Chesapeake Bay dissolved oxygen profiling using a lightweight, low-powered real-time inductive $CTDO_2$ mooring with sensors at multiple vertical measurement levels

a) Partnership as in Sec 3.8 with Doug Wilson serving as Project Lead.

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Baltimore, MD. Oceanographer and Principal Officer, 40 years
Darius Miller, Soundnine Inc. (S9) [CAGE Code 7AD41, DUNS: 078462398, EIN: 45-3980978]
Kirkland, WA. President and Principal Engineer, 16 years

b) **SOW 8** ***Pilot a cost-effective, real-time dissolved oxygen vertical monitoring system for characterizing mainstem Chesapeake Bay hypoxia***

c) **Proposal - Introduction**

Water quality impairment in the Chesapeake Bay, caused primarily by excessive long-term nutrient input from runoff and groundwater, is characterized by extreme seasonal hypoxia, particularly in the bottom layers of the deeper mainstem (although it is often present elsewhere). In addition to obvious negative impacts on ecosystems where it occurs, hypoxia represents the integrated effect of watershed-wide nutrient pollution, and monitoring the size and location of the hypoxic regions is important to assessing Chesapeake Bay health and restoration progress.

Chesapeake Bay Program direct water quality monitoring has been by necessity widely spaced in time and location, with monthly or bi-monthly single fixed stations separated by several kilometers. The need for continuous, real time, vertically sampled profiles of dissolved oxygen has been long recognized, and improvements in hypoxia modeling and sensor technology make it achievable. Recent results of Bever, et al. (2018) show that total Chesapeake Bay hypoxic volume can be estimated using a few analytically selected fixed continuous dissolved oxygen profiles.

Requirements

The RFP SOW 8 requests 4 outputs (paraphrased):

*1) lessons learned regarding a **reliable** infrastructure that sustains the deployment;*
*2**) reliable**/dependable infrastructure assessment of the gear deployed;*
*3) successes and challenges of the piloted equipment in collecting, storing, and providing **reliable** data in the summer season in the mainstem Chesapeake Bay;*
4) details of protocols to be adopted and invested in for deployment of vertical profiling infrastructure.

The highest priority requirement based on these (noted in 3 of 4) is ***reliability***. Based on our extensive experience designing and supporting real-time environmental monitoring systems, particularly in Chesapeake Bay, as well as familiarity with CBP and partners' interests, additional critical considerations must be:

- Whether the system and resulting data meet CBP and partners' data needs
  - Provision of desired parameters (in this case dissolved oxygen concentration – which requires coincident temperature and salinity for accurate calculation)
  - Adequate data quality – initially and over the whole of a seasonal deployment
  - Vertical resolution – the ability to capture the important features of vertical structure
  - Real-time data delivery that is timely, easy, and dependable
- Financial sustainability
  - Minimum initial cost to acquire and deploy
  - Minimal level of field support required during deployment
  - Long lifetime of equipment and ease/cost of off-season repairs, refurbishment, and calibration
- Flexibility – the system must be successful in all required locations, recognizing that diverse, often extreme physical environments and conditions will be encountered.

These requirements define our approach. There are two basic ways to acquire a vertical water column profile – by either a) moving a sensor package repeatedly through the water column, or b) locating sensor packages at multiple fixed depths, with vertical sensor spacing adequate to meet observational requirements. Either way, data must be regularly collected and transmitted from the *in situ* system location to an accessible data structure. Our proposed solution is b, the simpler and more reliable of the two options. This is described below, with rationale for how the approach best fits these requirements.

Approach *A lightweight, low-powered real-time inductive $CTDO_2$ mooring with sensors at multiple vertical measurement levels*

Sensors will be independent, integrated temperature / conductivity / dissolved oxygen (pressure optional) modules developed by collaborator Darius Miller, President and Principal Engineer at Soundnine. Units collect data and transmit inductively, clamped to a semi-taut mooring line with a surface data collection and cellular transmission buoy (Soundnine UltiBuoy). T/C/P sensors with inductive modems are manufactured by Soundnine Inc., and will integrate OEM fluorescence-based microDOT Dissolved Oxygen modules supplied by Precision Mechanical Engineering. *(Deliverable 2)*

Why fixed sensors instead of a profiler?

Reliable
- No moving parts, robust (but adjustable) attachment to mooring cable.
- Extremely low power, 2 AA $LiSOCL_2$ batteries will power sensors for a season at 15 minute sampling.
- Redundant data storage within each sensor and controller within the platform.
- Proven hardware with accurate individual sensor components
- Controller / communications buoy designed to be fully submersible to 10 meters to remain semi-taut and withstand surface wave conditions in any Chesapeake Bay water depths

Sustainable
- Sensor modules are low cost (estimated $4-5K) so spares are affordable
- Protected from fouling, modules and sensors should not require cleaning during season
- Full mooring with sinker is hand-deployable/recoverable by two people using a small boat

Flexible
- Modular components
- Works in any depth – deep or shallow - found in Chesapeake Bay
- Designed to withstand extreme Chesapeake Bay wave conditions

Meets Data Needs
- Samples are collected simultaneously at a prescribed fixed time interval
- Analysis below shows that a reasonable number of sensors can achieve accurate measurement of vertical hypoxia structure while still maintaining the reliability and sustainability advantages of a simple 'no moving parts' platform.
- Data are stored in two locations internally and transmitted in real-time to Soundnine's cloud-based storage system, where data QC will be performed per US IOOS QARTOD methodology (https://repository.library.noaa.gov/view/noaa/18659) The data will be made available to CBP and partners with low time latency and will include QC flags. Low power consumption of inductive technology allows 15-minute sampling for a full season deployment *(Deliverable 3)*.

While a single profiling instrument is an alternative approach, our experience with these devices is that they have more structural and logistical complexities and failure points (both in the profiling mechanism and in the mooring/structure supporting the profiler). These increase the risk of service visits in-season (cost) and associated periods of missing data***. Reliability is maximized by using the simplest solution that meets the requirements.***

Analysis

In evaluating the fixed vertical sensor approach, we considered, as Pilot example, deployment at CBP fixed monitoring station CB4.3E (38.55624 N, 76.39121 W) – about 2.5 km east of CBIBS Gooses Reef buoy, where there is real time surface environmental data nearby from GR, as well as bottom DO and pH data *(Deliverable 1)*. Additionally, this station is in a reasonably deep location (21-22m) and out of shipping channels (a problem when surface buoys are required for real-time communications, addressed below).

Figure 1A shows CB4.3E DO profiles from 2002-2018 June/July/August/September. With the assumption that we want to be able to at least match the ability of the existing sampling to resolve structure and measure vertical extent of hypoxia (DO < 2.0 mg/l) for use in DO volume estimates and forecast model comparisons, simulations were run with various fixed sensor depths. Table 1 shows how well different vertical sensor arrays capture full water column Vertical Hypoxia Extent - the amount of the vertical water column with dissolved oxygen concentration below 2.0 mg/l. For station CB4.3E, reasonable results can be achieved with as few as five or six sensors – graphical comparison of the six-sensor model is shown in Figure 1B. This is a preliminary analysis of sensor depths; it is likely that more rigorous placement analysis would reduce uncertainty even further.

Number of Sensors	Depths (meters)	R^2	% Variance	RMS Error (meters)
21	[1,2,3,…,19,20,21]	0.999	0.994	0.22
11	[1,3,5,7,…,17,19,21]	0.994	0.985	0.33
10	[1,5,7,9,…,17,19,21]	0.993	0.984	0.33
9	[1,6,9,11,13,15,17,19,21]	0.990	0.977	0.42
7	[1,6,9,12,15,18,21]	0.988	0.977	0.46
6	[1,7,11,15,18,21]	0.982	0.964	0.55
5	[1,7,12,17,21]	0.978	0.980	0.63

Table 1. Analysis of performance of various configurations of number and placement of vertical sensors

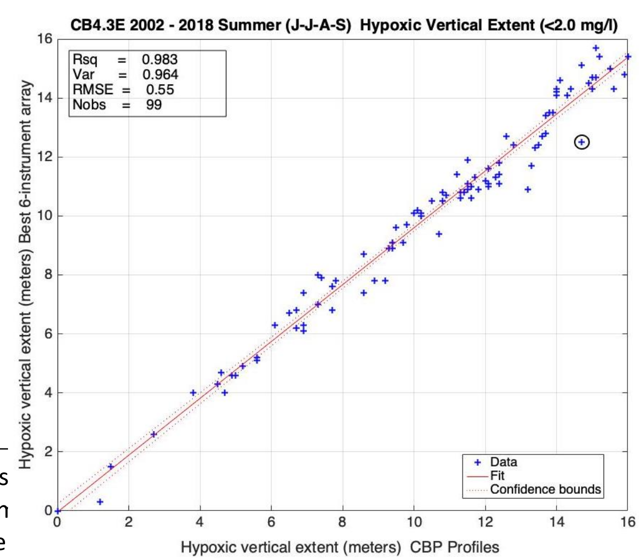
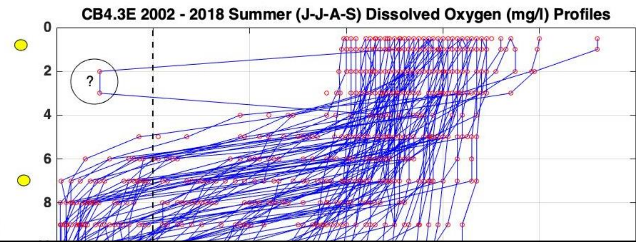


Figure 1. Measuring dissolved oxygen profiles with fixed depth s

(A) Profiles of dissolved oxygen from all 2002-2018 June-Septen al sample depth locations, connected by blue profile lines. Ye

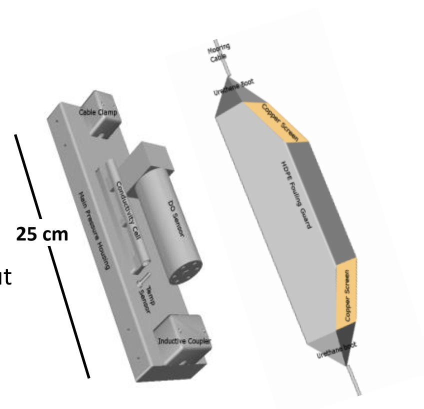
(B) Comparison of 'Vertical Hypoxia Extent (Meters)' calculated using measured profiles (X axis) and the same quantity calculated using a hypothetical array of six sensors shown in (A). Different arrays were tested; the results are shown in Table 1.



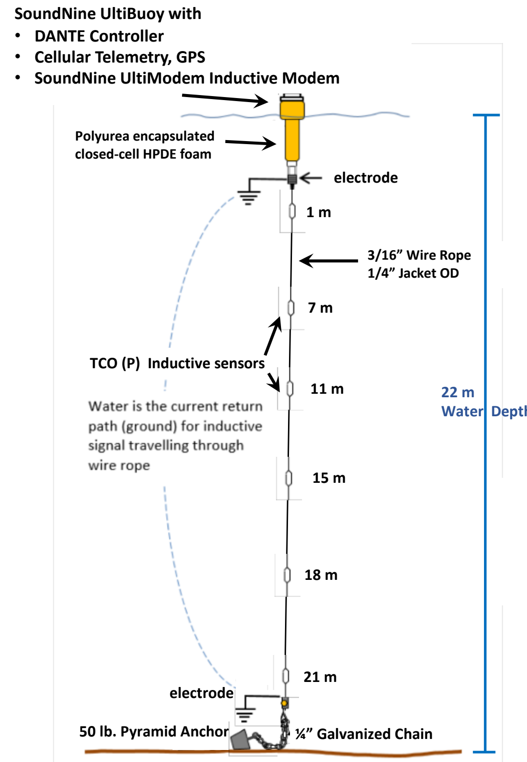
Expected Outcomes and Deliverables

We can meet the suggested Task Implementation timeline; comments on Tasks below (includes *Deliverables 4-7).*

System schematic (right) is based on the example of CB4.3E, but adaptable to other desired monitoring locations.
We have chosen a small, spar-like buoy to maintain a nearly taut mooring (and fixed sensor depths relative to the bottom) in all depths and conditions. The UltiBuoy electronics components are waterproof to >10 meters and will simply submerge in extreme wave conditions, storing data and retransmitting as necessary.
Sensors are tightly affixed to inductive cable but can be adjusted to meet sampling requirements.
Soundnine Inductive TCOP sensors provide accurate, low-power, measurements.
System is light enough to be deployed and recovered by 2 people from a small boat, and should require no maintenance during a season.



Rendering of Soundnine Inductive TCO(P) module, without cover showing sensors (left) and with protective antifouling cover (right).



Task 1: Kickoff meeting with Project Leads; current efforts; pilot locations. We are suggesting CB 4.3E for proximity to GR CBIBS; for moderate depth; for not being in conflict with shipping lanes. At this point in the timeline, application to USCG for Private Aids to Navigation should occur. The shipping lane issue can be problematic; many of the deep stations in the Chesapeake Bay where hypoxia is significant (including those considered in Bever, et al.) are located in designated ship channels where ship strikes are likely to damage a surface transmitting buoy (and where it is unlikely US Coast Guard will approve Private Aids to Navigation permits). We would work with VIMS researchers (see Letter of Support in (h)) to determine if there is a better (with respect to model validation) pilot location. Ultimately, we would work with them to find long-term solutions to this problem, including developing an optimal sampling array for non-conflicting locations, possibly utilizing interim non-real-time profiles with subsurface upper floats (for in-channel testing), as well as optimal vertical sensor placements. This inductive technology also lends itself to subsurface vertical arrays with a horizontally offset surface transmission buoy.

Task 2*:* We propose the *lightweight, low-powered real-time Inductive CTDO2 mooring with sensors at multiple vertical measurement levels* approach. This approach is based on our experience and our understanding of the project requirements. Establishment of details during Task 2 provides an opportunity to work with project leads to refine the approach to explain, modify, and finalize designs and protocols to make sure all requirements are met. A preliminary QAPP outline will be developed (ref. https://www.epa.gov/sites/production/files/2015-05/documents/assess4.pdf), to be fully completed utilizing experience gained during Tasks 3 and 4.

***Task 3**:* Soundnine and PME are in the process of integrating the PME DO sensor into an S9 inductive Conductivity-Temperature-Pressure module, resulting in a low-cost, standalone $CTDO_2$ inductive module. We will stage mooring building and testing activities out of Maritime Applied Physics waterfront location in Baltimore, where CWLLC has a working agreement, or other location provided by Project partners. Testing will include in-water testing and full sensor-to-client pipeline, including QC. QC procedures will be developed with assistance from Mark Bushnell, presently serving as National Coordinator for US IOOS QARTOD (see Letter of Support). We will also pilot making quality-controlled data available in the longer term through MARACOOS (the US IOOS Mid-Atlantic Regional Association). This has the advantage of easier access to certified data for the VIMS hypoxia model, which is publicly available through MARACOOS.

***Task 4**:* We propose an early June 2019 deployment using CWLLC boat or CBP partner-provided assets. Performance will be continuously monitored (data will also be available continuously to project participants) and maintenance will be conducted if necessary. Two interim platform visits will be conducted to evaluate fouling; if fouling is not affecting performance, sensors will not be cleaned. This will allow us to evaluate full-season capability. If available, we would like to integrate two Sea-Bird SBE37 inductive CTDO sensors owned by NCBO into the pilot deployment for independent sensor validation. These sensors are compatible with the Soundnine modem and data can be included in real-time transmission. The platform will be recovered in September 2019 using CWLLC or provided small boat.

***Task 5**:* Reports and presentations as requested, including final QAPP. CWLLC is located in Baltimore and available for in-person meetings.

***Task 6**:* Consultation, reports, briefings, and presentations as requested.

(d) **Experience / Qualifications of Offeror** (please see also (h), additional information)

Doug Wilson of CWLLC has extensive experience with ocean instrumentation; ocean data collection and quality control; and design, installation, and maintenance of coastal and estuarine moorings. This includes all aspects of designing and maintaining oceanographic observing systems, moored platforms, and sensors in Chesapeake Bay, Florida Bay and Florida Keys, Coastal Atlantic, Caribbean Sea, rivers and large inland lakes. He was an Oceanographer at the NOAA Chesapeake Bay Office (2001 – 2012), and during that time designed, deployed, and managed 10-buoy CBIBS system for environmental monitoring in Chesapeake Bay and tributaries. Work also included reports, publications, and presentations on results. He developed a real-time data system including data acquisition and storage, web display and access, and quality control using US IOOS Quality Assurance for Real Time Ocean Data (QARTOD) standard procedures. Doug Wilson has been active in Chesapeake Bay water quality and dissolved oxygen measurement, including CBIBS and other buoys, autonomous vertical profilers, and AUV deployments. He was co-PI in several proposal submissions to NOAA with Dr. Marjy Friedrichs of VIMS (and others) to provide dissolved oxygen profiles supporting the VIMS hypoxia forecast model, and as a result he is quite familiar with the ongoing work of VIMS and that of Bever, et al. (2018), and has an excellent working relationship with the community. Doug Wilson served on the U.S. IOOS QARTOD (Quality Assurance of Real-Time Oceanographic Data) Dissolved Oxygen Manual Team https://repository.library.noaa.gov/view/noaa/18659 (2015).

Darius Miller of Soundnine Inc. started his career in ocean instrumentation in 2003 when he was recruited to Sea-Bird Electronics by Ken Lawson with the support of mutual friends at the Edgerton Center at MIT. He became Principal Engineer of Sea-Bird in 2004. In his time at Sea-Bird he designed multiple new instruments, developed inductive communication systems, and participated in nearly every aspect of Sea-Bird's business.

After leaving Sea-Bird in 2009 he started a family and soon after started Soundnine Inc (S9) to continue developing innovative sensors and monitoring systems. Through Soundnine he has participated in countless monitoring projects with a wide variety of priorities including environmental compliance, education, and research. Please see the list of selected projects below