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Autonomous CTD Profiling from the Robotic Oceanographic Surface Sampler

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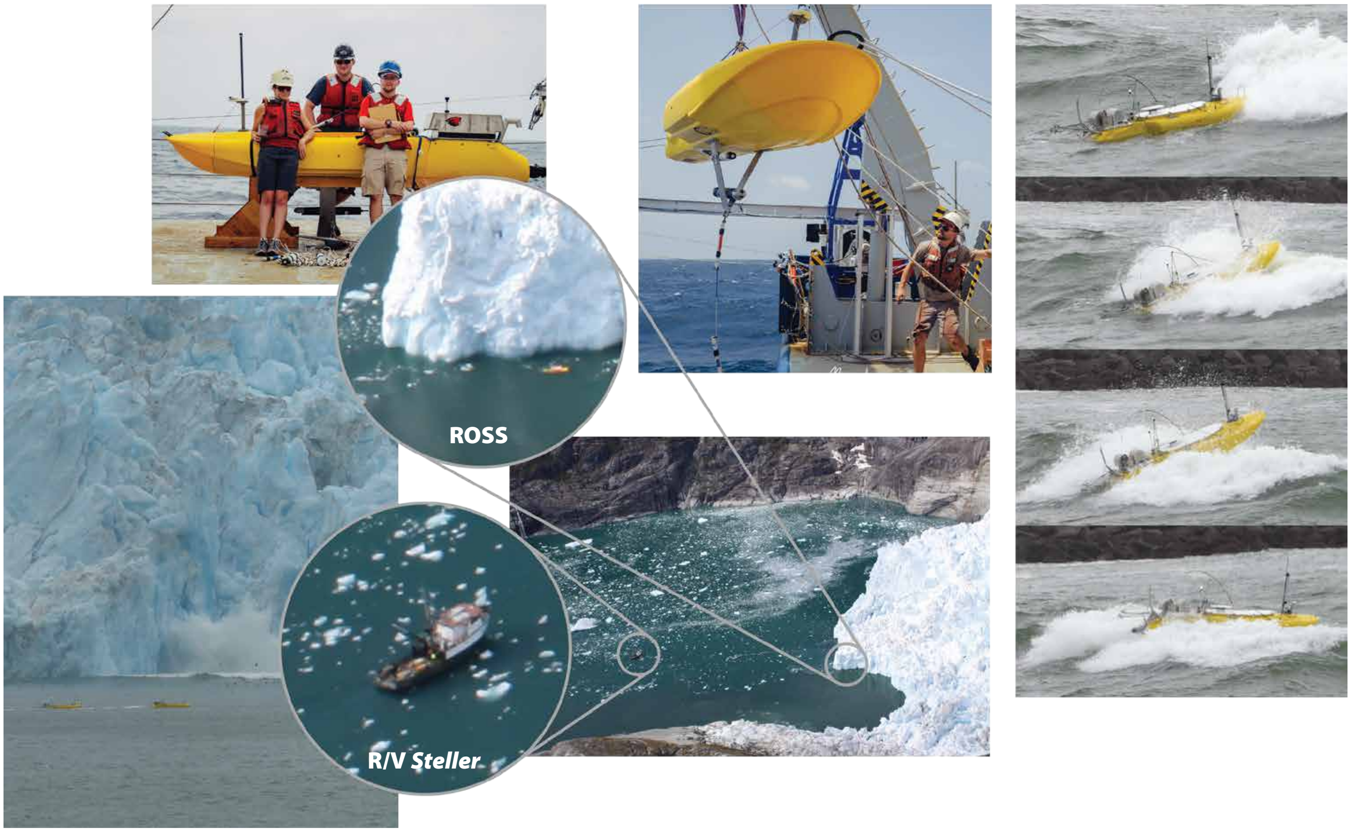

FIGURE 1. Clockwise from upper left: Lead engineer June Marion and students Nick McComb and Kevin Tennyson with ROSS (photo credit: San Nguyen); ROSS deployment from R/V *Roger Revelle* in the Bay of Bengal (photo credit: San Nguyen); ROSS CTD profiling through breaking waves on the Oregon coast (photo credit: Jonathan Nash); aerial view of ROSS sampling within meters of LeConte Glacier, Alaska (photo provided by Christian Kienholz); two ROSSs sampling in concert at LeConte during a small calving event (photo credit: Jonathan Nash).

The upper ocean is a complex sea of lateral variability on scales ranging from less than a meter to many hundreds of kilometers. Small-scale processes, in particular those that happen within the wave-influenced surface boundary layer, often elude detection, except during highly specialized field campaigns. Observational challenges stem from the fact that large manned vessels heave and roll, inducing large relative velocities between sensor packages and the sea surface. Additionally, ship-induced stirring of surface waters can contaminate near-surface observations around a large vessel. Fast, seaworthy, rapidly sampling autonomous craft overcome some of these issues, and they provide a complementary means to sample complex three-dimensional upper-ocean processes on the relevant spatial and temporal scales. Such processes are often associated with the lateral stirring of freshwater from rivers, localized rainfall, and ice melt, which can form small-scale filaments and fronts that may control irreversible transports near the air-sea and ocean-ice boundaries. Elucidating the structure of the associated instabilities and turbulent fluxes permits better understanding of air-ice-ocean interactions and feedbacks.

Advances in off-the-shelf autonomous navigation systems for consumer airborne drones have led to rapid growth in the development of unmanned craft. The technical challenges are no longer limited by control-systems hardware but instead are associated with total system integration: creation of a robust and seaworthy craft that is optimized to acquire reliable and systematic scientific observations in a harsh marine environment, and with sufficient redundancy of all mission-critical systems to recover from unforeseen failure modes under real-world operations. Here, we briefly describe the Robotic Oceanographic Surface Sampler (ROSS; http://ross.ceoas.oregonstate.edu), an autonomous surface craft developed at Oregon State University (OSU), that has been designed with three primary objectives in mind:

1. To operate from a surface-following reference frame, so as to provide uncontaminated observations as close to the sea surface as possible
2. To be deployable in groups of cooperative swarms in order to permit adaptive sampling of rapidly evolving three-dimensional phenomena
3. To be operational under harsh open-ocean sea states, resilient to failure, and inexpensive enough to be deployed in locations with significant risk of loss.

At OSU, ROSS developments have benefited greatly from the combination of seasoned expertise of our oceanographic field engineers and at-sea experience of our group, along with extensive involvement of undergraduate engineering students who collectively provide creative approaches and an enthusiastic work force. Unlike other autonomous oceanographic instrumentation, surface vessels can be tested on any body of water, and they can fail and be recovered during testing without large consequence, thus providing benefits for education/teaching and student involvement.

The ROSS platform was modeled after the Woods Hole Oceanographic Institution's jet-yak (Kimball et al., 2014), utilizing a commercially available Mokai gas-powered kayak outfitted with in-house control electronics, medium-range (O(10 km)) RF communications systems, and traditional oceanographic instrumentation (RDI acoustic Doppler current profilers [ADCPs] and RBR CTD systems). ROSS is optimized for open-ocean research with O(1–2 day) endurance and O(100–1,000 km) range.

In its first science deployments in the Bay of Bengal, ROSS towed a 20 m thermistor/CTD chain and was equipped with a 300 kHz four-beam ADCP for velocity measurements down to 120 m depth. Ten to one hundred kilometer transects were obtained parallel to R/V *Roger Revelle* and ORV *Sagar Nighi*, capturing near-surface dynamics and upper-ocean vorticity (MacKinnon et al., 2016). Here, we describe one specific part of the system, a rapid-profiling CTD designed to acquire profiles from the surface down to 150 m depth while underway at up to four knots (Figure 2).

On ROSS, the same high-speed Shimano electric fishing reel we use on traditional research vessels was modified for use in an automated, remotely operated mode. Similar to that on traditional research vessels, a retractable A-frame and a CTD capture mechanism was fabricated and equipped with magnetic Hall-effect sensors to detect when the CTD has been recovered and the A-frame retracted. Automation of deployment and recovery was found to be relatively straightforward; however, tangling of the profiling line (500 lb spectra) on the winch's spool turned out to be our greatest obstacle. Specifically, as ROSS heaves and rolls in open-ocean waves, slack can form in the CTD line, create "loose wraps" on the CTD winch, and cause a failure in the profiling system.

To prevent this failure mode, the CTD line was run through a bent fishing rod that served to passively absorb line tension fluctuations. In addition to this passive action, a flex sensor was integrated into the fishing rod to detect rod curvature, a direct proxy of line tension. Maintaining constant line tension during profile descents minimizes the likelihood of line tangles and also has the advantage of providing a relatively constant profiling speed for the CTD even when ROSS's motion is strongly influenced by surface waves. The resultant "heave compensation" (similar to that in the latest generation of shipboard CTD winches) is accomplished by using the measured line tension to control the winch speed; if a decrease in line tension is detected, line payout speed is reduced and tension restored. This is implemented through a PID (proportional integral derivative) controller and microprocessor that also monitors winch status, deploys and recovers the CTD, and holds the CTD at the surface between profiles. The controller also uses line tension and CTD speed to detect when the CTD has reached the bottom and initiates recovery. Bottom detection allows full-depth profiling despite rapidly changing bathymetry such as during cross-fjord transects. A separate onboard computer coordinates all data collection, navigation, and communication between ROSS and remote personnel via 900 MHz RF. Remote users interface with ROSS using a custom graphical user interface that enables real-time monitoring, command, and control of the ROSS navigation and profiling system.

In April/May 2017, ROSS was deployed in the vicinity of LeConte Glacier (in LeConte Bay/fjord and nearby Frederick Sound) as part of a larger field campaign to investigate ocean-glacier interactions. In this environment, ROSS provides a unique platform to complement the shipboard measurements—both to study the three-dimensional

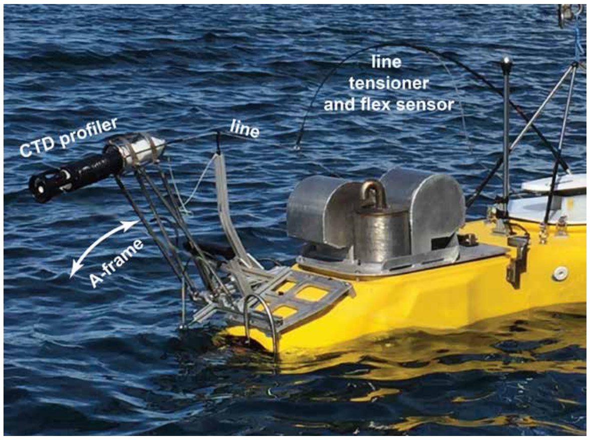

FIGURE 2. The ROSS rapid-profiling CTD system. A line runs from the CTD profiler (upper left), through a roller on a post, through the fishing rod tip and into the kayak hull to a Shimano electric fishing reel (not visible). The CTD is captured by a cage attached to a retractable A-frame. *Photo credit: Jasmine Nahorniak*

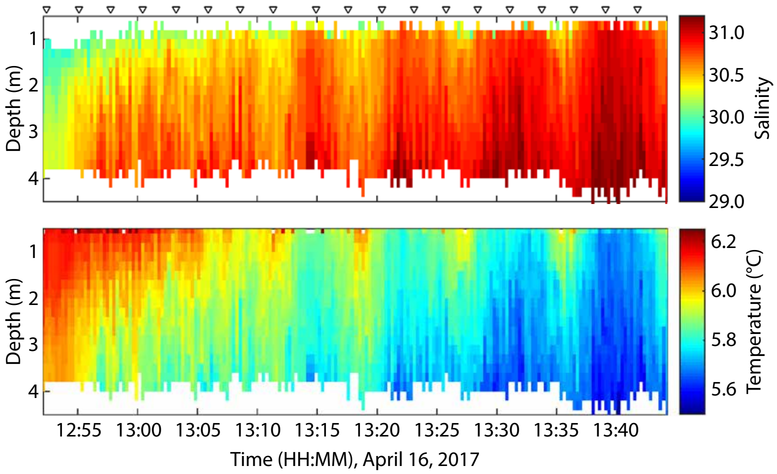

FIGURE 3. Salinity and temperature data collected during a 50-minute ROSS transect in Frederick Sound, Alaska, with the CTD/winch set in rapid-profiling mode and directed to obtain 200 CTD casts to 4 m depth. This demonstrated the reliability of the CTD deployment/detection/capture method and that repeated profiles can be obtained as quickly as once every 15 seconds. Triangles above the upper plot represent the time of every tenth CTD cast.

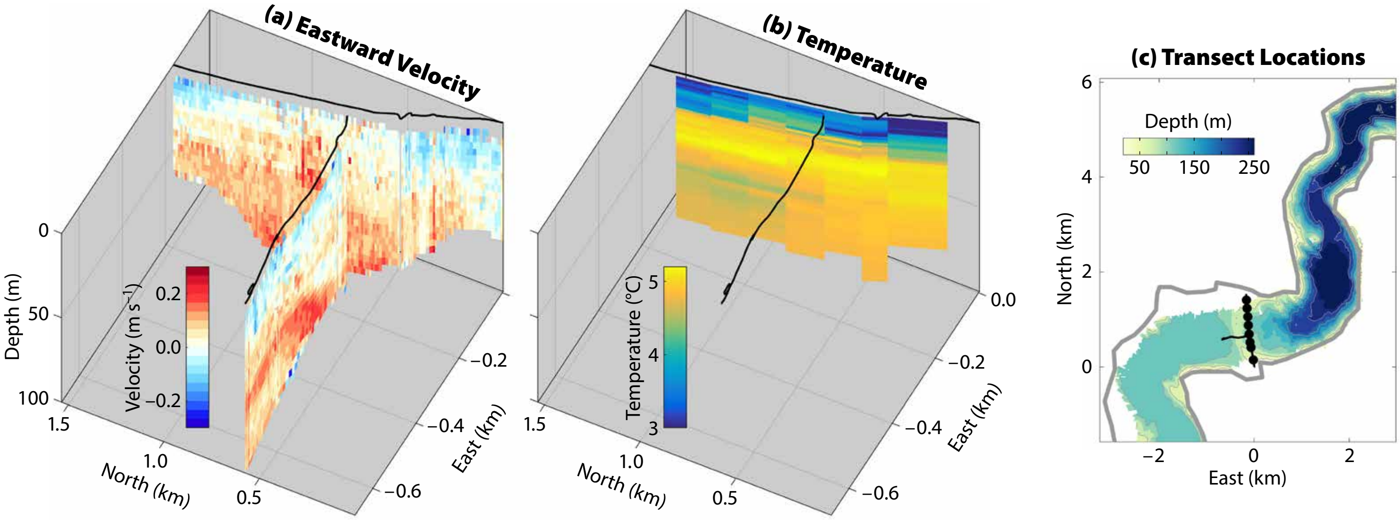

FIGURE 4. Cross section of temperature and velocity from a cross-fjord ROSS survey. ROSS tracks are shown in black. The velocity data (a) were obtained from the onboard ADCP, which collects data continuously. The temperature data (b) are from eight CTD profiles collected by ROSS during the cross-fjord transect. The local bathymetry and transect locations are shown in (c).

structure of flow features and to obtain measurements near the glacier where it is unsafe for manned vessels. In the shallow waters of Frederick Sound, ROSS obtained 200 CTD casts over 50 minutes (Figure 3). A deeper transect within the fjord shows cross-sill exchange with eight CTD casts between 50 m and 100 m depth, along with ADCP data in both the along- and cross-fjord sections (Figure 4). This demonstrates the utility of ROSS for automated high-resolution upper-ocean CTD profiling.

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