Interim Progress Report

ONR TFO: Predictions of AcousticS with Smart Experimental Networks of GlidERS (PASSENGERS)

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Major Goals

Ocean acoustic propagation has frequency-dependent sensitivity to a wide range of scales of ocean variability: from meter-scale gradients in the vertical to range-dependent gradients of hundreds of kilometers. As part of ONR's Task Force Oceans - New England Sea Mount Acoustics (TFO NESMA) collaboration, the Predictions of AcousticS with Smart Experimental

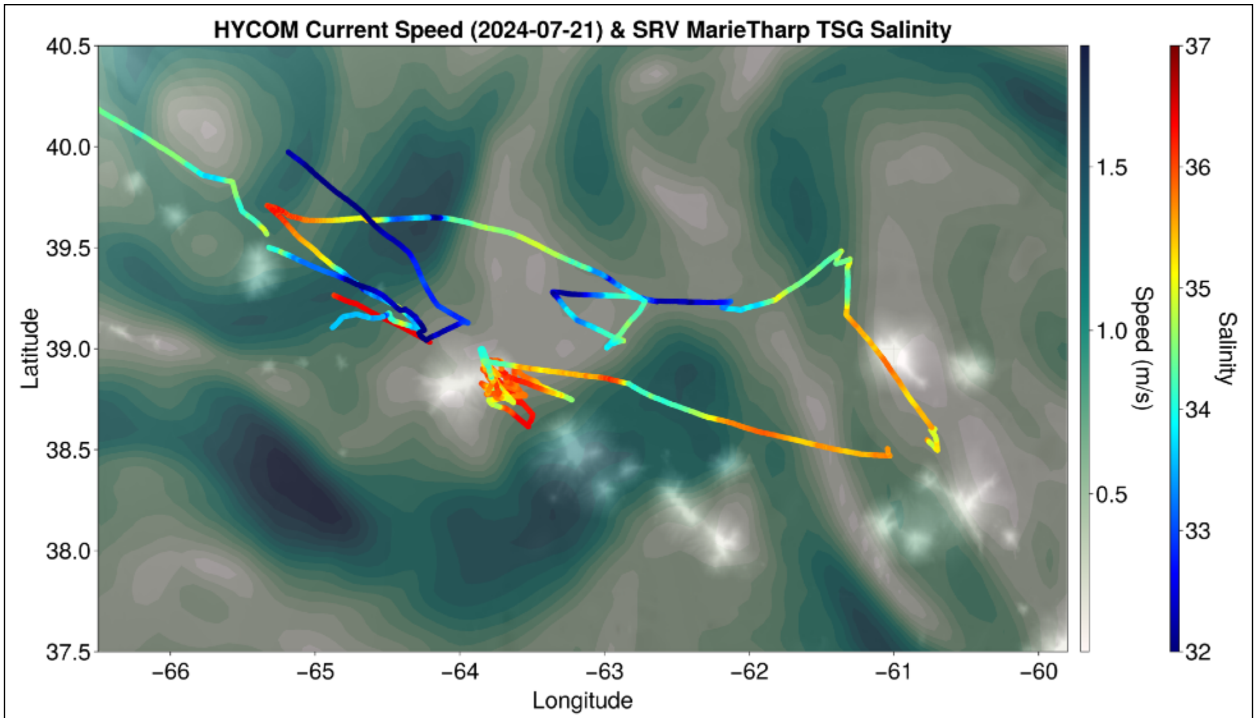

Figure 1: Map of the NESMA/PASSENGERS study region with Navy HYCOM current speed at 100m and track of SRV Marie Tharp overlaid ontop of the seamount bathymetry. The color of the track's color is the salinity measured by the TSG on the Marie Tharp.

Networks of GlidERS (PASSENGERS) team aims to improve the capability of data-assimilative ocean models to predict acoustic propagation in dynamic oceanography environments over the New England seamounts.

The Coastal and Polar Physical Oceanography (C2PO) lab at the Virginia Institute of Marine Science - William & Mary team led by PI Donglai Gong contributes to the TFO NESMA/ PASSENGERS collaboration through glider-based physical oceanographic and acoustic observations. Their field efforts includes the 2022, 2023, and 2024 field seasons with the goals of using underwater gliders to provide physical oceanographic data in the upper ocean and collocated hydrophone acoustics data. The C2PO lab was involved in the 2024 fieldwork in collaboration with the Ocean Research Project and their sailing research vessel Marie Tharp, as well as in coordination with the larger NESMA program led by YT Lin (SIO) in July and August (Figure 1). The fieldwork involved coordinated multi-ship operations by the R/V Roger Revelle, R/V Endeavour and the SRV Marie Tharp. This interim progress report focuses on the work done relating to the 2024 NESMA field campaign and some preliminary data analysis.

The PASSENGERS project paired numerical models with adaptive-sampling gliders to minimize ocean state and acoustics uncertainty. The team compared and contrasted different ocean data-assimilation approaches – such as the use of coordinated teams of gliders guided by

Figure 2: The deployment and recovery of VIMS NESMA/PASSENGERS gliders from SRV Marie Tharp and R/V Roger Revelle. Upper panel: SRV Marie Tharp near Kelvin Seamount in July 2024. Right upper panel: Deployment of SeaExplorer glider SEA064 in early July 2024. Lower left panel: Deployment of glider Sylvia in July 2024 led by Jack Slater and Fiona Gordon. Right lower panel: Recovery of glider Sylvia in July 2024 by Gong and Jerome Rand.

advanced algorithms on land versus best effort by human pilots. Simultaneously, the team collected a paired acoustic and oceanographic data set that will be ideally suited to evaluate and compare novel state estimation approaches both on land and at sea. The VIMS PASSENGERS effort included three focused field studies using a fleet of gliders to sample the ocean state along a bearing swath from the position of a known acoustic source to the first convergence zone (order 100 km) centered on the Atlantis II/Kelvin seamount. During the process cruises, the VIMS gliders sent their data back for assimilation into the Navy Coastal Ocean Model (NCOM) using a multi-scale 4D-VAR approach and Guidance for Heterogeneous Observation SysTems (GHOST) will control a subset of glider teams' waypoints and pathways. The gliders will be equipped with acoustic receivers and to complement moored acoustic array for additional verification of the acoustic state forecasting. The C2PO team at VIMS extended the PASSENGERS field effort to 2024 and in collaboration with the broader NESMA collaboration, Ocean Research Project (ORP), and ALSEAMAR. We deployed four gliders with three hydrophone equipped gliders (one SeaExplorer X2 and two Slocum), and one physical oceanography glider with co-located CTD, ADCP, and turbulence sensors (Figure 2). These gliders were used to provide physical oceanographic context for the dynamic Gulf Stream study region.

The experiments will take place during strong changes in stratification and sound speed profile structure in the dynamically energetic Atlantis II Seamount Study area. Results of these studies are being used to address the overall research goals of the project and lay the groundwork for using mobile underwater receivers to study acoustic transmission and scattering.

Overarching goals for the PASSENGERS collaboration include:

(1) Determine the effect of operational-scale ocean state variability on acoustic propagation and coherence times
(2) Improve the capability of data-assimilative ocean models, paired with smart, adaptive-sampling gliders, to predict acoustic propagation in a strong frontal and eddy-rich environment
(3) Compare the impact on acoustic forecast fields of novel glide sampling data assimilation algorithms to traditional methods of glider sampling and data assimilation
(4) Evaluate the uncertainty of acoustic state estimates and forecasts by comparing with field observations from mobile acoustic receivers

For the VIMS team, we have focused on the preparation, deployment, piloting, and sensor integration of the four gliders and the analysis and synthesis of glider data measuring ocean state variability. The passive acoustic data collected are being analyzed and shared with ocean acousticians for in-depth analysis and interpretation.

Accomplished:

<u>NESMA 2024 Field Campaign:</u>

The C2PO lab participated in the NESMA 2024 field campaign in July and August 2024. PI Gong, glider engineer Jack Slater, graduate research assistant Ricardo Bourdon, and undergraduate research assistant Fiona Gordon prepared and deployed four gliders, two SeaExplorers SEA064 and SEA094, and two Slocums Sylvia and Electa, for NESMA-PASSENGERS field campaigns (Fig. 2) in July and August 2024. Three gliders were from VIMS and one (SEA094) was on loan from ALSEAMAR equipped with a new 4 channel PAM system. As in previous PASSENGERS field years, the two Slocum gliders Sylvia and Electa were equipped with CTD and custom integrated Loggerhead LS1 passive acoustic monitoring system. SEA064/MARACOOS03 is a SeaExplorer X2 glider with CTD, ADCP, and turbulence

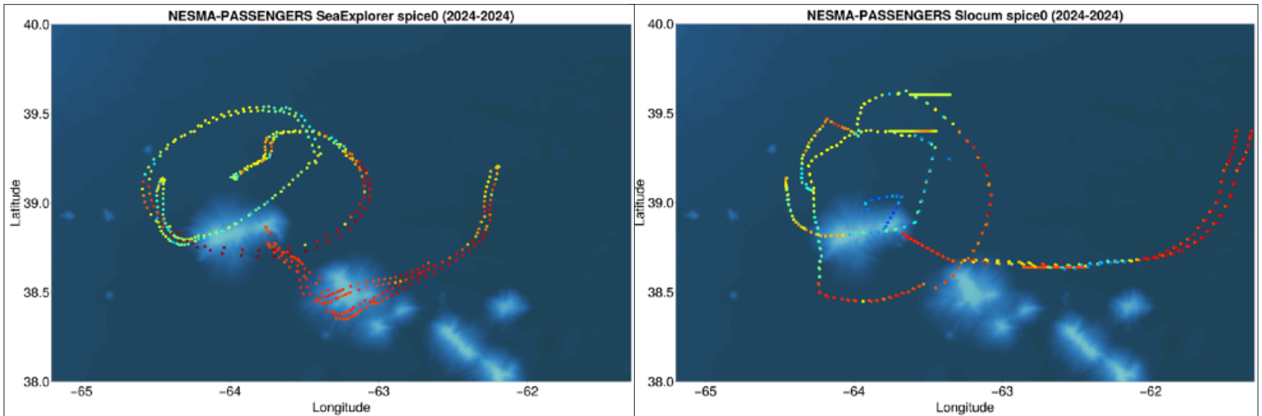

Figure 3: Deployment of VIMS gliders for NESMA 2024 in July and August with color indicating Spice at 10-20 m. Left panel: The track for the two SeaExplorer X2 gliders. Right panel: The track of the two Slocum gliders.

sensors that was integrated for the NORSE DRI project. All the gliders were 1000m rated, with Sylvia and Electa buoyancy engines upgraded specifically for the 2024 field season.

SRV Marie Tharp:

One key factor in the operational success of the VIMS glider team in the 2024 field season is the addition of SRV Marie Tharp to our operational plan (Figure 1 left). She is a 70 ft steel hulled sailing research vessel owned by the Ocean Research Project. Her Captain Matt Rutherford and science coordinator Nicole Trenholm joined the NESMA effort in May 2024. The plan for SRV Marie Tharp was for her to take a primary role in the deployments and recoveries of the gliders and other small mobile assets during the course of the processes cruises with the larger R/V Roger Revelle and R/V Endeavour serving as backups. This effectively gave the larger vessels more time to conduct vessel-based experiments and sampling, complementing each other maximizing the strengths of both crewed and uncrewed platforms. In between glider operations, the SRV Marie Tharp joined multi-ship acoustic experiments with the Roger Revelle and Endeavour collecting surface TSG data as well as conducting CTD casts. In total 20 CTD casts were collected. A shipboard pole mounted ADCP was also deployed for the first half of the cruise but the mount started to fail in rough sea state later the cruise and the ADCP had to be removed.

For the July 2024 IOP cruise, Gong and Bourdon were on SRV Marie Tharp. They deployed and piloted the two SeaExplorer gliders. Slater and Gordon were on the R/V Roger Revelle and they deployed and piloted the Slocum gliders. For the August cruise, Bourdon joined the R/V Roger Revelle and assisted with physical oceanographic sampling aboard the ship including standing Fast CTD watches with MOD from SIO. Slater and Gordon joined the SRV Marie Tharp and conducted the final recoveries of the deployed gliders. Gong was on land piloting for August. A plot of all the glider tracks for the 2024 field season are shown in Figure 3.

Glider sampling during July and August 2024:

Due to the fact that the Gulf Stream was generally located south of the Kelvin Seamount throughout the July IOP, the team decided to mostly focus on the Kelvin seamount for the July field campaign. Operating in pairs, the two SeaExplorer X2 gliders where deployed on 7/10/24 as soon as the SRV Marie Tharp arrived at Kelvin seamount (Figure 3 left). The two Slocum gliders were deployed on 7/11/24 once the R/V Roger Revelle arrived on station (Figure 3 right).

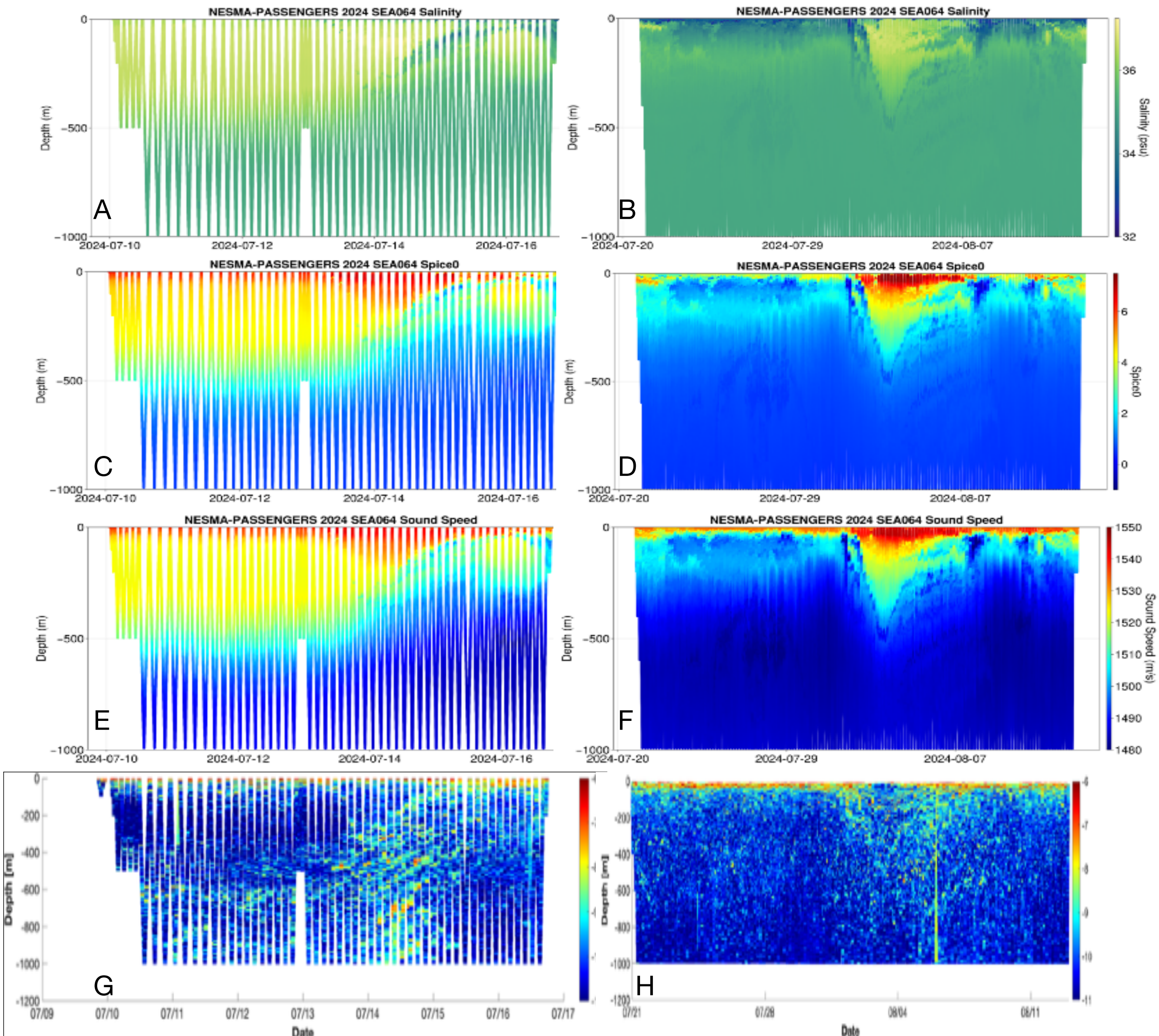

Figure 4: Salinity (A, B), Spice (C, D), Sound Speed (E, F), and TKE dissipation rate (G, H) profiles from SeaExplorer glider SEA064 from two consecutive deployments. Left panes are for 7/10/24 to 7/16/24 and right panels are for 7/20/24 to 8/13/24. Salinity and/or Spice can be used as proxies for Gulf Stream and Slope waters. Spicy water is warm and salty. TKE dissipation rate is shown in log(W/kg).

The gliders were near the north wall of the GS and were pushed southeastward initially and then northeastward after arriving at the Atlantis II seamount. This initial deployment trajectory gave us the opportunity to receive from the WHOI TR mooring located south of Atlantis II seamount. The gliders also served as remote mobile receivers for the first set of SUS experiments from the R/V Roger Revelle. When the GS pushed the gliders outside of the eastern boundary of the study region, the Marie Tharp team chase them all down and reposition them back in the box. One of the SeaExplorers, SEA094, spun a leak at this point and its mission unfortunately had to end early. However, nearly a week of multi-channel hydrophone data were collected by it including one set of the SUS experiments. Analysis of this acoustic dataset is ongoing. All the gliders were successfully recovered from the sailing research vessel and they were recharged and redeployed upstream of Kelvin seamounts a few days later on 7/20/2024. SEA064 and Electa then each conducted counterclockwise surveys of the Kelvin seamount region through the period of cruise turnaround from IOP1 to IOP2. All the gliders were recovered a bit earlier than originally planned by 8/13/2024 due to the impending arrival of a hurricane remnant and the SRV Marie Tharp sought safety in the Gulf of Maine.

Water mass and sound speed properties:

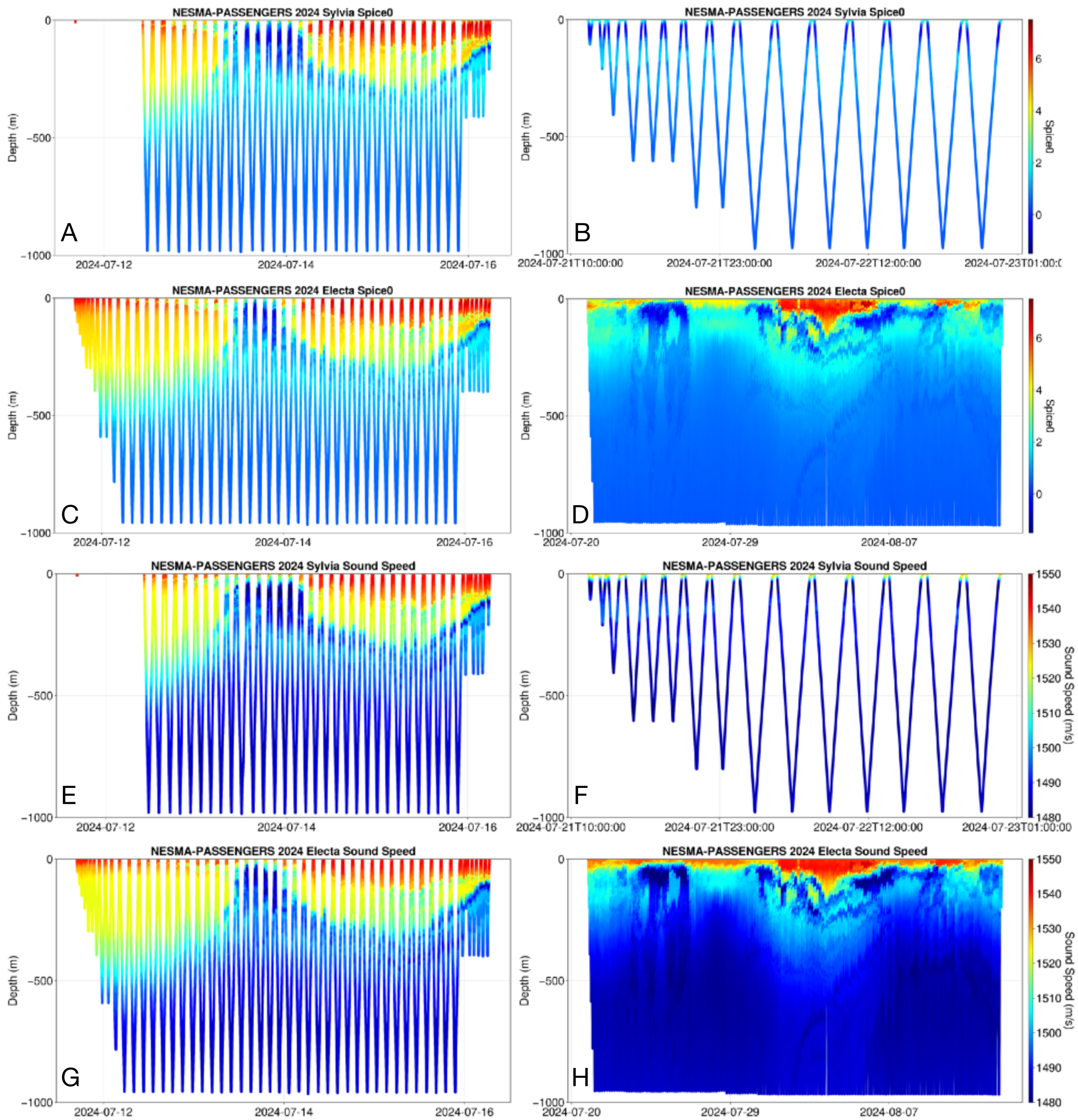

Figure 6: Plot of spice (A-D) and sound speed (E-H) sections for gliders Sylvia (A, B, E, F) and Electa (C, D, G, H) during NESMA 2024. The left columns are for the first set of deployment between 7/11/2024 and 7/16/2024. The right columns are for the second set of deployment between 7/20/2024 and 8/13/2024.

Because spice is so closely correlated with sound speed, it is a useful parameter for identifying the different water masses in the New England seamounts region. Gulf Stream water is spicy (warm and salty) while slope water is not (cooler and fresher) (Figure 4). Using a salinity of >36.2 or spice of >4 to identify Gulf Stream water for NESMA 2024, the SeaExplorer glider SEA064 encountered the Gulf Stream water twice, once during the initial deployment east of the Kelvin seamount, the second time in early August when the glider was in between the Kelvin and Atlantis II seamounts for a period of time and SEA064 was just touching the north wall of the Gulf Stream. As the only platform with turbulence sensor during the July IOP1 cruise, the Rockland Scientific MicroRider sensor on SEA064 enabled us to study the turbulence and mixing activity across the north wall of the Gulf Stream during its initial crossing. Extensive enhanced subsurface turbulence activity were observed across the entire north wall down to depths of >1000m (Figure 4G). The least turbulent water was seen inside the Gulf Stream at 200-400m.

During the second deployment for SEA064, it can be seen in the sound speed section (Figure 4 lower right) that there is a 400m thick layer of sound speed minima centered around depth of 600m north of the Gulf Stream. This coincided with a cyclonic flow pattern that was observed north of Kelvin seamount. Internal tidal oscillations can also be seen at depths between 150 and 650m. Close to the Gulf Stream, there were thin layers of acoustic ducts hugging along the north wall. The TKE dissipation level observed during the second deployment also saw enhanced values across the northern boundary of the GS as the glider dipped into and out of a Gulf Stream feature (Figure 4H). A similar picture emerges from Electa's data. She took a slightly different path than SEA64 with a couple of days of lag in timing, the water mass layering and the sound speed profiles seen were even more complex with multiple layering

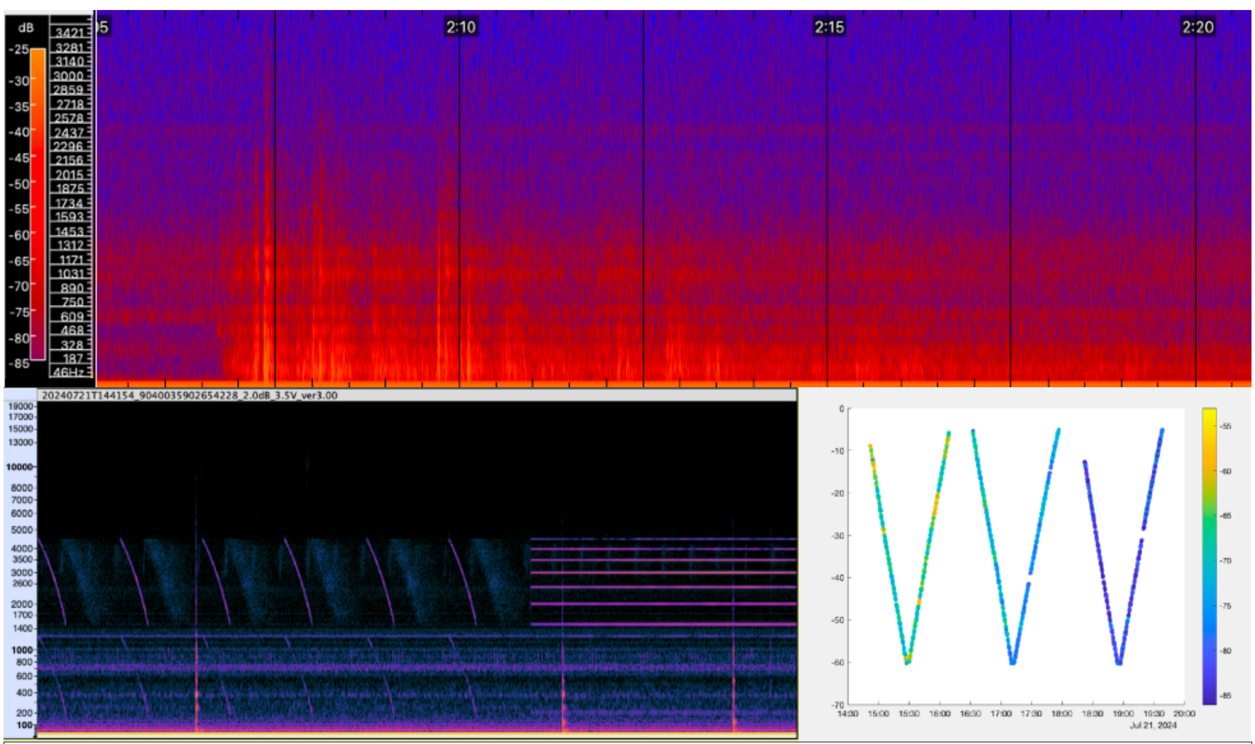

Figure 7: Glider PAM recording of various sources deployed during NESMA. Top: SUS signal detected at 20240714T002509 by Sylvia. Bottom left: Sylvia's recording of the AUV towed source during NESMA IOP1 during multi-ship operations. Bottom left panel: Spectrogram from the glider's PAM. Bottom right panel: Detection of the source signal during the glider's dive and climb. The color indicates signal strength.

observed (Figure 6 D and H). Taken together a complex picture of hydrographic and acoustic variabilities emerges.

PAM and motion data from gliders:

Preliminary analysis of the PAM data from the gliders show successful detection of multiple sources including the WHOI TR mooring, Remus 600 AUV towed source, as well as SUS deployments. These sources were detected both in the single channel hydrophone on the Slocum glider as well as by the 4 channel system on SEA094. The SUS detection in particular showed multiple arrivals consistent with multiple paths. Slater plans to analyze the PAM for all the gliders for his M.S. thesis and run Bellhop model to study the multi-path geometry.

We have also leveraged the support for NESMA-PASSENGERS and NORSE in developing a solution for using glider's motion to sense ocean turbulence using an IMU sensor based on validation data provided by SEA064's MicroRider turbulence sensor. This work is based on the initial work done by Ferris et al **[1]** in validating the metholology. The work is continuing both in terms of hardware development, data analysis, and software development leveraging internal funding and external funding from NOAA.

Training:

C2PO's glider engineer Jack Slater led the field team for VIMS on the R/V Roger Revelle in July 2024. This was his third NESMA/PASSENGERS cruise with increasing responsibility each time. In addition, graduate research assistant Ricardo Bourdon, and undergraduate research assistant Fiona Gordon were trained and participated in the NESMA/PASSENGERS project as part of the VIMS team. Ricardo is a new Ph.D. who joined VIMS in September 2023 and is working on various data analysis and model studies for ONR funded projects such as NORSE and NESMA/PASSENGERS. Bourdon received glider operations and piloting training from during the field campaign Gong. Fiona Gordon, a senior at W&M who joined the lab in January 2024, received glider technology development, operations, and data processing training directly from Gong and Slater. Each team pairs contributed to glider preparation, deployments, piloting, and recovery efforts, splitting the watch schedule for glider piloting. Cross training of the team in each other's roles and responsibilities enabled the team to take turns and over both legs of the cruise on different vessels. NESMA was the first time that Gordon and Bourdon were at sea for an extended research cruise.

Slater has also started graduate school at VIMS while continuing to work as glider engineer with Gong. He will focus his research on the passive acoustic data from NESMA/PASSENGERS. He has been learning to process the passive acoustic data recorded during NESMA-PASSENGERS and conducting match filtering to match the signals to the sources. Next he will learn to model acoustic propagation using Bellhop and apply it for the NESMA/PASSENGERS datasets and compare with observational data. He will also learn to process hydrographic and ADCP datasets and use the combined PO and acoustic data to better understand the impact of PO processes on acoustics.

A new Ph.D. student, Ricardo Bourdon is working on NESMA/PASSENGERS and NORSE DRI's physical oceanographic data focusing mainly on the ADCP and turbulence data collected by SEA064. By combining the microstructure turbulence and ADCP current data, he will focus his research on understanding flow-bathymetry interaction at the seamount impact acoustics propagation and scattering.

Dissemination:

Over the course of three field seasons for PASSENGERS and NESMA (2022—2024), the VIMS C2PO lab conducted 10 glider deployments using two Slocum gliders and two SeaExplorer gliders. Our initial data analysis has focused on characterizing the oceanographic condition of the upper ocean, the variability and structure of the surface mixed layer, and map out the water masses associated with the Gulf Stream. The position of the Gulf Stream is the zeroth order factor in ocean state estimation and the dominant consideration in logistics. We also observed significant tidal/inertial and supertidal oscillations in the upper water column that varies in strength on the event scale.

The sharp front between slope sea water and Gulf Stream water is an area of enhanced flow shear and turbulence dissipation, often seen with interweaving layers of water masses. This is a region for the potential development of flow instabilities and enhanced energy transfer from the submesoscale to the microscale and drive slope water formation and transformation. Gong, Bourdon, and Ferris are planning further investigation of these complex flow and mixing regions. Variability in atmospheric forcing such as transient weather systems and storms, as well as the constantly changing oceanographic condition such as the position and orientation of the Gulf Stream and its rings, and the entrainment of shelf water into the study region further complicates the analysis as the sampling space and time scales often alias the variability of the system itself. Reanalysis model that assimilates all observational data would be highly useful for future synthesis efforts.

Gong and Slater has been participating in the biweekly NESMA group meeting in 2024. Initially this was focused on field work planning and logistics, and now it has transitioned to data analysis and interpretation. Over the past year, we have started to analyze the passive acoustic data from the 2023 and 2024 process cruises. We were able to detect and identify the MIT Lincoln Lab's MF source (2023), WHOI TR source (2023, 2024), SUS (2024), and AUV (2024) towed source in the glider hydrophone data. As part of the multi-ship experiment over Kelvin seamount in the July 2024 IOP1 cruise, both the gliders and the SRV Marie Tharp joined the "parade" with the AUV source leading the way. Glider Sylvia provided right guard and made consistent detections of source over 3 yo's (Figure 7). The next step is to dig deeper into the dataset and investigate signal timing for multi paths analysis and the signal strength variability as a function of the local oceanography.

A concerted effort led by Ferris has aimed to better understand the characteristics of submesoscale instabilities in subpolar regions, which require special attention due to intense mechanical forcing (from winds and complex literal topography), rapidly evolving fronts, and preexisting turbulence from competing instabilities --- features ubiquitous in the ice-free sub-Arctic but not yet included in proposed mixing parameterizations. The team published **[1]** on submesoscale instability in the presence of preexisting turbulence in June and have partnered with new collaborator Jeffrey Carpenter at the Institute of Coastal Ocean Dynamics, Helmholtz-Zentrum Hereon to finish **[2]**, which is expected to be submitted in late 2024 or early 2025.

Plans:

With the field campaign for NESMA-PASSENGERS complete, Gong's team will be focused on data analysis and synthesis in the coming year. There is a wealth of hydrographic, currents, turbulence, and hydrophone data from the three field seasons. We have made significant progress in signal detection. The next step is to use the signal timing information and the help of propagation model(s) to study multi-path propagation and the impact of local oceanography on the acoustic propagation and detection. The acoustic study will be conducted in coordination and in collaboration with the other NESMA/PASSENGERS acoustic teams.

For his M.S. thesis based on NESMA-PASSENGERS and NORSE experiments, Slater will start using Bellhop model to help him interpret the observed arrival times from different sources in the glider hydrophone dataset. This is will be done in collaboration with the physical oceanographic analysis conducted and modeling conducted by Bourdon and Gong.

The successful 6 day deployment of the ALSEAMAR SEA094 glider with 4 channel hydrophone a validation of the sensor technology. The system was able to detect multiple sources. Future work will be done to develop onboard processing capabilities for automatic source detection and direction finding. Multiple deployment such systems could enable source localization.

The team also plan to continue to work with SRV Marie Tharp for future ONR studies. Specifically, it could be an excellent platform for towing moderate sized acoustic arrays. Given the quiet nature of the sailing vessel, this combination could result in significantly enhanced noise floor. Furthermore, we have engaged in conversations with Ocean Power Technologies (OPT) to jointly develop an glider launch and recovery system for uncrewed surface vehicles. This would be highly useful and much more cost efficient for future ONR projects that involve complex glider and float deployment and recovery logistics.

Technology Transfer:

The VIMS team worked on the integration of the Loggerhead hydrophone system into the Slocum glider for NESMA-PASSENGERS. This integration was also used for the NORSE DRI in the Nordic Seas in 2023. We successfully conducted multiple deployments of the first commercially integrated ADCP and turbulence sensing platform for the SeaExplorer glider with realtime telemetry for both NESMA-PASSENGERS and NORSE. This integrated package is now a popular sensor suite for other users.

We also worked with ALSEAMAR to borrow and deploy a 4 channel PAM equipped SeaExplorer glider (SEA094 with the AURIS package) for the NESMA-PASSENGERS field campaign. This was the first test of this particular sensor system for U.S. naval oceanography. Gong hopes to acquire such a system for the next round of ONR DURIP. The system also inspires our lab to continue the development of our own custom PAM solution with emphasis on onboard processing as the next step.

Once we have completed the development of IMU based turbulence sensor technology for the underwater glider, we hope to commercialize the technology with a commercial partner to broaden the ability to make turbulence observations in the ocean for more users.

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[2] **Ferris, L.**, **Gong, D** (2024). Damping effects of viscous dissipation on growth of symmetric instability. *arXiv Physics [physics.ao-ph].* doi.org/10.48550/arXiv.2406.16818

[3] **Ferris, L.**, Carpenter, J., **Gong, D**. Overturning instability in forced ageostrophic oceanic flows. *In preparation*