8-2023

Phased Array Sonar Exploration of 4-Dimensional variability in Oceanic Flow Structures

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Link Foundation Fellowship Report

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Ocean Engineering and Instrumentation Fellowship 2022

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August 4, 2023

1 Introduction

Vertical transport of heat, momentum, and nutrients in the ocean is often driven by small scale, three dimensional instabilities whose cumulative effect is visible in global climate and global patterns of ocean productivity (Belcher et al. 2012; Dong et al. 2022; Taylor and Ferrari 2011). These features are very difficult to observe with standard oceanographic instrumentation directly; observations typically focus on the larger scale conditions that result in small scale instabilities, or measure the mixing that results (D'Asaro et al. 2011; Thomas et al. 2013). Direct observations of the 3D structure of these instabilities are a missing link in our understanding their physics and impacts. Here I show preliminary results from a new towed phased array Doppler sonar (TPADS) developed by the Multiscale Ocean Dynamics group with Office of Naval Research support which we hope will fill this measurement gap by allowing observations of three dimensional structures at scales of 10's to 100's of meters.

TPADS works on a similar principal to an acoustic Doppler current profiler (ADCP). A pulse of sound is sent out from the instrument which reflects off scatterers in the water column. This reflection is Doppler shifted by the relative motion between scatterer and instrument, allowing velocity to be estimated (Pinkel 1980). A typical ADCP uses four beams that are physically pointed in a beam pattern that allows the three components of velocity along a 1D profile to be estimated. TPADS uses a phased array approach. We combine measurements from 32 acoustically sensitive elements in a process known as beamforming to generate a 2D fan of beams with an aperture of 120°. TPADS is mounted on a compact tow body which is deployed behind a ship (figure 1). As it is towed, the fan shaped beam pattern moves through the ocean, generating a 3D view of ocean velocity.

2 Results

2.1 Deployments

Over the course of my fellowship support I assisted with two TPADS deployments at sea. Both deployments were a chance to test deployment strategies and data analysis software and techniques.

The NORSE field deployment was the first operational deployment of the TPADS system in support of a large oceanographic project and the first ever test of a 32 channel TPADS system. TPADS was deployed for roughly 18 cumulative hours in the Norwegian Sea, sampling a region where cold, fresh Arctic water and warm salty Atlantic water come together under strong atmospheric forcing (Brakstad et al. 2023), creating complex 3D structures, including sharp fronts and small scale convective instabilities. TPADS was deployed with the array looking downward, with the array looking sideways and up, and with the array looking upward and with the beam pattern oriented in the direction of ship motion at depths between 20 and 100m. I was the science lead for TPADS on my

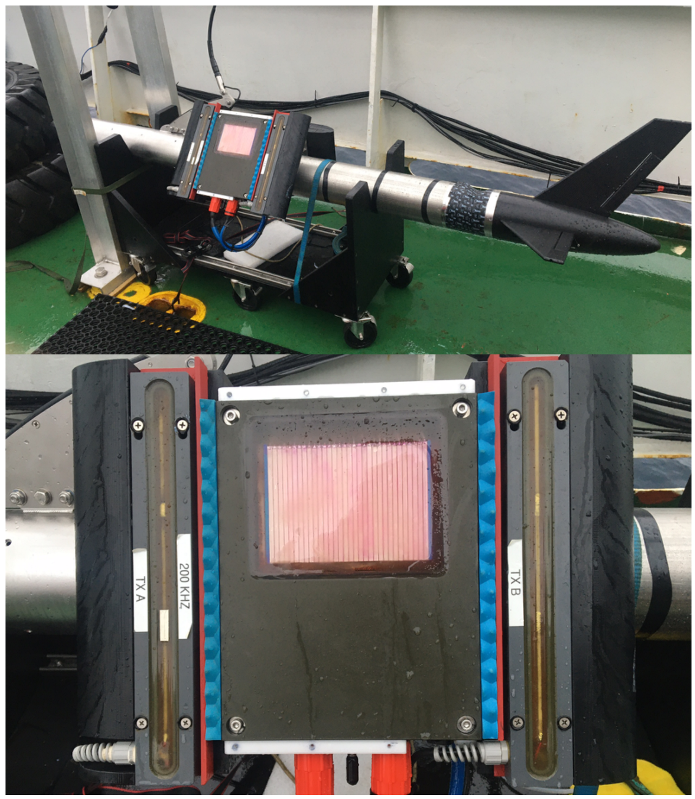

Figure 1: The TPADS system pre-deployment on NORSE. The top photo shows the full tow body with the array mounted in the middle, looking up. The bottom photo shows a close up of the array. Receive elements are visible through the pink urethane filler on the upper side of the gray pressure case. Transmitters sit either side of the receive array.

watch, so was responsible for planning and executing deployments, including choosing array orientations and tow depths and monitoring data as it came in.

We recently completed a second test of the TPADS 32 channel system over two day trips in San Diego. The purpose of these deployments was to follow up on the lessons learned from NORSE deployments, and fix some of the issues that impacted the system on its first test. We tested TPADS to depths of 300m, added additional acoustic absorbing material behind the array, and tried to minimize platform motion, particularly in the vertical. We were also able to test a new inertial navigation unit integration, which will allow us to better correct for platform motion. I served as chief scientist on the second day of this trip.

2.2 Data processing

One of my major goals in advance of the NORSE cruise last fall was to develop a robust and ideally real time data processing pipeline. Data from TPADS is transmitted up a fiber optic cable, and recorded on a computer on the ship at over 300kHz on each of 64 channels. The challenge is to take this immense volume of data and turn it into estimates of velocity in $\sim$3.5m range bins across 31 radial beams at $\sim$2Hz. This process, in its simplest form, has two steps. First raw data must go through a beam forming algorithm which generates our 31 radial beams. This is done following Smith, Pinkel, and Goldin 2015. Then velocity must be estimated for each of these beams for each range bin. This is done by estimating the frequency of the signal over successive $\sim$5ms segments of beamformed data, and then using the two way travel time of the signal to estimate range (Pinkel 1980). I built a data processing pipeline that reads in raw data, generates velocity estimates, and plots velocity, signal intensity, and signal quality in real time in time for the NORSE cruise (figure 2). Having a real time view of incoming sonar data allowed us to see how charges in tow depth or tow dynamics affected the incoming data and keep an eye on the range and data quality of the system.

The real time data processing generates a first pass data product that is good enough for examining system performance in real time and doing basic analysis, but it leaves out several processes in pursuit of efficiency and simplicity. Using the large catalogue of NORSE data I have made significant progress on a second pass processing routine that gets the most out of the system. This routine will include matched filtering integrated with onboard navigation sensors, a deglitching algorithm to remove interference from other sonars, and incorporate data from environmental sensors, including water temperature and depth.

The final data processing stage is to generate a product where velocity measurements are geolocated, smoothed, corrected for platform motion, and ideally projected onto an earth referenced coordinate system. I have developed algorithms that geolocate data, accounting for the attitude of the platform, and allow us to bin data in georeferenced bins (figure 4). Using data from the June 2023 deployment, I have been able to generate good agreement between measured IMU velocity and measured sonar velocity (figure 3), which is the first step in removing platform motion from sonar measurements. I have also started

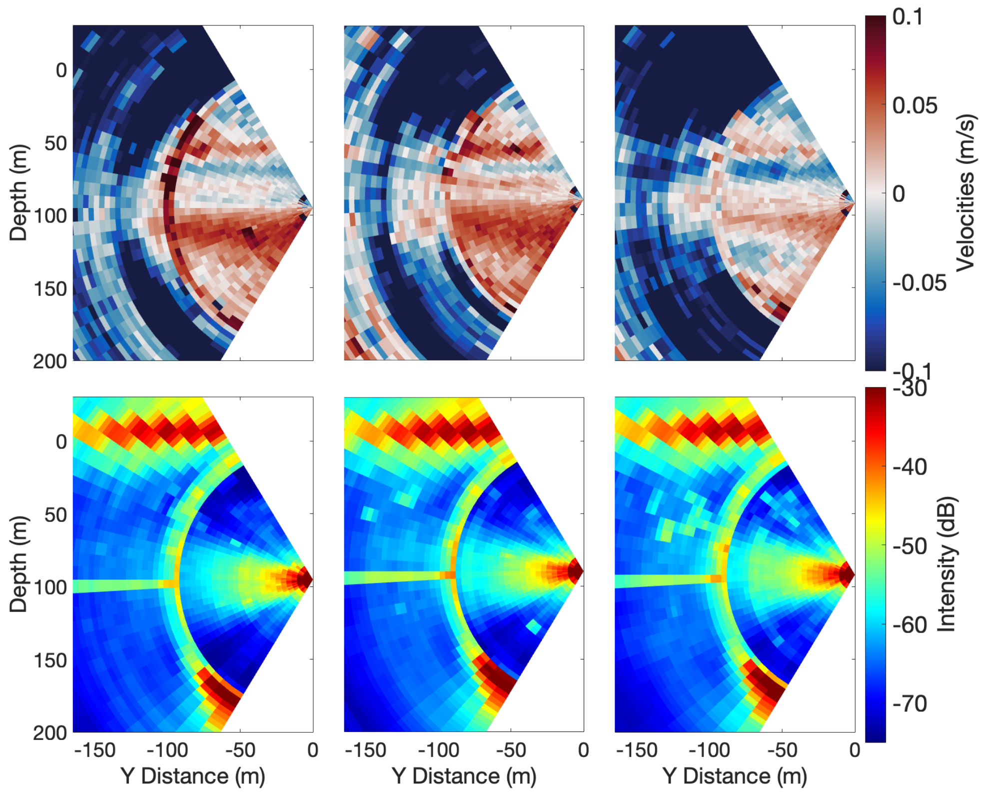

Figure 2: This figure shows three samples of velocity (top) and intensity (bottom) data after first pass processing from the NORSE field campaign. Velocity data is captured over 31 beams arrayed in a fan shape, with ∼3.5m range resolution. Intensity data show a strong surface return as a horizontal band at zero meters. Velocity data shows the evolution of a series of shear layers at the base of the mixed layer around 50m depth, visible as horizontal bands of positive and negative velocity.

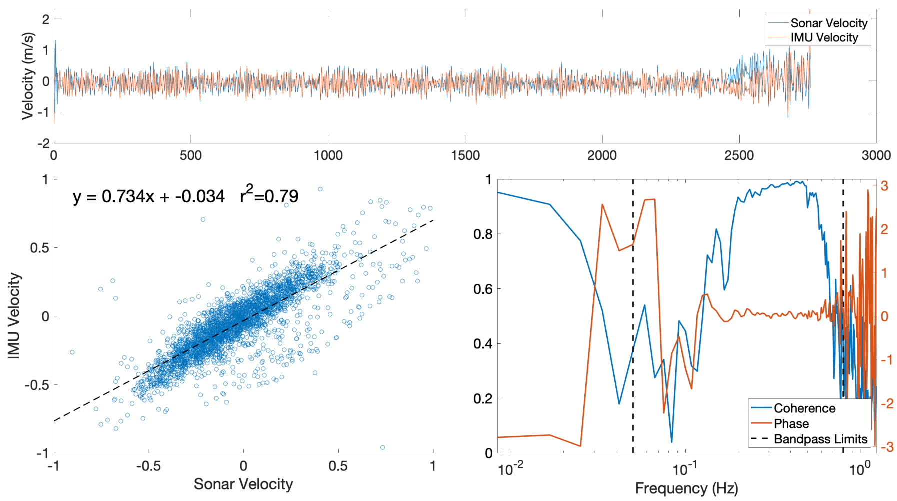

Figure 3: Comparison of vertical velocity measured by the onboard inertial measurement unit (red) and vertical velocity measured by the sonar (blue). IMU accelerations are band pass filtered between 0.05Hz and 0.8Hz (Surface wave band) before integration. The majority of platform motion falls in the surface wave band, and our two velocity estimates show high coherence and zero phase lag through this frequency range. The slope of the regression between the two signals is less than one, as expected for a sonar measurement made in the presence of finite noise, which will bias sonar velocities low.

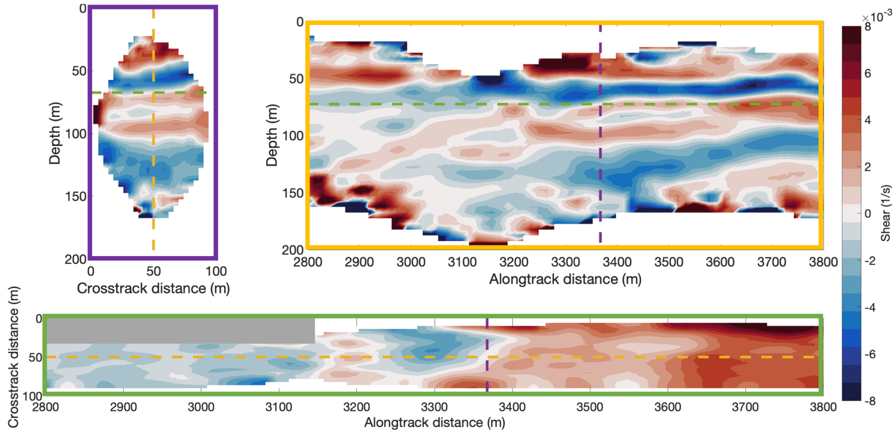

Figure 4: This plot shows three cross sections of measured shear across the volume sampled by TPADS during the NORSE cruise. The purple axes show a vertical cross-section perpendicular to the ship track, yellow shows a vertical cross section parallel to the ship track, and green shows a horizontal cross section at a selected depth. The location of each cross section is marked in the other two with a colored line. Shear is calculated from geolocated data that integrates gps position and instrument depth, as well as instrument attitude, to calculate velocity and shear in each bin.

work on a method to use the pitch of the platform to separate out the along and cross track velocity components, allowing for estimates of both horizontal velocity components in each bin.

3 Significance/Impact

TPADS represents a unique observational capability that promises to allow observations of the full 3D ocean velocity field and advance understanding of complex small scale ocean features. Over the last year, with Link foundation support, I have helped to deploy TPADS in support of major collaborative scientific projects and I have developed the ability to obtain spatially mapped measurements of at least two interdependent velocity components over a three dimensional volume. We continue to explore deployment strategies, software, and algorithms that are tailor made to answer pressing scientific questions concerning the structure and physics of small scale instabilities, so their effect on global patterns of climate and ocean productivity can be unraveled.

4 Next Steps

I have been selected for a Link fellowship for the 2023-2024 academic year to continue my work on TPADS. This fellowship will fund ongoing development of TPADS software and algorithms. New developments in the June 2023 field test, including navigation sensors integrated into the array, higher sample rates, and deeper tow depths promise higher quality data. I plan to continue work on motion correction algorithms and spacial mapping of data, as well as investigating how TPADS can be used to measure (and ultimately correct for) the surface wave field. Additionally I plan to publish a paper describing the technical details of the TPADS system and presenting some of the promising data described above.

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