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PLATFORM FOR HADAL AUTONOMY AND GENERAL EXPERIMENTATION

(PHAGE)

BY

LILLIAN M. MUIR

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE

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MASTER OF SCIENCE THESIS
OF
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ABSTRACT

Due to the harsh environment and inaccessibility of the deep-sea, most oceanographic equipment is rated to sample above the hadal region (6000 meters and below). A few deep-sea landers and piloted vehicles have ventured into deep ocean trenches to sample at the ocean floor, but the hadal water column remains under-sampled. A full ocean depth profile and hadal samples can provide information on ocean circulation, deep-water mixing, trench overturning rates, and the ocean environment.

The Platform for Hadal Autonomy and General Experimentation (PHAGE) is a full ocean depth profiler rated to 11 km. Designed around a 24 bottle CTD rosette, PHAGE is an untethered system that autonomously descends to the bottom of the ocean to profile with a CTD and sample the water column at a relatively low cost. Taking only 24 water samples spaced over the entire ocean depth has a high the likelihood of missing important features of the water column (i.e. thermocline or oxygen minimum). An adaptive sampling software was developed for analysis of the water column to identify and sample the desired features while PHAGE is underway. Because the system is untethered, acoustics are the only form of communication. Acoustic ranges were used to track the submerged vehicle using a range-only tracking technique.

In September 2018, the vehicle was tested to 8377 meters in the Puerto Rico Trench. PHAGE was able to sample bottom water and generate full ocean depth profiles. An overview of PHAGE and a performance analysis are presented throughout this thesis to help with future deployments.

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CHAPTER 1

Introduction and Background

The majority of oceanographic profiling methods are focused on upper ocean sampling due to accessibility. Because of this, very little is known about the hadal region (below 6000 meters). To merge the gap between the upper water column and the hadal sampling, the Platform for Hadal Autonomy and General Experimentation (PHAGE) presented in this thesis was designed as a full depth ocean profiler.

1.1 CTD Rosette Sampling

The most common ship profiling and sampling device is a conductivity, temperature, and depth (CTD) rosette system. A standard CTD rosette is made up of a sensor system (e.g. SeaBird sbe9plus) and a rosette of sampling bottles (e.g. Seabird sbe32) [1, 2, 3]. Rosettes are typically tethered systems lowered over the side of a ship with a wire and winch to maintain communication throughout the sampling process [3]. This communication allows the CTD data to be viewed in real-time and the sample bottles to be closed by a command from the operator [2, 3, 4]. CTD rosettes are commonly rated to a depth of 6800 meters. Instrumentation costs increase substantially for deeper ratings due to the need for stronger (titanium) housings.

The strength of the cable also limits the depth rosettes can reach. The wire needs to be able to hold the static and dynamic loads on the system for the full depth of the cast. The weight of the cable itself must be considered as a part of the static load, which will increase as more is spooled out [5]. A common wire for CTD casts is 0.322 inch diameter cable, which weighs 0.474 lbs/m in seawater and adds an extra 2,844 lbs for a 6000 m cast. This extra weight will increase the load close to the working limits for the system [5]. Larger diameter wires can be used, but have similar problems because they weigh more per unit length. The only other option to increase depth for a CTD rosette is

a costly, specialized synthetic wire. Shipboard rosettes are not used below 6000 m due to this wire safety limit. A few ships have measured properties below this limit using only the CTD sensors, which decreases the weight by removing the rosette [6].

Shipboard CTDs can operate at vertical speeds up to 60 m/min, so a full 6000 meter profile can take two or more hours to descend and longer to ascend due to the duration of sampling [7]. A shipboard CTD requires the vessel to maintain station over the drop site for the entire operation, using engineers, deckhands, and science technicians throughout [7]. Given the operating costs of scientific vessels, often more than \$25,000 per day, a deep CTD cast can consume a significant amount of expensive ship time and resources.

While 6000 meters is a deep profile to the abyssal zone, the ocean has many hadal regions (6000 meters or deeper) including the Mariana Trench (11,022 meters) and Puerto Rico Trench (8,742 meters) [8]. Very little is known about the ocean below 6000 meters because of the lack of oceanographic instrumentation rated to these depths [9, 10, 11].

1.2 Water Masses

A primary motivation for sampling deep water is determining the source, which provides information on the deep thermohaline circulation and environment. Antarctic Bottom Water (AABW) and North Atlantic Deep Water (NADW) are two major deep-water sources in the ocean [12]. These water masses are known to circulate throughout the world's oceans for hundreds or perhaps thousands of years [13, 14]. Each water mass can be identified by specific physical and chemical properties [12, 13, 15, 16]. NADW is considered to be warmer and salty with a potential temperature around 2.75 °C and a salinity of 34.9‰. AABW is known to be colder, fresher water at 0.7 °C and 34.7‰. Potential temperature is the temperature the water would reach if it was brought adiabatically to surface pressure. It is used instead of measured *in-situ* temperature because it takes into account the temperature change due to compressibility of water.

Figure 1 shows the potential temperature and salinity ranges of the water masses on a TS diagram [17, 18, 19, 20].

Figure 1. Potential temperature, salinity diagram of the Atlantic deep sea water masses.

These deep-water sources are known to overlap and mix, so there is no definitive boundary where the water masses meet [21]. AABW has been found surrounding the Puerto Rico Trench in Figure 2, entering from the east as shown by the data samples circled in white [22, 23]. On the Greater Antilles Outer Ridge, north of the Puerto Rico Trench circled with black, mixing is seen between AABW and NADW through measurements in the nepheloid layer. The water sampled closer to the trench demonstrated more Antarctic properties than that farther north [21]. NADW has been observed southeast of the trench at 16°N at 55°W and mixing of the sources is known to occur down to 6°11'S and up to 40°N [23, 24, 25].

Figure 2. Labeled areas of the Puerto Rico Trench.

Even with the water masses of surrounding areas determined, estimating the ratio of AABW to NADW in the trench is difficult due to the unknown circulation patterns and lack of hadal water samples. Many models assume stagnant trench water to avoid these complications, but the measured water properties in the trench indicate there is circulation [26, 27, 28]. Ventilation is thought to occur from upwells induced by a combination of temperature differences, geothermal heating, steep topography, boundary currents, eddy transport, internal waves, and recirculation gyres; but there has not been enough hadal data collected to determine the strength of each of these mechanisms [26, 27, 29]. A few water current-measuring devices have been deployed for deep sampling in the Mariana and Puerto Rico Trenches. These devices found slow currents through the trenches of 0.5-0.7 cm/s and 1-5 cm/s respectively [27, 29, 30]. While very small, these flow rates indicate some trench overturning and recirculation, dispelling the notion that the water is stagnant.

1.3 Circulation Age of Water

A water sample can be used to determine the age of the water, mixing, and then be used to estimate the overturn rate of the trench. The age of an ocean sample is the amount of time since last exposed to the atmosphere [31]. Ages are determined through the amount of radiocarbon ($\Delta^{14}\text{C}$) accumulated in the water sample since surfaced. Each water source retains an initial carbon-age at the surface, which increases the difficulty of carbon dating when mixing is involved. AABW has been determined to have -137‰ (parts per thousand) to -167‰ initially, while NADW has -57‰ to -70‰ [16, 32, 33]. To determine the ventilation age, these reservoir values need to be removed from the radiocarbon sample in proportion to the contribution of each water source.

Because of these difficulties, different methods to estimate the deep ocean age have produced variable results. The deep-water age estimates near the Puerto Rico Trench range from 250 to 600 years old, with the sampled data surrounding the trench showing 250-300 years [31, 32, 33, 34, 35]. The estimates are inconsistent due to the unknown ratio of NADW to AABW, the methods of estimation, and the depth of the sampling. One method determines the percentage of AABW from the amount of SiO_2 , NO , O_2 , and PO_4^* (phosphate adjusted by Redfield ratio of O_2 consumption) in the sample [12, 15, 16, 36]. Upon determining the deep-water source ratio, the radiocarbon sampled can be converted into age.

1.4 Current Hadal Research Platforms

Landers are the main platforms for sampling the hadal ocean. Landers are untethered, adaptable platforms that sink and land on the ocean floor [37, 38]. General design concepts for a full ocean depth lander are presented in [37]. Expendable weights are typically mounted to the bottom of the vehicles for the descent, while syntactic foam or glass spheres are used for buoyancy to return the system after the weights are released [11, 37, 38]. As a research platform, landers can easily be equipped for a variety of re-

search tasks at a low cost. Lander instrumentation commonly includes camera systems, water samplers, sediment cores, CTD sensors, and baited traps [11, 38, 39]. Because of this versatility, most deep sea exploratory programs like DEEPSEA CHALLENGE, HADEEP, and HADES use landers as the primary data collection sources [11, 38, 39].

Few piloted research vehicles have ventured to the hadal region. The successful vehicles include the DEEPSEA CHALLENGER, Nereus, Kaiko, and ABISMO. The primary purpose of deep vehicles is bottom exploration. They are more capable than landers and attempt to capture the environment through video, still imagery, biologic samples, geologic samples, bathymetric mapping, CTD data, and small water samples [40, 41, 42, 43]. Two of these systems managed to make only a few dives to the hadal region before being lost (Kaiko and Nereus) and others have been retired (DEEPSEA CHALLENGER and ABISMO) [40, 44, 45].

1.5 Acoustic Navigation

A challenge of operating unmanned and untethered vehicles underwater is the lack of satellite communication for accurate tracking. One method for locating autonomous underwater vehicles (AUVs) is using acoustic ranging from known global coordinates to estimate the position [46, 47]. In this method, location is estimated from the acoustic measurements and a motion model of the system. The motion model calculates the new position estimate from the vehicle's kinematics, the previous position, and the time interval between measurements. The estimated position is then corrected by the acoustic measurements and used in the next estimate. Acoustic variability will cause the estimation error to increase over time. The model is only corrected when an acoustic signal is received, and will be less accurate the more infrequent the measurements are [46, 47, 48].

Range-only navigation methods use the two way travel time between the ship and vehicle [46, 47]. Alone, these raw measurements create an unobservable system where

an estimate of the distance can be made, but bearing remains unknown. By changing the relative location of the system and ship, the location of the AUV can then be estimated by overlaying the distance estimates to determine where they consistently overlap [46, 47]. Examples of range-only navigation are used in [48] and [49].

The primary problems with acoustic tracking systems are cost, equipment deployment, and inaccurate or noisy measurements [47]. Cost increases with each device added or by upgrading to more accurate equipment. Even a single transducer pair requires expensive ship time for the tracking. Acoustic estimation methods depend strongly on the quality of the range measurements. Beyond the inherent noise within the system, measurement errors also depend on the variable sound speed profile [47]. Range calculations will use a pre-determined sound speed profile like, the Munk profile, a constant sound speed, or the measured profile. Measurement error depends on how close this estimate is to the actual sound speed profile and how much ray bending occurs as the sound travels through the water column [48].

Figure 3. SolidWorks Design of PHAGE

1.6 Scope of PHAGE

The goal of the Platform for Hadal Autonomy and General Experimentation (PHAGE) is to provide a scientific platform capable of collecting environmental profiles, and water samples at the full ocean depth of 11 km. The instrument has the ability to record water properties with a variety of sensors while autonomously collecting large quantities (240 L) of non-pressurized water and small pressure retaining samples (120 mL). The design can be seen in Figure 3 and is described in detail in Chapter 2.

PHAGE expands the capabilities of the CTD rosette into the hadal region by being untethered and autonomous. This system will help address the knowledge gap between shipboard CTD profiles and prior hadal vehicles. Figure 4 shows the under-sampled hadal region of the Puerto Rico Trench compared to the upper levels of the Atlantic Ocean expanded from the World Ocean Circulation Experiment transect along 66 °W [50]. This knowledge gap is exhibited across all the world's trenches for all data types.

Figure 4. The World Ocean Circulation Experiment transect along 66 °W expanded to full ocean depth for temperature.

The system has been built and tested over the time period of this thesis. Testing occurred in the Puerto Rico Trench at the locations marked in Figure 5. The hadal area from Figure 4 was sampled with PHAGE and the results will be presented in Chapters 3 and 5.

Figure 5. Puerto Rico Trench deployment sites of PHAGE.

1.7 Statement of Problem

This thesis primarily focuses on the engineering aspects of the PHAGE system, and will discuss the development of the adaptive sampling system, underwater positioning, and sensor evaluation. The general mechanical and software design of the vehicle will be explained in Chapter 2 to provide context. The adaptive sampling system is an algorithm that analyzes the water column to take water samples at important oxygen, temperature, and salinity locations. This adaptive capability is used to supplement samples taken at regular depth intervals. The adaptive method is explained and analyzed in Chapter 3.

The underwater positioning is done using a range-only tracking system. The range

is calculated using the two way travel time of the signal between the ship and two acoustic release devices. Using the ship's GPS coordinates and an estimated triangle, the underwater position can be estimated as presented in Chapter 4.

After the cruise, the performance, sensor data, and water samples were analyzed. The buoyancy, drag, and speed were used to evaluate how the system traveled through the water column, which will help on future deployments. The sensor results were compared to the shipboard CTD rosette casts in the Puerto Rico Trench. The bottom water samples were analyzed to verify the water remained uncontaminated on the ascent, confirming PHAGE is able to accurately sample, and determine deep water properties. This general system evaluation is presented in Chapter 5.

CHAPTER 2

Concept and Design of PHAGE

PHAGE is designed to be a full ocean depth profiler that operates and collects water samples autonomously. It is a hybrid between a conventional CTD rosette and a lander, with an 11,000 meter depth rating. Figure 6 shows the final SolidWorks model of PHAGE with the main parts labeled. This chapter provides background to the system design and operations. Section 2.1 explains the mechanical design of the system, while the software system that operates the vehicle is described in Section 2.2.

Figure 6. A labeled diagram of the PHAGE SolidWorks model.

2.1 Mechanical System Design

PHAGE is designed to have a large payload to profile and sample the water column while maintaining enough buoyancy to return to the surface. By removing the tether and making the vehicle autonomous, PHAGE is able to sample any depth of the ocean without

requiring continuous ship support time. This autonomy allows the ship to perform other tasks while PHAGE is underway. The system has a 24 bottle CTD rosette for 10 to 12 liter Niskin bottles, as seen in Figure 7. The profiler travels at a nominal speed of 60 meters per minute through the water column, while profiling with a CTD and triggering Niskin bottle samples throughout the water column like a conventional CTD rosette. A more descriptive analysis of the speed is presented in Chapter 5.

Figure 7. Completed PHAGE system based on a CTD rosette with electronics mounted below the Niskin bottles.

Niskin bottles do not maintain the pressure of the samples, which allows the water to depressurize during the ascent. This depressurization can destroy biologics in the water or cause a change in water properties as the dissolved gas is released. To more properly study a deep environment and understand the deficiencies of the Niskin samples, the water has to be held at the original pressure. A Scripps Institute of Oceanography team designed pressure retaining samplers for this purpose. The Scripps samplers are pre-pressurized and closed prior to deployment of PHAGE. At depth, they open with a motor to take small (120 mL) samples. The pressurized chamber retains the sample pressure

on the ascent. When desired, the high-pressure samplers can be added to PHAGE in the place of two Niskin bottles per sampler.

Every aspect of PHAGE needs to be able to withstand the immense pressure of the hadal region while maintaining buoyancy. The system is rated for the full ocean depth of 11,022 meters (11,022 dBar or 1088 atm). The electronics bottle, containing the embedded computer and power circuitry was designed out of Titanium (Figure 8) to withstand the pressure and maintain a dry operation area for the electronics. The endcap is 1.25 inches thick to withstand the pressure force acting on the flat surface. The bottle and hemispherical end can be thinner, at 0.55 inches because the curve distributes the force more evenly. It was tested to 11,962 dBar in a pressure facility and 8,377 meters (8,377 dBar or 836 atm) in the Puerto Rico Trench.

Figure 8. Cross-Section of electronics bottle to show titanium thickness and electronic layout.

Similar to many lander designs, PHAGE uses syntactic foam to provide buoyancy for the ascent and expendable steel weights are attached to the bottom for descent. The syntactic foam has a density of 42 lb/ft³ and is strong enough to withstand crushing at depth. The in-water weight of the vehicle was minimized to reduce the total amount of foam needed. The frame is made of aluminum to reduce weight, while being strong enough to support the syntactic foam and 24 full Niskin bottles during recovery. Many parts, like the electronics shelf and skids, are made of a plastic with similar density to

sea water making them neutrally buoyant. In total, 36.4 ft³ of foam is used to provide sufficient buoyancy.

Figure 9. A 400 lb drop weight being lowered into water prior to attachment to PHAGE.

Steel drop weights are attached for the descent of each dive as seen in Figure 9. They are released on the bottom to allow the system to float back to the surface. The weight hangs between the release mechanisms using a lanyard system. There are four release methods on PHAGE for redundancy.

The primary release mechanism is a burn wire activated by a software time. Energizing the burn wire circuit causes the wire to dissolve in seawater and release the weights. The backup mechanisms are two Benthos acoustic releases shown in Figure 6. These releases are activated through an acoustic command sent from a shipboard transducer. They will work if acoustic communication is maintained and will send a confirmation status signal. The failsafe release mechanism is a passive corroding galvanic link. This link slowly dissolves when exposed to salt water and can be sized for different dive durations. In the event of software failure and a loss of acoustic communication, the galvanic link will eventually corrode and the weights will be released.

The acoustic releases also have the capability of ranging with the ship. This range command is used to track the location of PHAGE throughout a dive (Chapter 4). Determining the location of the system allows for the sample coordinates to be geolocated.

Figure 10. Beacon set up on the top of PHAGE.

Beacons are used to detect the system after surfacing. A radio frequency beacon and an Iridium beacon are mounted on the top of the foam as seen in Figure 10. These systems activate upon hitting the surface and send out their respective signals. A radio direction finder (RDF) mounted on the ship can use the radio beacon's signal to determine the bearing to the vehicle relative to the ship. The Iridium beacon obtains the GPS coordinates of the system and sends the position via email to the operator over satellite. This position is also published on metOcean's website for access by the operator. The radio beacon information is received immediately, while the iridium satellite connection takes several minutes and is dependent on Internet connectivity.

The location from the beacons provides the region to search for recovery of surfaced PHAGE. Only a few inches of the yellow foam are visible above the water. To increase visibility, an orange flag and a radar reflector stick a few feet above the surface. A strobe attached next to the other beacons is helpful for night recoveries. The complete set up of

the identification systems can be seen in Figure 10. The cover over the beacons provides protection from snagging on the launch or recovery rigging.

The large titanium lifting bail above the foam allows for easy launch and recovery. It is connected through the foam to the frame in order to support the vehicle. For launch, the system is lifted by the bail using a pull pin release. The drop weights are lowered over the side until they are fully supported by the vehicle's release sling. PHAGE is then lowered into the water and the pin is released. The size of the bail was designed to facilitate recovery. The large target is relatively the easy to hook as the ship approaches it, and the shape directs the line to the top of the bail.

Figure 11. Dr. Chris Roman using the attachable ladder to access the beacons and attach the flag.

After initial testing, a detachable ladder was added to the system to provide safe access of the top of PHAGE (Figure 11). This made launch and recovery easier by providing access to the beacons for activation and to the lifting bail for rigging. Skids were added to provide stability while on deck and to help control the movement along the deck during launch and recovery.

2.2 Software System Design

The PHAGE software is a compilation of Python scripts that run on a RaspberryPi during deployment. The system uses serial communication and the Lightweight Communications and Marshalling (LCM) communications library to monitor and control the system [51].

LCM uses a publish and subscribe channel system for inter-process communication on the local machine or over a network. The channels are identified by a name and use pre-assigned data types assigned in LCM configuration files (see [51] for examples). Data published to an LCM channel passes on the local network and can be read by subscribing processes. The LCM logger records the published messages in a binary log file [51].

The software system also communicates over serial ports to the devices connected to the embedded computer. For the Puerto Rico tests, the CTD, bottle trigger mechanism, and high-pressure sampler motor controllers were connected to serial ports. The serial information is handled by device specific drivers and published over LCM to be logged and used by other processes.

Before the dive, the user writes a mission plan to dictate how the software will operate. The mission plan is made up of global parameters for the dive and sample bottle descriptors (Figure 12). The dive is described by the global parameters of bottom time and system launch latitude. The other global parameters are abort conditions, which include the maximum mission time, the maximum depth, a battery cutoff, and a CTD communications abort. The burn wire is activated to release the weights if any of the abort flags are activated, the time exceeds the mission time, or the system goes deeper than the limit. This logic ensures the system will try to return if a fault occurs.

Once the global parameters are determined, each desired sample bottle is set. The bottles are described with a Bottle ID number, a Trigger parameter, a Value for the bottle


```

#all depths and velocities are positive
GLOBAL
  mis_timeout 06:00:00      # sec or min:sec or hr:min:sec
  bottom_time 00:05:00     # sec or min:sec or hr:min:sec
  max_depth 8600           # positive meters
  enable_battery_abort 1    # (0) no (1) yes
  battery_cutoff 20        # percent capacity
  enable_ctd_abort 1       # (0) no (1) yes
  latitude 19.5            #latitude in decimal degrees
ENDGLOBAL

BOTTLE
  number 1
  trigger DEPTH
  value 5000
  state UP
ENDBOTTLE

```

Figure 12. An example mission file with the global parameters and a bottle setup.

to close at, a State the vehicle will be in when the bottle closes, and possibly a Delay time for a bottle triggered on the bottom. Each Bottle on PHAGE has an ID number. The Niskin bottles go from 1 to 24, whereas the high-pressure bottles are identified with 101 and 102. When the Trigger is depth, the Value determines the depth at which to trigger the bottle (bottom, surface, depth number). The State options are Down, Bottom, Up, and Surface, which are determined through a velocity estimate based on the change in depth over the change in time. If a bottle is set to Bottom, a Delay can be set for the bottle to close at different bottom times. More parameters are used for the adaptive software and are described in Section 3.1.

This mission plan is parsed to check for valid inputs and published for use in other processes. The mission executor process reads in the global parameters to execute the dive plan. Throughout the dive, the mission software tracks the dive time, checks the abort flags, reads in the CTD pressure, determines the State, and activates the burn wire when appropriate.

The bottle monitoring and triggering process receives the bottle trigger information from the mission parser. It then monitors the state of the vehicle and the depth. When all the trigger conditions are met, the process sends a serial command to close the specified bottle. A return communication lets the software know a sample was successfully taken. Due to the travel time between the software to registering the correct depth and closing the bottle, the sample will be within a meter of the desired sampling depth.

Taking up to 24 Niskin samples throughout the water column at preset depths provides a sparse representation of the water column and may miss important hydrographic features. To ensure specific aspects of the water column are sampled, an adaptive software system has been incorporated. This software is described in more detail in the Chapter 3.

CHAPTER 3

Adaptive Software Design

The adaptive software is designed to supplement the depth-specific samples by locating and sampling at features in the water column based on the collected data. Figure 13 shows the temperature, salinity, and oxygen profiles from a PHAGE dive in the Milwaukee Deep, at the Puerto Rico Trench. The points show 20 possible sample depths. The bottles are spaced at 500 meter intervals with two bottom sample bottles and two bottles above 500 meters. The samples are spread out in depth sampling schemes obtain a representative sampling of the profile, but have a high likelihood of missing water column features. For example, the deep thermocline seen in 13(a) between 5000 and 5500 meters will not be sampled with this sample spacing. Other features that could be missed are a local salinity minimum around 950 m, in 13(b), and an oxygen minimum near 700 m, in 13(c), as well as other gradients, local maximums, and local minimums.

Figure 13. The temperature, salinity, and oxygen profiles of the Puerto Rico Trench.

The adaptive software provides PHAGE the capability to autonomously analyze the water column and sample interesting features specified by the operator. The input parameters of the adaptive software are discussed in Section 3.1. The algorithm for the adaptive processing is presented in Section 3.2. The hadal zone test results are presented and analyzed in Section 3.3.

3.1 Adaptive Bottle Parameters

The adaptive algorithm takes input parameters specified by the user to describe the desired sample locations. The user provides information about which sensor to analyze, where to search, what value to search for, and what bottle to close. Knowledge of the water column can help the user to better identify these inputs. The configuration information is provided in terms of the adaptive bottle parameters of Trigger, Range Window, Value, and Offset. The Bottle ID and State from Chapter 2 are also used, but the State will always be Up for the adaptive bottles because the descent profile is needed to find the water column features. The descent profile is analyzed on the ocean bottom, and the algorithm sets the bottle trigger depths for the ascent, as explained in Section 3.2. Figure 14 shows the specific adaptive software parameters and the options for each.

Figure 14. The input parameters of the adaptive bottle software.

The Trigger is the water property to be examined for the water column feature. This parameter is limited to the water properties measured by the sensors on PHAGE during sampling. For the Puerto Rico tests, the Triggers were salinity, temperature, oxygen, and density.

The Trigger parameter search is then narrowed using the Range Window. The Range Window is an optional parameter that allows the profile to be parsed out into depth ranges. The range is set by the upper and lower bounds of the area of interest. The possible inputs include Surface, Middle, Bottom, and user specified depth numbers. The Surface input starts the analysis at 50 meters depth to avoid the complexity of the surface layer. Figure 15 shows examples of different Range Window options. The default for the Range Window is the entire profile (Surface to Bottom) as seen in 15(a). The upper water column can be examined by setting the deeper range to middle as seen in 15(b), while 15(c) shows the hadal region from 5000 meters to the bottom. The Range Window allows more minute changes in the profile to be identified, especially smaller gradients and local maxima and minima. Knowledge of the water column from previous dives or CTD casts allows the Range Window to be specified accurately, enabling the system to sample the small changes.

Figure 15. Examples of the Range Window parameter. (a) Entire profile from Surface to Bottom. (b) Upper ocean profile from Surface to Middle. (c) Deep Range Window from 5000 meters to Bottom.

The Value indicates how the trigger parameter will be analyzed within the Range Window. The Value can be a minimum, maximum, gradient, or a specific number to be found along the selected Trigger's profile.

The gradient is calculated by first smoothing the data with a moving average filter and then taking the derivative of the Trigger parameter with respect to time. The data array is smoothed with a square function convolution of length 240 (24 samples per second for 10 seconds) to avoid the inherent noise of the sensor, while maintaining the general trend of the curve. An acausal smoothing is performed by averaging past and future samples around the current time, which is possible because the analysis is performed on stored data while PHAGE is on the bottom. The minimum or maximum of the gradient is calculated from the smoothed data array.

Another optional parameter is an Offset for a gradient Value (the default is 0). This parameter adds on a depth offset to the determined gradient value's depth allowing for sampling water masses above and below the expected gradient or for sampling different parts of the gradient. Because depth is considered a positive number, a positive offset will provide a deeper sample and a negative offset will be shallower.

These parameters for the adaptive system generate a flexible profiling system that can be used to sample oxygen minimums, thermoclines, haloclines, local values, and adjacent water masses.

3.2 Software Algorithm

The goal of the adaptive software is to translate the identified water column features into sample depths for the trigger monitor to use. The software receives the bottle information from the mission planner, records the CTD data feed, locates the features along the water column while on the bottom, and sends the calculated depths to the Trigger Monitor software. Each CTD data sample contains temperature, salinity, oxygen, depth, and a timestamp. Using these pairings, a specific Value of a Trigger parameter

can be related back to the sample depth. An Algorithm describing this adaptive process is presented in Appendix A.

3.3 Results and Analysis

The adaptive algorithm was tested through simulation prior to the in-water testing of PHAGE. The simulation proved the software could identify the water column feature from the descent profile and close a bottle at the specified depth. All possible input parameter combinations were tested to ensure the process would not crash in the middle of a dive. After ensuring the robustness, the adaptive sampling was tested on the research cruise in the Puerto Rico Trench. The results are presented throughout this section along with additional figures made in simulation to demonstrate all of the adaptive properties.

To verify the using the descent profile to locate water features for sampling on the ascent, the stability of the water column was analyzed. The temperature and salinity differences between the descent and ascent depths were under 0.08°C and 0.01 PSU. These low values indicate the Puerto Rico Trench is stable enough for this sampling scheme. For future deployments, the stability of the water column should be verified prior to using the adaptive software.

The success of the temperature adaptive bottle sampling can be seen in Figure 16. The targeted temperature features were thermoclines marked by a local maximum on the gradient plot in 16(a) in the mixing area between water masses. These are sampled using a Value of gradient. The main thermocline below the surface mixed layer is successfully sampled with Bottle 2 in 16(b). A hadal thermocline was identified below 5000 meters after the first deep dive. Bottle 5 was able to sample this local gradient by limiting the Range Window to 5000 meters and below. For demonstration of a Value input of a specified number, Bottle 10 was added in simulation to sample water at 3.5°C .

A problem that appeared with the gradient function is that it activates on the largest change in parameter over change in time, which may not be the desired location. The

Figure 16. Examples of temperature adaptive sample bottles. (a) Absolute value of temperature gradient profile. (b) Temperature Triggered adaptive bottles activating at thermoclines (Bottles 2, 5) and a set Value (Bottle 10) of 3.5°C . (c) Offset parameter (100 meters) example on either side of Bottles 2 and 5.

water column can be variable, and the largest gradient may not be the desired part of the thermocline; especially if the mixed layer is irregular, the Trigger sensor does not acclimate as expected, or there is a seasonal gradient present. Limiting the Range Window helps to avoid sampling at an incorrect location, but prior knowledge of the water column is needed to perform this task correctly. The gradients in 16(b) were sampled after a complete dive, so the water column was analyzed to learn the approximate depths of the gradients and sample the correct locations. To avoid the steep seasonal Temperature gradient, the Range Window was limited to 300 meters and below. Sampling above the 300 meters could be done with the Depth Trigger or manually with a shipboard CTD.

An Offset parameter was tested around both of the thermoclines, as seen in 16(c). Bottles 4, 5, and 6 demonstrate how the Offset allows the system take representative samples of the gradient and its surrounding water masses. Whereas, Bottles 1, 2, and 3 show how the Offset can be used to sample different locations along a thermocline.

Figure 17(a) shows the successful sampling of the salinity maximum (Bottle 1), the halocline (Bottle 2), and a local salinity minimum (Bottle 3). To avoid sampling the surface layer gradient, the Range Window was adjusted to sample between 200 meters and the Bottom for Bottle 2, which requires knowledge of the water column. Figure 17(b) shows the sampling of oxygen Trigger points. Bottle 1 shows sampling an oxygen maximum, while Bottle 2 shows sampling the oxygen minimum. The sampling in the Puerto Rico Trench integrated depth prescribed sampling profiles with adaptive bottles.

Figure 17. Examples of adaptive bottles at minimums and maximums. (a) Bottles closing at salinity maximum (Bottle 1), halocline (Bottle 2), and local minimum (Bottle 3). (b) Bottles closing at oxygen maximum (Bottle 1) and oxygen minimum (Bottle 2).

Figure 18 is an example of the combination of Depth and adaptive samples. The same depth distribution from Figure 13 was used, but the upper four bottles were replaced by the adaptive bottles. Bottles 17 and 18 sample the shallow and deep thermoclines respectively indicated by the black squares in 18(a). The black triangle for Bottle 20 shows a local salinity minimum in 18(b). Lastly, the black circle indicates the oxygen minimum zone at Bottle 19 in 18(c).

Figure 18. An example of the combination of depth distributed bottles (red stars) with supplemented adaptive bottles (black marks). Bottles 17 and 18 are thermoclines, Bottle 19 is the oxygen minimum, and Bottle 20 is the salinity minimum.

Figure 18 demonstrates a potential sample scheme that can be used, but any combination of bottles is possible. Each dive throughout the research cruise had a different combination of depth, time based, and adaptive bottles to sample all areas of the profile. Overall, the adaptive system located and sampled the water column features as desired. Due to the variability of the water column, the system needs specific instructions to prevent incorrect points from being sampled. Knowledge of the water column allows the specification of features and select ranges. This is done to avoid erroneous points and make the system more likely to hit the features.

CHAPTER 4

Range-Only Navigation

During testing, the system was monitored with range-only tracking to provide an estimate of the vehicle's location while deployed. When submerged, the acoustics are the only means of communication between the ship and PHAGE. The acoustic releases on the vehicle can send the state of the release command, release (released or not), range measurements, and a status check. The transducer is omnidirectional, so there is no way to determine the bearing of PHAGE from a single range. A rough estimate of the location can be calculated using multiple ranges, the ship's GPS, and a model of PHAGE's vertical motion. The test cruise used the triangulating process described in the following Section for tracking.

Image not to scale

Figure 19. PHAGE to ship triangle used for calculation of position.

4.1 Triangulating Tracking Method

The triangulating method uses range signals and a modeled depth estimate to create a triangle that determines the horizontal distance PHAGE is from the ship. This distance is then plotted as a circle around the GPS location of the ship. As more circles are estimated, the overlap location will indicate the position of PHAGE.

The right triangle is formed, as seen in Figure 19, using the range as the hypotenuse, the estimated depth of PHAGE as one side, and the horizontal distance away from the ship as the other. The only knowns in the system are the ship's GPS coordinates and the range. This leaves two sides of the triangle as unknowns.

The depth of PHAGE can be estimated through a motion model which attempts to estimate the depth when each range is received by simulating the ascent and descent. Inputs to the model include the launch time, bottom time, and expected speeds. A graphic user interface (GUI) allows for later adjustments of the inputs to fine tune the model. Due to the seawater density change, the vehicle speed varies with depth. To simplify this problem, a linear speed profile is set for the ascent and descent of the system. The speeds are determined from the weight, buoyancy, drag coefficient, and density as explained in Chapter 5. When a range is received, the model calculates the expected depth using the velocity and time between measurements. If set correctly, the model depth will be close to the actual depth.

With the depth estimate, the horizontal distance away from the ship is calculated to determine a circle of potential locations around the ship. PHAGE could be at any point along the circle. By repeating this process with multiple ranges and ship locations, the circles will overlap at fewer and fewer locations until there is only one likely location.

Figure 20 shows an example of the range-only tracking successfully pinpointing PHAGE where all the circles overlap (identified by the red box) around $19^{\circ} 42.6' \text{ N}$ by $-66^{\circ} 27.47' \text{ E}$. The green and blue points indicated the ship GPS location when the

Figure 20. Triangulation with ranges and ship locations working to locate PHAGE (inside the red box).

range was received with the color identifying with which release produced the range. To de-clutter the plots and account for horizontal movement, only the most recent 50 ranges are used.

To help the ship track the state of PHAGE while underway, the ranges are plotted against the elapse time since that measurement. For example, Figure 21(a) shows the most recent range plotted at time 0, while the first range received was 5000 seconds before it. Figure 21(b) shows the all the ranges received throughout a dive. The descent

is shown by increasing ranges as the ranges (around $-70,000$ seconds), while the ascent is decreasing ($-10,000$ to 0 seconds) and bottom is relatively flat (top of the plot).

The inconsistency of the acoustics will lead to the gaps in the data. Typically, only one release provides ranges at a time. This is thought to occur based on which side of PHAGE the ship is on because the foam is likely blocking one release from ranging while the other has a direct path. For example, Figure 20 is mostly green because the ship is on the same side as release 1, with the foam blocking release 2.

(a)

(b)

Figure 21. Ranges received from PHAGE while operating (a) A live plot of PHAGE on descent. (b) A simulated plot to show the full dive of ranges.

The range-only tracking faced many of the common problems mentioned in Chapter 1. The main uncertainty with the tracking is caused by errors within the depth model. If the speeds or start time are incorrect, the triangulation will estimate an incorrect

horizontal distance. If the model sets the velocity too slow, the estimate will be larger than expected. If too fast, the depth will be greater than the range, and lead to an ill-conditioned solution. These errors are exacerbated by short horizontal distances relative to water depth. To show this incorrect result on the plot, a small circle is shown to notify the operator the estimation is wrong and should not be trusted (Figure 22).

Another potential source of inaccuracy is the sound speed profile and the possibility of ray bending, causing the range to be different than a straight path. The instrument

Figure 22. Example of range-only tracking errors when model is set too fast causing the triangle to become imaginary.

Figure 23. A comparison of the sound speed profiles.

calculated the distance from the two way travel time using a constant sound speed of 1500 m/s. While this estimate is reasonable for the upper water column, the actual sound speed varies based on water properties and depth, so the deep water sound speed is much greater than the constant 1500 m/s. Figure 23 shows the sound speed profile in the Puerto Rico Trench compared to the constant sound speed profile and the Munk profile. To compensate, the range is adjusted using the actual sound speed profile if known from prior sampling or the Munk sound speed profile to get a closer result.

To determine the effect of ray bending throughout the profile, the ray traces in Figure 24 and 25 were performed using the BELLHOP model with the measured Puerto Rico Trench sound speed profile [52]. During testing, the ship attempted to remain within a horizontal distance of 1.5 kilometers of PHAGE. This distance was used as the range for the tracing evaluation. Rays were plotted to show the farthest distance traveled at

8370 meters depth and 1500 meters range. This ray appears relatively direct between the ship and the vehicle, showing very little bending. Figure 24(b) shows the relationship between the added distance due to bending and the horizontal distance if PHAGE is parked on the bottom. This error is calculated through comparison of the length of the ray with sound speed already taken into account to the straight line distance between the end point of the ray and the source. Because the effect of sound speed variation has been removed and the depth is much greater than the range, the errors from ray bending are very small, remaining less than 0.1 meter for the distances of interest. This analysis suggests ray bending has little effect at our ranges of interest because vertical distance

Figure 24. Deep ray trace and horizontal distance error. (a) Trace at full ocean depth and 1500 meters horizontal distance. (b) Distance error of ray bending when PHAGE is on the bottom with adjusting different horizontal distances. The two error curves were generated by the different rays paths that reached the source location.

is much greater than the horizontal so the sound is hitting the density gradients at high grazing angles. The range field was extended out to verify the error would continue to increase as the grazing angle increased, reaching 20 meters of error at a 10 km range.

Shallower ray traces show much more prominent bending as seen in Figure 25 due to the sound speed profile manipulating the shallow angle rays. The distance error of the rays along the vertical profile at a 1.5 kilometers horizontal distance is plotted. This error has a larger ray bending effect. The shallow rays experience the most bending because they hit the density fronts at low grazing angles. The deeper the ray, the less bending seen (Figure 25(b)). The error decreases as the depth increases until it is approximately equal to the error from Figure 24. The ray bending will greatly effect the range data when PHAGE is shallow. The error between the direct path and the ray can be used to correct the range measurement if the horizontal range is known.

When set up correctly, the range-only tracker system can determine the location of the deployed system for operational purposes. The interface allows for the motion model to be tuned using the speed estimation (Chapter 5) increasing the tracker accuracy. Chapter 6 establishes ways to make the system more robust through filtering the errors.

Figure 25. Shallow ray trace and vertical distance error. (a) Shallow water trace with horizontal distance set to 1500 m and changing depths. (b) Distance error of ray bending when PHAGE at a horizontal distance of 1500 meters with adjusting depths.

CHAPTER 5

System Evaluation and Testing Results

The overall performance of the system was analyzed to determine how it behaved and to better understand the sensor data. In this chapter, the profiler weight and buoyancy are reviewed to assess the vertical speeds and ballasting. This is followed by an assessment of the sensor data. Lastly, the water samples are discussed in the context of the Puerto Rico Trench. This analysis will to establish the best practices to operate the profiler on future deployments.

5.1 System Analysis

After testing PHAGE in the Puerto Rico Trench, the data was examined to determine the vertical speeds, buoyancy, and drag of the system. Predictions of how the system would behave were compared to the measured data to determine how to predict the movement of the system through the water column.

5.1.1 Buoyancy and Weight Analysis

The vehicle is operated with enough ballast and buoyancy to ascend and descend through the water column at desired speeds. As the pressure increases throughout the profile, the water becomes compressed, increasing its density. The buoyancy force (F_B) on an object is directly related to the density of the surrounding water and also increases. The in-water weight of an object (W) can be determined from its weight in air minus the buoyancy as shown in Equation 1, where m is the mass of the object in air, ρ is the density of the object, ρ_w is the water density, and g is gravity. This can also be expressed in terms of volume (V) in Equation 2.

$$W = g \left(m - m \left(\frac{\rho_w}{\rho} \right) \right) \quad (1)$$

$$W = g(m - V\rho_w) \quad (2)$$

If an object is compressible, the volumetric strain (ε) caused by pressure needs to be taken into account. Equation 3 uses the Modulus of Elasticity (E) and Poisson's ratio (ν) to calculate the percent deformation of one axis from a three-dimensional stress. The foam is assumed to be homogenous and compress evenly, so ε will be the same for all axis. By using the pressure profile (P) and density profile (ρ_w), a volumetric strain profile can be created to show the amount of strain at each depth. The strain-adjusted in-water weight of the object can be calculated using Equation 4.

$$\varepsilon = \frac{-(1 - 2\nu)P}{E} \quad (3)$$

Figure 26. Foam buoyancy change throughout the profile from density increase and foam compression.

$$W = g(m - (1 - \varepsilon)^3 V \rho_w) \quad (4)$$

For PHAGE, the syntactic foam is the most significant compressible component. Without taking into account compressibility, the foam buoyancy increases 12.2% from the density change between the surface and 8370 meters. Compression of the foam is calculated using the Modulus of Elasticity and Poisson's ratio provided from the manufacturers at 570,000 psi and 0.35. The foam volume is compressed by 1.95% due to pressure. When this value is combined with the density difference, the buoyancy decreases from compression by 6.09%. Overall, the foam will increase the buoyancy force by 6.15% between the surface and the bottom. For a foam volume of 36.4 ft^3 , this equates to a 48 lb increase in buoyancy at 8370 meters from the surface buoyancy.

5.1.2 Fall Rate and Drag Analysis

The speed of PHAGE can be estimated from the forces acting on the vehicle using the standard drag equation (5). At steady state velocity, the drag force (F_D) will equal the net buoyancy force, ($F_w - F_B$). For pre-testing calculations, the drag coefficient of 0.82 (a long cylinder) was assumed to predict the velocity of the vehicle.

$$F_D = \frac{1}{2} \rho A v^2 C_d \quad (5)$$

Using the measured speed of the vehicle during deployment, the actual drag coefficient was calculated. The found drag coefficients averaged 0.73 on descent and 1.02 on ascent. The difference between the coefficients is assumed to depend on the part of the vehicle facing the flow. During descent the weights break the flow and effectively extending the length of the vehicle and reducing the drag, while the blunt face of the foam causes more drag on the ascent. With these drag coefficients, the velocity of the system can be better estimated for various ballasting conditions and water densities (Figure 27). Being able to estimate the profiling speed can help determine the drop and

Figure 27. PHAGE downward velocity profile compared to estimated profile.

ballast weights necessary on future dives, as well as assist in the tuning of the motion model for the range-only tracking system (Chapter 4).

The estimated speed of the vehicle upon hitting the bottom can be used to calculate the additional distance the system travels after the drop weights hit the bottom. Ideally, the weights are hung far enough below the vehicle to allow for the vehicle to remain above the bottom for this overshoot. In Figure 28, the vehicle was traveling 57.5 m/min before the bottom and overshoot by 0.9 meters. The weights are hung 3 meters below the vehicle to avoid contacting the bottom.

5.2 Sensor Analysis

The sensors attached to PHAGE were customized to reach the hadal region. The temperature and conductivity sensors on the CTD are specified to an initial accuracy of 0.001°C and 0.0003 S/m at any pressure with a stability of $+0.0002^{\circ}\text{C/month}$ and

Figure 28. The bottom of a vehicle's drop profile where the 0.9 meter overshoot can be seen after traveling 57.5 m/min.

+0.0003 S/m/month. The Digiquartz pressure sensor is "immune to environmental effects" and has an accuracy of 0.015% of full depth range [1]. Figure 29 shows the comparison of the sensors to the shipboard CTD sensors. The mix layer demonstrates a large error for both sensors due to the shipboard CTD being a night profile and PHAGE a day profile. Under the mixed layer, the sensors have an error of 0.021°C and 0.0025 S/m. These errors are higher than the initial accuracy having not been recalibrated in over 8 months, but are within a reasonable error to assume they are accurate.

The oxygen sensor uses a permeable membrane to measure the dissolved oxygen in the water. Due to the plasticity of the membrane, the sensor experiences a hysteresis from deformation under pressure, shown by the blue line in Figures 30 and 31. Seabird acknowledges this problem and has guidelines to properly correct for it through a provided software for automatic correction or an adjustment algorithm [53]. The algorithm to

Figure 29. Comparison of the temperature and salinity sensors on PHAGE to the shipboard CTD sensors and Percent Error using CTD data as actual.

Figure 30. The oxygen sensor's hysteresis (blue) and the corrected values (red) for a short PHAGE dive compared to the shipboard CTD's raw (yellow) and hysteresis corrected (purple) data. Seabird suggested oxygen correction plots of the oxygen profile (left), the oxygen level on bottom to see hysteresis change (top right), and the oxygen verses potential temperature.

Figure 31. Seabird suggested oxygen hysteresis correction plots applied to a dive with 15 hours at pressure.

manually correct data is provided in [54]. Both methods use tuning parameters (H1, H2, and H3) to bring the measurement closer to the actual value. When adjusting these constants, Seabird suggested minimizing the hysteresis gap of oxygen against pressure (left plot) and of oxygen against potential temperature (bottom right) while attempting to eliminate the decay of oxygen when at constant pressure on bottom (top right). The red line on the plots shows the hysteresis corrected for using Seabird's algorithm, while the yellow and purple lines show the shipboard CTD's raw and corrected data as a reference.

A problem with using this correction is that the H values varied for each dive depth and length. For some dives, the system remained on the bottom for hours effecting the membrane more. The correction for the short PHAGE dive used $H1 = -0.037$, $H2 = 5000$, and $H3 = 2000$, while the long dive used an $H1 = -0.051$, $H2 = 5000$, and $H3 = 2200$. Because of this inconsistency, each dive needs to be adjusted based on time at pressure to get repeatable up and down casts.

5.3 Water Sample Analysis

The bottom water sampled from the Puerto Rico Trench was analyzed to determine the age and the source. Figure 32 compares the TS diagram of the bottom water sampled to the identified values of deep water sources. The bottom water is just outside the expected boundary of NADW, which indicates a small amount of AABW is probably present, but the primary source should be NADW.

Three different samples were sent to Woods Hole Oceanographic Institute to be carbon dated. The results of the carbon dating showed the radiocarbon ($\Delta^{14}\text{C}$) at -113.15‰ , -113.59‰ , and -118.93‰ . The percent Modern carbon age of these samples supplied from the lab is 900 years, 905 years, and 950 years with an error of ± 30 years for the first

Figure 32. TS plot of water masses and water sampled

age and ± 25 years for the second and third. Percent Modern is a weighting technique for carbon dating described in [55]. For comparison purposes, the conventional carbon ages were calculated from the $\Delta^{14}\text{C}$ using Equation 6 to be 965 years, 970 years, and 1020 years.

$$t = -8033 \times \ln\left(1 - \frac{\Delta^{14}\text{C}}{1000}\right) \quad (6)$$

Unfortunately, the tracer elements of SiO_2 and NO used in [12], [15], and [16] to determine the deep-water ratio between AABW and NADW were not measured, but O_2 and PO_4^* were. The radiocarbon reservoir levels used for calculations were -140‰ for AABW and -57‰ for NADW [16, 33].

These tracer elements indicate around 18% AABW in the mixture (reservoir levels established in [16]). Using the radiocarbon formula, Equation 6, and adjusting it based on surface ages and expected mixing ratio, the water is around 355 ± 25 years old. This estimate is older than the surrounding water measurements of 250 to 300 years, but not as old as the deep trench estimates of 600 years. Because the water in the trench is only about 100 years older than the surrounding water, the trench has the expected overturning current established in [26, 27, 29, 30].

CHAPTER 6

Conclusion and Future Work

Overall, PHAGE withstood the immense hadal pressures and operated as intended. The software was able to determine the State, profile the entire water column, and release the weights when desired. The drop weights and lead ballast were adjusted based on the sampling payload and desired fall rate of each dive. Testing at different speeds provided data to calculate the drag coefficients, so estimation of the vertical speeds will be more accurate for future deployments.

All of the release mechanisms proved to work. As the primary release source, the burn wire activated and dissolved when desired on all the trench deployments. The acoustic releases were used successfully on a previous engineering cruise and during in-air testing. Luckily, the galvanic release was never needed during the ocean tests but showed corrosion upon recovery and in lab tests.

The profiler's location was identified upon surfacing using the beacon system and then spotted with the flag and bright foam. Range-tracking provided an idea of when and where the system would surface. To locate the vehicle, the radio beacon had a quickly identified the bearing to the vehicle. The Iridium beacon took longer but provided precise GPS coordinates. Once the location was identified, the flag and radar reflector helped to identify the system by sight. For the night recovery, the strobe easily identified the vehicle from over a kilometer away.

Currently, the mission file is tedious to set up correctly. It uses a specific input format and requires all the bottles set individually. To make the inputs more user friendly, a graphic user interface (GUI) is being designed to generate the mission file.

The adaptive system performed well throughout the trench sampling. It managed to sample the gradients, maximums, and minimums of the water column. Currently, the

adaptive software is used for salinity, temperature, and oxygen measurements. The next step for the system is to make it adaptable to more sensors.

Range-only tracking was effective but highly variable based on the motion model inputs. Unfortunately, it was difficult to tune the vehicle model to match the vertical speeds of PHAGE, which generated errors in the tracking system. The GUI allowed for adjusting the inputs without restarting the software, so the tracking could be tuned while PHAGE is underway. Tuning the system allowed for repeatable fixes to be set and a location to be determined. For future renditions of this range-only tracking system, the range and model errors can be filtered using the Kalman or Particle filtering techniques presented in [46, 56] and implemented in [49, 57]. By implementing one of these filtering techniques and incorporating a Bayesian estimation of the known PHAGE drop location, the range-only estimate can become less dependent on the estimate of the velocity making it more accurate.

Unfortunately, the Scripps samplers had a low success rate due to mechanical issues with the motor drives. Scripps is analyzing the successful pressurized samples and is working to improve the success rate of their samplers.

The oxygen sensor will be temperamental at any hadal depth due to the hysteresis, but oxygen measurements from shipboard CTD and water samples can be used to better correct for the hysteresis. The age of the water is difficult to correctly estimate, and there is no universal standard for deep-water aging. The most complete methods consider the mixing ratio of AABW to NADW, but it is still difficult to determine the accuracy and requires knowledge of the tracer elements in the sample. For future deep dives, sampling chemical tracers would help determine the deep-water ratio to refine the the actual circulation age.

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APPENDIX

Algorithm for Adaptive Sampling

The adaptive software creates a *bottle list* of the adaptive bottles specified. The system then enters a passive while loop of recording the CTD data feed while PHAGE is descending. This loop is broken when the system reaches the Bottom. On the Bottom, each bottle is analyzed to find the Depth location of its adaptive parameters in the water column.

A data array is generated from the CTD sensor the Trigger identified and is narrowed to the depths specified in the Range Window. With this narrowed array, the Value is calculated using the identified method. The Value of the water feature is converted into Depth for triggering of the bottle on the ascent. For the gradient Value, the Offset is added to the found Depth.

```
Algorithm Adaptive Software System
Receive Adaptive Bottles from Mission Plan
for each Adaptive Bottle received do
    Save Adaptive Bottle Data to bottle list
end for
while mission state is DOWN do
    Record incoming CTD data points to arrays for each
    sensor (Salinity, Temperature, Oxygen, Depth)
end while (mission state is BOTTOM)
for each bottle saved in bottle list do
    Isolate correct CTD data array from TRIGGER parameter
    Determine the indices of the depths specified by RANGE WINDOW
    Limit TRIGGER array to between RANGE WINDOW indices
    Search limited TRIGGER array for matching VALUE
    if VALUE of Adaptive Bottle is MAXIMUM do
        Find the maximum value in the isolated data array
        Determine the index of that value
        Use that index to determine the depth of that data point
        Save DEPTH
    else if VALUE of Adaptive Bottle is MINIMUM do
        Find the minimum value in the isolated data array
```

```

        Determine the index of that value
        Use that index to determine the depth of that data point
        Save DEPTH
    else if VALUE of Adaptive Bottle is GRADIENT do
        Smooth the data using convolution
        Calculate the change in TRIGGER value over change in time
        using smoothed data
        Determine the maximum of the calculated gradient
        Determine the index of that value
        Use that index to determine the depth of that data point
        Add OFFSET distance to DEPTH calculated to get new DEPTH
        Save DEPTH
    else if VALUE of Adaptive Bottle is a number do
        Find the value that is closest to the number specified
        Determine the index of that value
        Use that index to determine the depth of that data point
        Save DEPTH
    end if
    Send BOTTLE ID and DEPTH to the BOTTLE TRIGGER SOFTWARE
end for

```

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