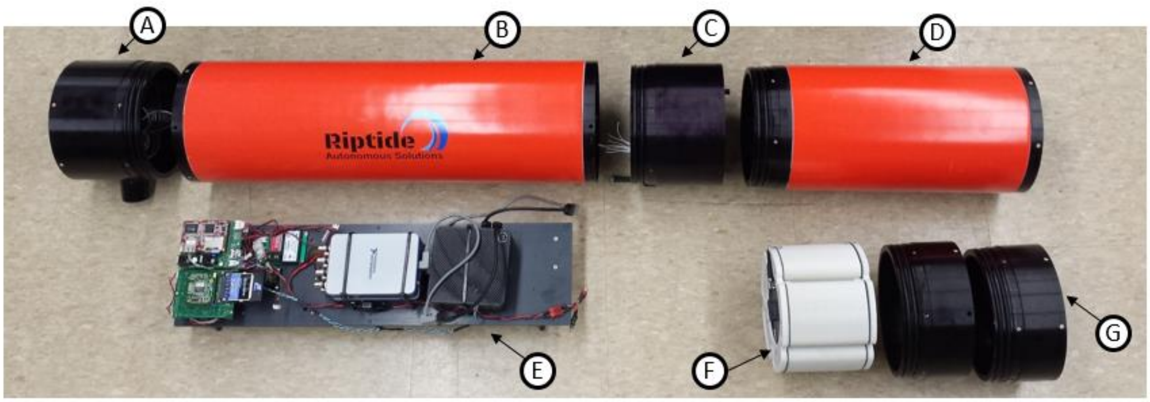

Figure 1.2 UI Riptide hull sections and UI instrumentation payload.

E. WHOI Transducer Section
F. Instrumentation Section (24" long)
G. Seacon Connectors (2) Section
H. UI Battery Section (12" long)
H. Instrumentation Payload
I. Battery Holder (1)
J. End Caps for Tank Testing (2)

Figure 1.3 UI Riptide assembled with instrumentation and battery

2. <u>Development of UEP (Underwater Electric Potential) Sensors.</u>
   Additional 3” diameter Ag/AgCl electrode UEP sensors have been fabricated. Figure 2.1 shows a 3-axis UEP sensor and a 1-axis carbon sensor. The design of the carbon sensors has been updated. The Ag/AgCl and carbon UEP electrodes were used with the new SASM and NI DAQ systems to record saltwater test tank data. The DAQ systems and test tank results are discussed in the subsequent sections.

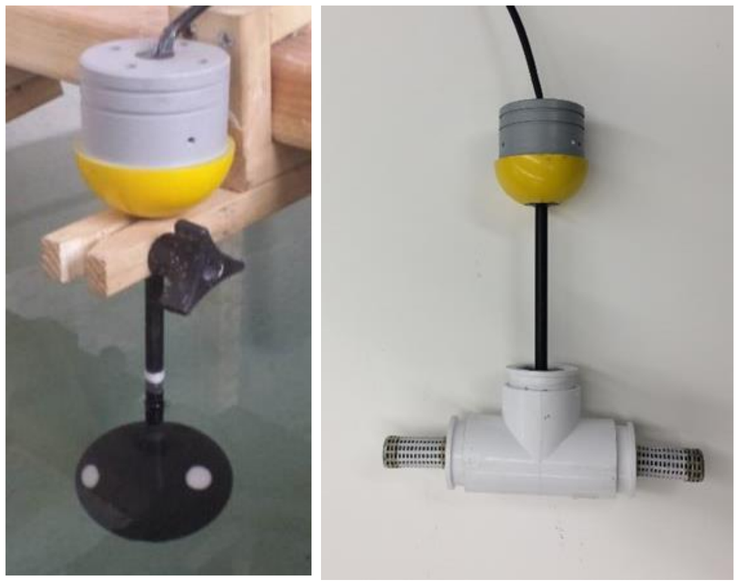

Figure 2.1 3-axis, 3” diameter Ag/AgCl ball in a salt-water test tank and 1-axis carbon electric field sensors.

3. <u>Development of Data Acquisition Systems for the Riptide.</u>
   The approach taken for measuring magnetic and electric field data with the Riptide UUV has primarily focused on the development of the Stand Alone Sensor Module (SASM) which could be mounted to any COTS UUV and a NI-DAQ based system housed in the instrumentation payload section as a back-up should the SASM prove ineffective. The waterproof SASM has been constructed and tested both in the UI laboratory setting and in-water at ARD mounted to a UI AUV. The SASM is capable of recording six channels of 24-bit data at 2K SPS allowing simultaneous recording of a three-axis magnetometer and three axis electric field sensor data. In addition, the SASM includes a Memsense IMU with a recording rate of 100 SPS. This system is powered by a minimum of four standard 9V batteries and can be mounted onto almost any COTS UUV. The SASM is shown partially disassembled in Figure 3.1, it is 30 inches in length and 2.5 inches in diameter.

   Upgrades to the SASM during this reporting period include a new micro-processor for the A/D conversion, a redesign of the mounting system to improve wire harness clearance and room for additional battery storage, and improved software to increase the sample rate to

Figure 3.1 Stand Alone Sensor Module (2.5” dia. by 30”) with 1-axis carbon EF sensor probe.

5 kHz. Data taken in the UI saltwater test tank, discussed in section 4, shows the relative performance of the two DAQ systems.

4. Saltwater Tank Testing

Figure 4.1 shows the experimental setup for the SASM and NIDAQ based systems. Both experiments use the same 3” Ag/AgCl electrodes with the SASM having an additional single axis carbon electrode pair. Recordings were made with no active signal in the tank to capture the noise floor of both systems.

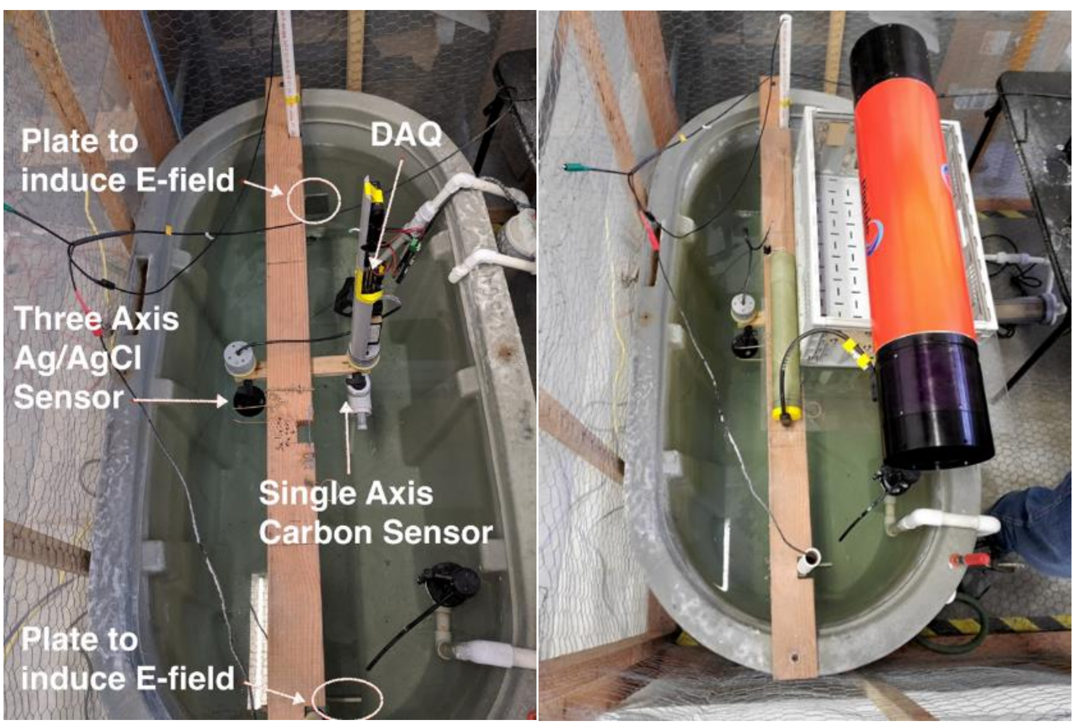

Figure 4.1 Saltwater test tank with SASM (left) and NIDAQ Riptide Section (right).

The results for the NIDAQ system, see Figure 4.2, show a noise level of 2.18, 4.35, and 1.89 uV_{rms}/m for Axis 1,2,3 respectively. These are slightly higher than previous measurements made with the NIDAQ system connected directly to a laptop. The length of the lead wires and the fact that a portion of the waterproof connectors prevent the use of shielded twisted pairs between the pre-amp and DAQ is likely a contributing factor for the increased noise in the system.

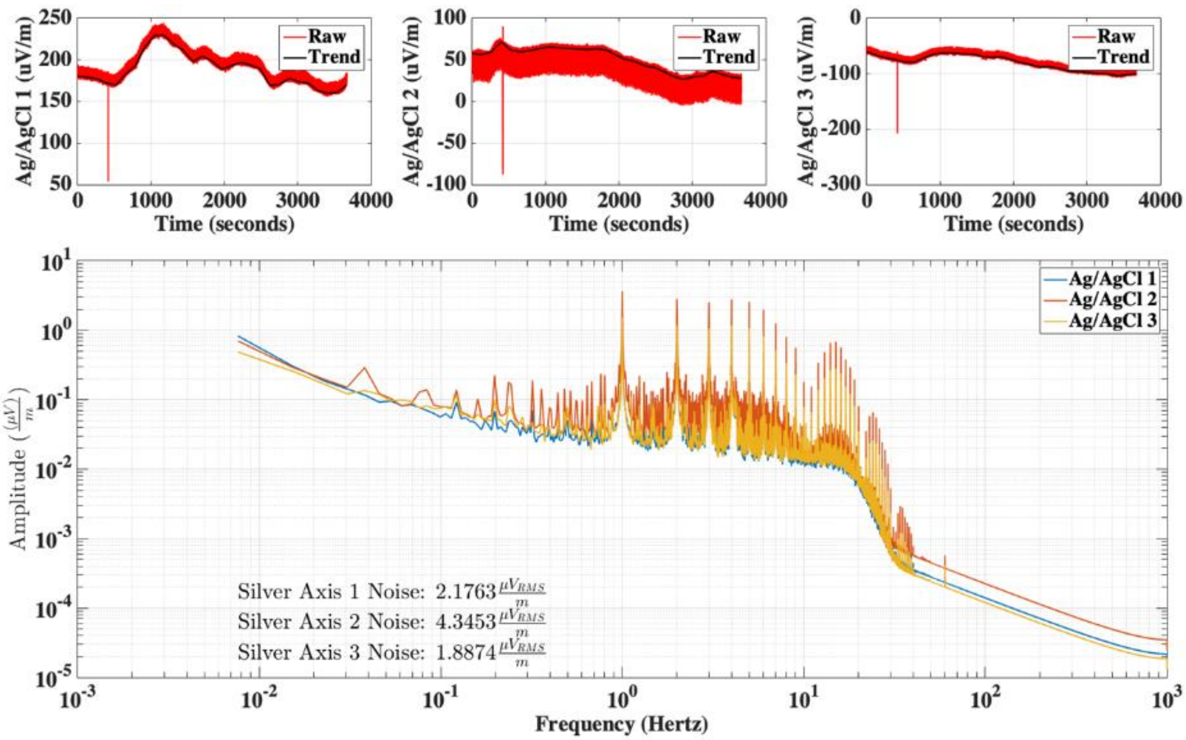

Figure 4.2 Riptide NIDAQ recording with 3” Ag/AgCl electrodes.

The SASM results, see Figure 4.3, show a noise floor of 0.553, 0.555, and 0.796 uV_{rms}/m for the Ag/AgCl electrodes and 1.80 uV_{rms}/m for the single axis carbon electrode pair. The noise floor is considerably lower than the Riptide NIDAQ system and is lower than similar measurements made with the NIDAQ system connected to a laptop.

A pair of stainless-steel plates are connected to a Keithley 6221 DC and AC current source to provide signals in the saltwater test tank. A frequency sweep with 0.07, 0.7, 4.7, and 17 Hz was programmed and recorded, see Figure 4.4, and the signal to noise levels were calculated from the data, see Figure 4.5. While the carbon electrode had a higher noise floor than the Ag/AgCl electrodes, the signal to noise ratio was very similar.

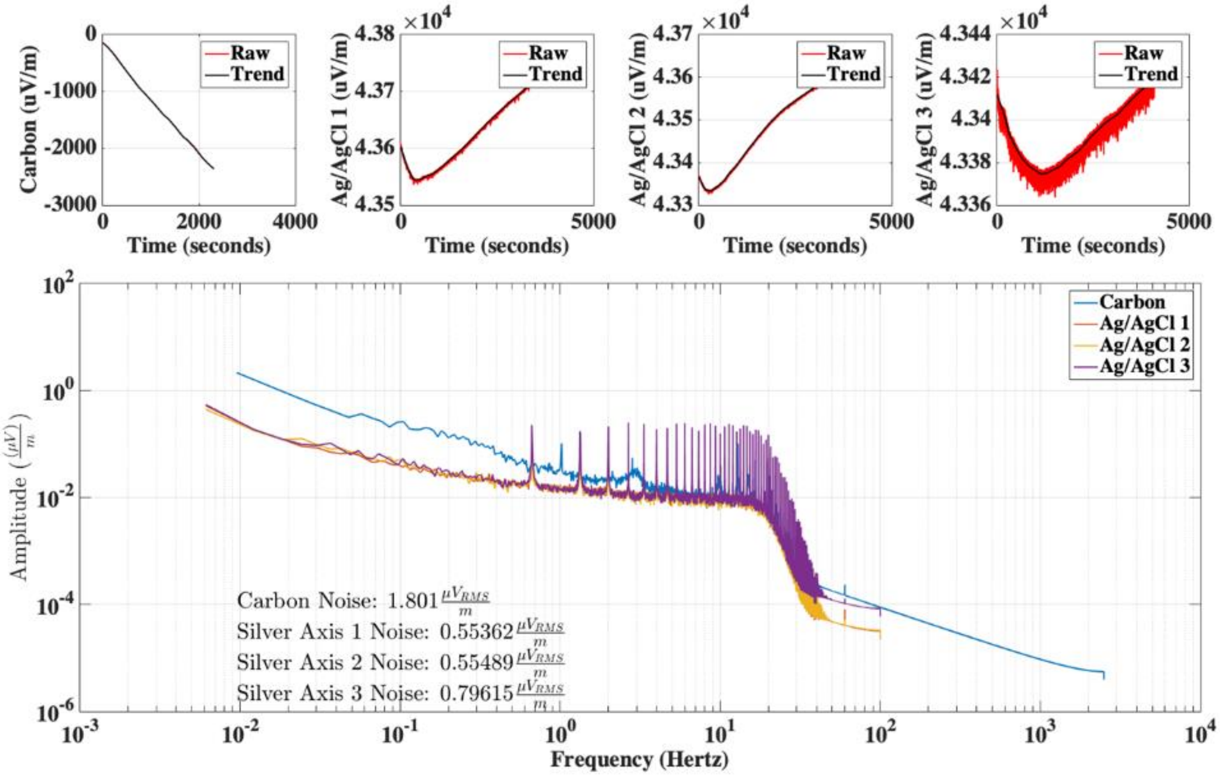

Figure 4.3 SASM EF signal recording with 3" Ag/AgCl electrodes and single axis carbon sensor.

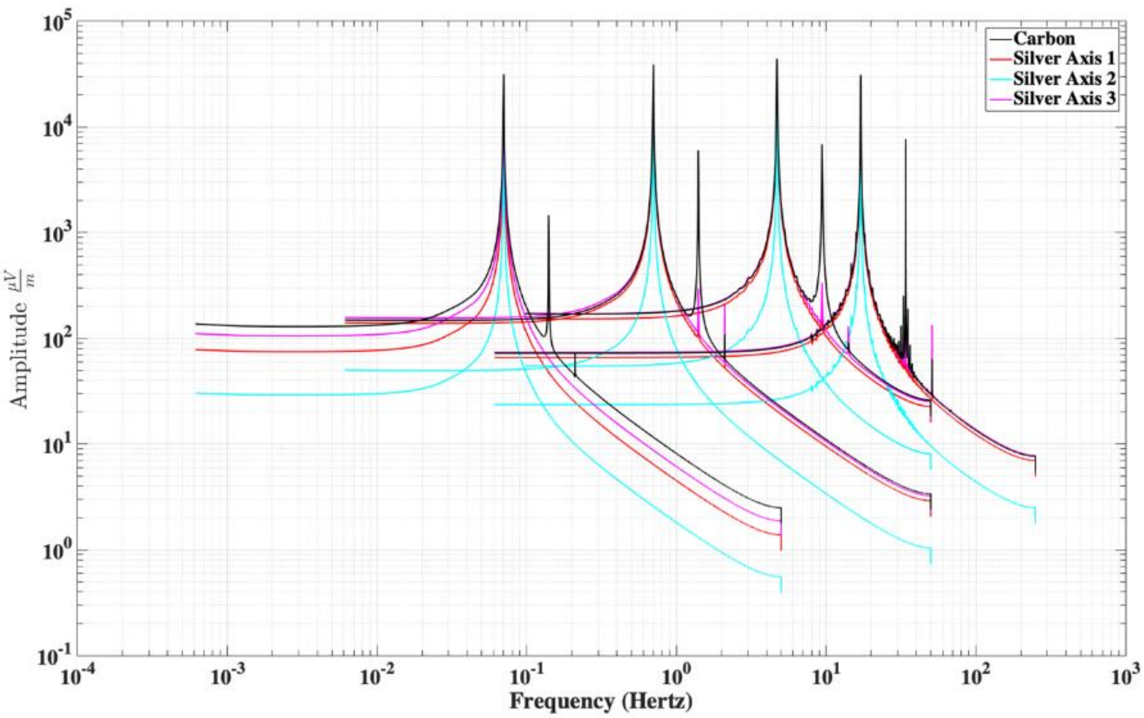

Figure 4.4 Carbon and Ag/AgCl Electrode Tank Data Frequency Sweep.

Signal to Noise Ratio

Frequency (Hertz)	Carbon (dB)	Silver Axis 1 (dB)	Silver Axis 2 (dB)	Silver Axis 3 (dB)
0.07	62.474	63.867	63.828	63.92
0.7	44.9	45.881	45.9	45.998
4.7	33.197	33.754	33.781	33.722
17	29.433	29.944	29.946	29.934

Figure 4.5 Carbon and Ag/AgCl Electrode Sweep Frequencies and Signal to Noise Ratio.

5. UUV Navigation and Tracking

An approach for combining ultra-short-baseline (USBL) and long-baseline localization (LBL) data in a post-processing extended Kalman filter was developed and presented in a paper at Oceans 2019 in Seattle, WA. The goal was to improve localization accuracy and reduce localization uncertainty for autonomous underwater vehicles (AUVs) performing oceanographic survey measurements. The method was evaluated using logged LBL navigation data from field testing and simulated USBL data. Localization accuracy was evaluated by comparing state uncertainties of the independent and combined systems. Uncertainties of USBL localization data were estimated using a Monte-Carlo simulation at each AUV position. The results indicate that combining USBL data improves localization accuracy, especially when the USBL data includes depth telemetry measurements. Although this approach was evaluated by adding USBL data to logged LBL field-testing data, it could be applied to any navigation approach, including dead reckoning.

Current UI UUV navigation utilizes an extended Kalman filter (EKF) to combine a kinematic model, LBL ranges, and sensor measurements to navigate. An expansion of current EKF implementation was investigated in post-processing. This expansion included USBL position measurements within a post-process EKF using UI UUV field test data collected at SFOMF, August 15-19, 2016. The simulation results, see Figure 5.1, suggest that AUV localization can be greatly improved in post-processing through the inclusion of USBL position measurements in the EKF.

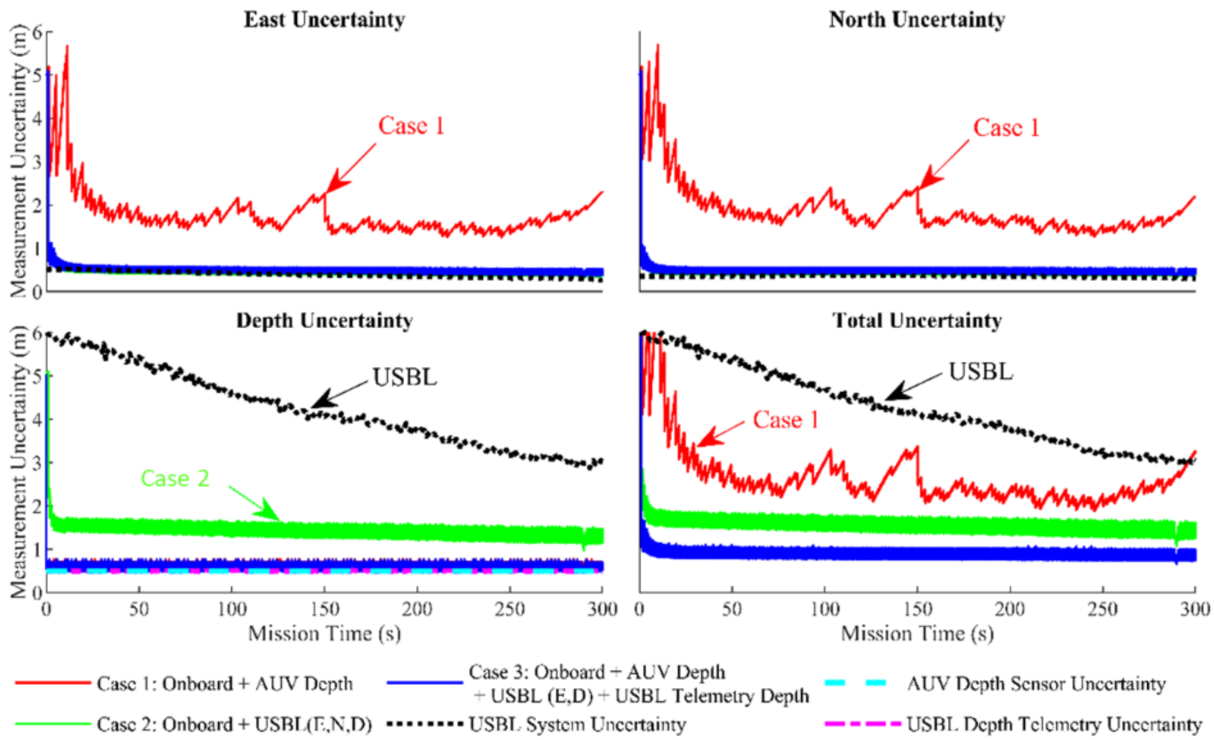

Figure 5.1 Measurement uncertainties for post-processing EKFs combining USBL and LBL localization data. AUV depth sensor uncertainties and USBL system uncertainties (with and without depth telemetry) are shown for comparison.

Combining two or more independent measurements can greatly improve estimation confidence, especially in field testing. The low uncertainty of the USBL system depends significantly on using telemetry depth, which is relayed from the AUV-mounted USBL receiver. Without this pressure-based measurement, depth uncertainty is high (~ 3m) and total uncertainty is similarly degraded. In this specific case, adding the logged LBL data can greatly improve the uncertainty results, specifically because of the accuracy of the onboard pressure-based depth sensor. Another significant advantage of combining USBL and LBL measurements in a post-processing EKF is the orientation information recorded on the AUV. Although not evaluated in this work, onboard INS measurements allow for estimation of orientation, information which is not available when tracking an AUV solely with a USBL system. By combining both measurement systems in PP-EKF, you can improve localization accuracy and reduce uncertainty while simultaneously estimating the orientation of the AUV. This is particularly important for oceanographic survey measurements where measurements of magnetic and electric field are recorded along the three Cartesian directions.

6. Testing at Acoustic Research Detachment

Field testing at ARD was conducted on August 8th, 2019 to verify navigation and tracking software, in-water testing of the SASM with new hardware and software upgrades. Additionally, new text-to-speech updates to the base-station software were tested.

What opportunities for training and professional development did the project provide?
Attended IEEE/OCEANS 2019 Seattle, WA, USA, October 27 – 31, 2019.

How were the results disseminated to communities of interest?
E. Wolbrecht, D. Pick, J. Canning and D. Edwards, "Improving AUV Localization Accuracy by Combining Ultra-Short-Baseline and Long-Baseline Measurements Systems in a Post-Processing Extended Kalman Filter," OCEANS 2019 MTS/IEEE SEATTLE, Seattle, WA, USA, 2019, pp. 1-7, doi: 10.23919/OCEANS40490.2019.8962683.

What do you plan to do during the next reporting period to accomplish the goals and objectives?

- Prepare the Riptide UUV and Stand Alone Sensor Module for in-water testing.
- Complete the final report.

REPORT DOCUMENTATION PAGE

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The major goal for the project was to develop and demonstrate the sensors, data acquisition and other equipment needed to conduct Underwater Electric Potential (UEP) and magnetic signature measurements with a commercial off the shelf (COTS) Unmanned Underwater Vehicle (UUV). The COTS UUV was not delivered to the UI researchers in time to allow for in ocean tests. The project was successful in demonstrating the use of UI research UUVs to make UEP and magnetic measurements in an ocean environment at the South Florida Offshore Measurement Facility. The project developed the Stand Alone Sensor Module (SASM) which can be mounted to any COTS UUV to enable the recording of UEP and magnetic field measurements. The SASM is capable of recording six channels of 24-bit data at 5K SPS allowing simultaneous recording of the internal magnetometer and a UI developed three axis electric field sensor consisting of a 3" diameter ball sensor with 3-axis Ag/AgCl electrode pairs featuring an UI designed embedded low-noise pre-amplifier. The final version of the SASM successfully demonstrated a noise floor of less than 1 uVrms/m with Ag/AgCl electrodes in tank tests at the UI.

15. SUBJECT TERMS
UUV, Electric Field Sensors, Electric and Magnetic Field Measurements

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