Citation: J.K. O'Brien, R.A. Krishfield, M.-L. Timmermans, and J.M. Toole (2023), Proc. IEEE Oceans 2023-Limerick, 10 pages. doi: 10.1109/OCEANSlimerick52467.2023.10244491.

The Tethered Ocean Profiler, TOP

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***Abstract*— The mechanical and electrical design and control system firmware/software for the Tethered Ocean Profiler (TOP), are presented. TOP is designed to autonomously sample the evolving upper polar ocean water properties from 200 m depth to within 15 cm of the ice-ocean interface while drifting with the sea ice. In addition, by repeatedly traveling up to the ice-ocean interface, TOP is able to estimate the evolving draft of the floe supporting the instrument. To date, 7 TOP systems have been fielded in the Canada Basin sector of the Arctic. Engineering data and initial scientific findings based on those data are reported and plans for system enhancements discussed.**

Keywords—oceanography, under-ice profiler, conductivity, temperature, depth (CTD) sensor

I. Introduction

TOP (Fig. 1), is designed to autonomously sample the evolving upper polar ocean water properties from 200 m depth to within 15 cm of the ice-ocean interface while drifting with the sea ice and telemeter the observations to shore-based users in near real time throughout all seasons. In particular, the TOP seeks to: 1) provide information on the variations of the ice base depth, under-ice meltwater and ocean heat content including within the upper few meters of the water column, and 2) document the evolution of the mixed layer and near-surface temperature maximum layers across seasons. Typically in the past, these observations have required manned ice camps, but recent technology has enabled automated buoys to acquire ice data (e.g. Ice-Mass Balance buoys), measurements at discrete depths near the ice-ocean interface (e.g. Arctic Ocean Flux buoys), and high-vertical-resolution upper ocean profiles to within a few meters of the ice bottom (e.g. WHOI Ice-Tethered Profiler, ITP). In a single package, TOP is able to make comparable measurements.

The Ice-Tethered Profiler (ITP) program was conceived around the turn of this century to fill a gap in global ocean observing by providing year-round observing capabilities for the Arctic Ocean beneath sea ice and freely disseminating the observations in near-real time [1]. The ITP instrument [2] was designed to collect observations of sea water properties below the Arctic ice cover in all seasons at high vertical (~1-m), temporal (~1 d), and horizontal (few km) resolution over extended periods (1 year or longer). The first prototype ITP, deployed in late summer 2004, laid the groundwork for this major observing system utilizing improved instrumentation for sampling upper ocean water properties and sea ice drift throughout the deep Arctic Ocean. Since 2009, the ITP program has operated as an element of the NSF Arctic Observing Network. To date, 128 ITP systems have been deployed throughout the Arctic and collectively returned some 130,000 records of upper Arctic Ocean water properties that have been made publicly available. (A record consists of a vertical profile or short time-series of temperature and salinity measurements, with a subset of systems returning additional parameters such as dissolved oxygen, velocity, or bio-optical parameters.)

A shortcoming of the original ITP system design is its inability to sample all the way up to the ice-ocean interface; the upper grounding plate for the inductive modem telemetry circuit that is fitted on the tether 5-7 m below the base of the surface buoy blocks the ITP from traveling shallower. Observing to within ~15 cm of the ice-ocean interface allows for a better characterization of the seasonally varying heat content and salinity of the waters in direct contact with the sea ice. This is particularly important in spring and summer when solar heating and subsequent ice melt is a huge source of buoyancy that causes the upper ocean to stratify, at times all the way to the ice-ocean interface [3]. To address this observing gap, the Tethered Ocean Profiler (TOP) was conceived, designed and prototype tested. This paper

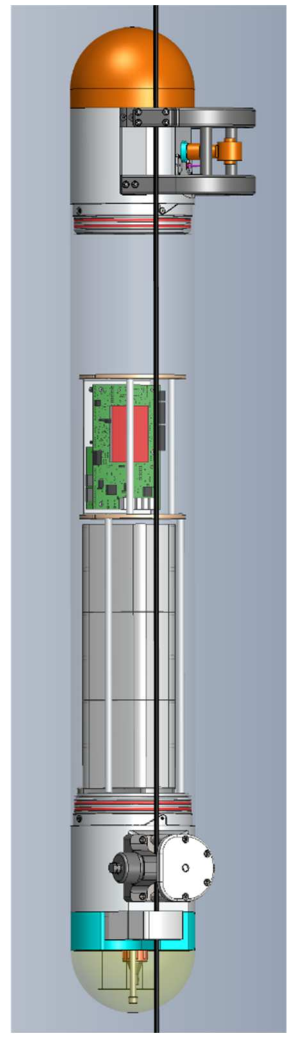

Fig. 1. ***Tethered Ocean Profiler (TOP) vehicle shown with transparent main housing tube.***

Research supported by the Arctic Observing Network program of the U.S. National Science Foundation.

describes the TOP system and presents examples of scientific analyses based on data from operational instruments. Section 2 that follows presents the mechanical design and control firmware of the TOP and documents the CTD sensor that has been employed to date. This is followed by a review of the TOP profiling performance (Section 3) and examples of scientific analyses supported by TOP observations (Section 4). The work concludes with a discussion of future plans.

II. TOP DESIGN

Similar to the ITP, the TOP system (Fig. 2), consists of a buoyant surface package housing telemetry electronics that supports a jacketed wire rope tether, and a cylindrical vehicle able to propel itself vertically along the tether carrying sensors to sample the water profile. The vehicle travels up and down the tether based on an operator-defined schedule. Sensor data collected during profiles are relayed from the underwater vehicle to the surface buoy using inductive modem hardware followed by satellite telemetry to land-based servers.

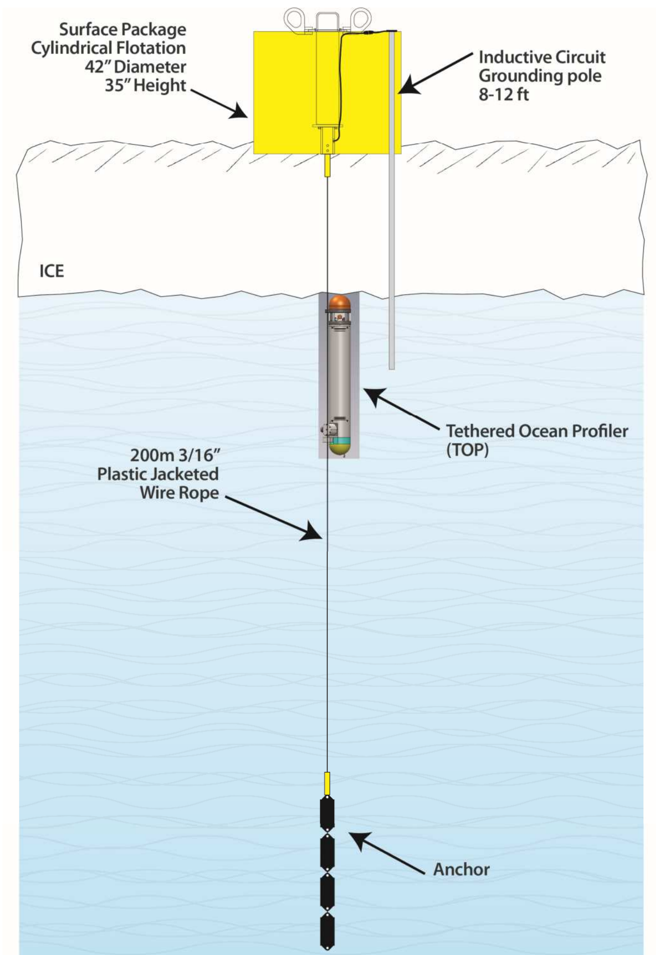

Fig. 2. ***Schematic drawing of the TOP system.***

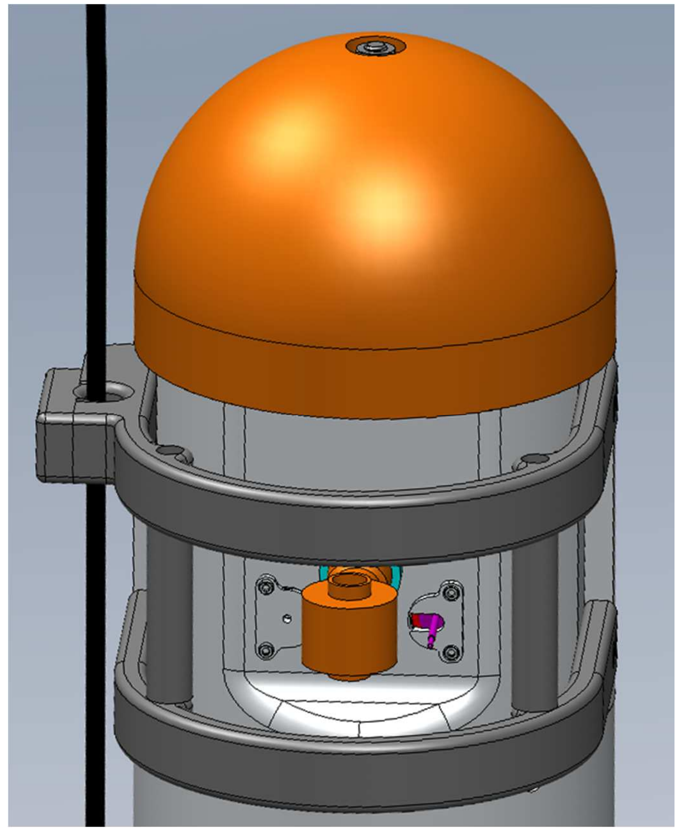

Fig. 3. ***Upper end cap sensor suite and flotation***

A. Mechanical

The initial TOP design specification was to sample water properties between the ice-ocean interface and 200 m depth. The TOP vehicle uses standard 6.5" O.D. x .25" wall thickness 6061 aluminum pipe for the main housing. The upper- (sensor) and lower- (drive system) end caps are also manufactured from 6.5" O.D. 6061 aluminum bar stock. All three of the components are anodized.

Atop the upper end cap is a Divinycell HCP50 hemispherical flotation element that increases the separation between the center of buoyancy and center of gravity, reduces drag for up-going profiles and is the contact point when the profiler gently bumps the underside of the ice floe. This dome is held in place with a nylon threaded rod and nut.

The side or face of the upper end cap has 3 orifices (Fig. 3). Facing the sensor suite from left to right are the Keller pressure transducer port, the Solumetrix inductive conductivity cell and the Solumetrix temperature sting. These sensors are behind two acetal plastic U-shaped guards that protect the sensors from banging into the sides of the hole when being deployed through an ice floe. On the left side of the upper guard is the upper mooring cable guide also made from acetal plastic. This guide is removed during profiler attachment to mooring cable and then re-applied with 4 bolts capturing the mooring cable. The friction between this guide and the plastic jacket on the mooring cable is negligible. No ITP-style roller guide system is required, simplifying the design.

The external underside of the lower end cap has three ports; 1) Soundnine inductive modem cable coupler stem with O-ring seal 2) Subconn DBH8F Ethernet bulkhead 3) SAE#4 pressure port. A 2" thick piece of High Density Poly Ethylene (HDPE) serves as a standoff around the IM coupler and bulkhead connector. Finally, a hemispherical-shaped piece of HDPE is added to streamline the profiler shape during down profiles and also protect the IM coupler and bulkhead connector.

A magnetically coupled pinch roller drive system is mounted to the side of the lower end cap. Internal are a 12-VDC Maxon motor with Gysin gear head, motor mount and internal magnetic coupling. External are a drive shaft with two 59mm 76A durometer urethane roller-blade wheels, 2 high quality ceramic bearings, the external magnetic coupling and a drive wheel shroud. A thin-walled cup-shaped titanium barrier separates the internal and external magnetic coupling components. This barrier seals to lower end cap with an O-ring. Adjacent to the 2 drive wheels and perpendicular to the drive shaft is a housing for the pinch roller mechanism that captures the spring which applies force to the third pinch roller wheel which in turn, forces the mooring cable into the natural v-shaped groove that results from placing the 2 rubber roller blade wheels beside each other. Forcing the mooring cable with spring pressure into the V-shaped space is what gives TOP excellent traction on the wire even during periods of high ice floe drift speed. This drive system arrangement produces profiler velocities through the water column of 18-19 cm/s as compared to 25 cm/s with ITP. The pinch roller housing is easily pivoted out of the way when placing the profiler on the mooring cable by removing one screw. At this time, one half of the IM cable coupler is also removed to facilitate installing the profiler on the mooring cable.

Internally, a simple chassis system is made up of 6061 aluminum rods, sheet metal chassis plate and acetal plastic discs. The chassis system, mounted to the lower end cap, is designed to hold lead ballast weight, 3 Electrochem 3PD1341 battery packs (1.3kWh each), the Soundnine inductive modem module, the Linux controller/logger PCB, and motor controller PCB. The CTD electronics are mounted to the 'roof' of the upper end cap.

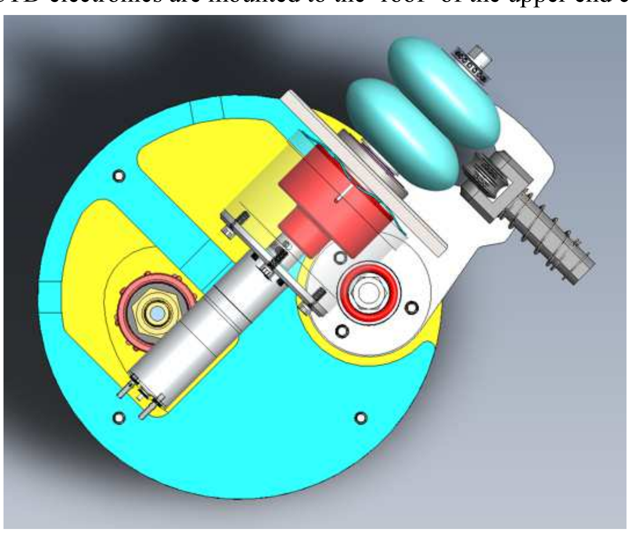

Fig. 4. ***Lower end cap, pinch roller drive system***

TOP was designed from the outset to be modular in that alternate upper end caps could be designed to be used with other CTDs and other water property sensors as long as the interface to the main housing tube was adhered to and the sensors were within the constraint of an 11" hole in the ice. If the sensor payload were to change and this resulted in a heavier overall package, the main housing tube could be made longer to displace more water and offset the heavier package. The drive system, inductive modem system and logger system would not need to change. As of this writing we have designed 4 different upper end caps that support: Solumetrix sensor suite, D-2 Hybrid CTD, RBR OEM transverse CTD, and the AML Oceanographic CT•XchangeTM Sensor. The Solumetrix sensor suite was utilized on the first 10 TOPs with the other sensor end caps scheduled for testing in summer, 2023.

B. Electronic Hardware

TOP employs the same Linux-based logger/controller currently used in the ITP surface packages. It features a TS4200 Linux single board computer about the size of a credit card mounted to a custom WHOI designed baseboard which handles power switching, RS232 and logic level communication as well as Ethernet and USB high speed data. An ATmega1284P serves as a supervisor IC that operates on a few micro-amps of power while asleep. An additional motor controller board was developed that consisted primarily of a low power MAX14871

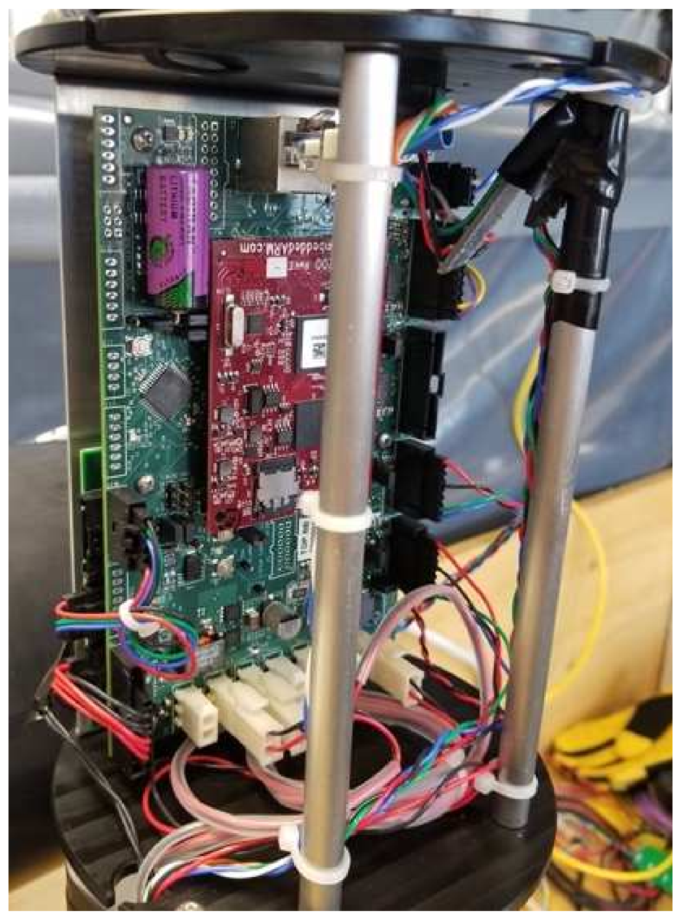

Fig. 5. ***Linux Logger/Controller and Motor boards***

motor driver IC, a series of latching relays that controlled freewheel/brake and drive states, an ATmega1284P micro and two i2c bus current sense amps.

C. Firmware/Software

The programming code for both the supervisor firmware and the Linux logger/controller software is written in the C programming language. The supervisor firmware is responsible for waking the Linux controller on schedule and receiving any external signals for manual wake and inductive modem communication from the surface. It is also the communication link between the TS4200 Linux computer and the motor controller board. The supervisor in conjunction with the motor controller is responsible for measuring and reporting voltage, current and board temperature during operation. The supervisor also acts as a watch dog to the Linux computer.

The Linux software consists of three main processes that run in parallel. They are: the Control process (control), the Logger process (logger), and the Inductive Modem Module (IMM) process. The control process runs throughout a sampling operation and would be considered the main process. Sampling is guided by a user-defined schedule of activity set before each TOP is deployed but able to be revised during a mission via satellite telemetry.

All data files to be transmitted are added to a file queue at the conclusion of a sampling operation. If data transmission is temporarily not possible, transmission of the queued files will be attempted at the next scheduled IMM session. At the conclusion of a profile that has telemetry selected in the configuration file, the control process will send a message to the IMM process telling it to initiate communication with the surface package. Once communication is established with the surface package above, the IMM process, working off the file queue, transmits an engineering log containing profile meta data, depth-based engineering data, and a raw CTD data file. A daily controller log and daily IMM log are telemetered on the next transfer after a day change. All the data are simple ASCII human-readable files that utilize the same Linux controller timestamp for continuity and are compressed with BZIP2 compression before being transmitted inductively up the mooring cable at nearly 5x the speed of ITP inductive modem communication. The IMM process transmits files in 4096 byte-sized packets that include a header with checksum and awaits acknowledgment from the surface before continuation. Packets can be rejected with a NACK (not Acknowledged) packet and re-transmitted. Average data transmission rate for multi-packet files is approximately 370 bytes/second.

After sending data to the surface package, the profiler IMM process checks to see if the surface controller has any files to send down to the profiler. If so, the modems reverse their master/slave relationship and data transfers from the surface package down to the profiler in an identical manner as described above. The three primary files that would be sent down to the profiler are *'prf_mission.cfg'*, *'prf_schedule.cfg'* and *'prf_command.txt'*. These files will be described in greater detail later in this document. Upon receipt of any of these files, a message is sent to the control process which triggers a handler event to act on the reception of these files. When transmission is complete, the IMM process sends a message back to the control process that data transfer is concluded, initiating return to low-power sleep sequence.

Logger processes are implemented for each sensor serial port; currently, 4 serial ports are available for sensor data streams. The minimum required data stream is that from the CTD sensor because the profiler can't operate without knowing its depth. If depth is not available the profiler would simply travel up or down until the *max_time* parameter has been exceeded. Three additional data streams can be logged and time-stamped with the same clock via additional logger processes running in parallel. The logger process is responsible for power control to the sensor port and receiving and time-stamping incoming data. The timestamp is marked by the reception of the first byte after the specified line termination character. Each line terminated by this character has a unique timestamp measured to milliseconds. The logger process is also equipped with methods to send strings to the sensor. However, a typical setup is to simply configure a sensor so it will stream data at a set rate and in a set format when power is applied. Most modern sensors can do this and save these settings to EEPROM. Additionally, the logger process has the ability to echo complete records to the control process via UDP packets. In this way CTD records are echoed to the control process and then parsed, enabling the control process to know via pressure where the vehicle is in the water column and at what velocity it is traveling.

The supervisor uses the DS3231 real-time clock (RTC) with an integrated temperature-compensated crystal oscillator (TCXO) and crystal. This part has an alarm feature which is programmed whenever the Linux computer goes to sleep. When the alarm time is met, the supervisor receives an interrupt signal which brings it out of its low power sleep state and causes the supervisor to apply power to the Linux computer. The Linux computer 'rc.local' file calls a script which starts the control process, IMM process and the required logger processes. The control process asks the supervisor for the wake event code which can be one of several events such as the PROFILE_NOW_EVENT or the MANUAL_WAKE_EVENT and so on. If it is MANUAL_WAKE_EVENT, the control process will give the user 60 seconds to stop all processes and manually control the profiler from the Linux prompt. If the user fails to stop all processes in the allotted time, it will simply check for the next scheduled wake item, program this alarm and go back to sleep. If the wake event is equal to PROFILE_NOW_EVENT then a profile will begin. The control process reads 2 files, the first is the prf_schedule.txt which is generated from *prf_schedule.cfg* and is essentially a queue of different profile types which the user wants to perform and when. The program looks at the first line in this list. It checks that this time has just passed and looks to see what profile type is requested. The second file that it reads is *prf_schedule.cfg* which contains a list of profile types with a unique index number and profile parameter list that describe the specifics of this profile. A commonly used profile type is the “yo-yo” type. This is a profile in which the vehicle starts wherever it is in the water column, drives to a specified shallow depth stop, pauses for a specified number of seconds, and then drives down to the deep depth stop. All profiles have a user definable sensor warm up and warm down time period before and after a profile operation. A yo-yo sampling program will be described for this example (Fig. 6).

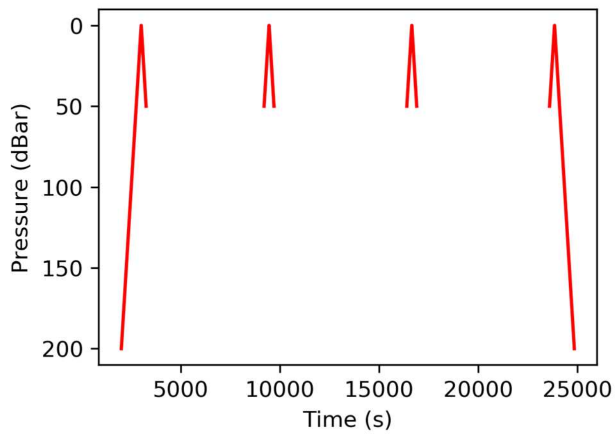

Fig. 6. ***8-hour depth-time plot of a yo-yo sampling program***

The control process performs the following steps:

- Increment the profiler counter number
- Power on sensors for *ctd_warmup_time* seconds
- Start recording data
- Ramp (PWM) motor to full speed using *ramp_time* parameter and specified *direction* up/down
- Drive up until reaching *slow_depth* pressure
- Begin ramping down motor to 50% PWM duty cycle over *slow_time* parameter seconds
- Either stop because *shallow_depth* parameter has been reached or because motion has stopped because profiler is bumping the ice floe
- Set the brake
- Pause for *pause_time* seconds (This gives a user defined period of time to sample the water at the ice-ocean interface before resuming profiling)
- Ramp (PWM) motor to full speed using *ramp_time* parameter and specified *direction* up/down
- In this example, drive down to *deep_depth* parameter. (Down profiles have an automatic 1 meter ramp down to slow momentum before stopping)
- Set the brake
- Continue sampling for *ctd_warmup_time* seconds
- Close all data files
- Power off all sensors
- Compress data files if specified in mission config
- Add data files to telemetry queue
- Delete current profile request off prf_schedule.txt queue
- Initiate telemetry session (if specified in mission configuration) by sending message to IMM process
- Monitor the IMM process in case something causes it to exceed the *max_session_time* parameter and continue to feed the supervisor watchdog timer
- Wait to receive the IMM transfer complete message and then begin the shutdown sequence
- During the shutdown sequence the control process looks at the next line in prf_schedule.txt where it retrieves the scheduled start date and time for the next profile
- Sends a message to the supervisor to set the next alarm time
- Sends shutdown “-h now” Linux command
- Linux shutdown script changes the state of a GPIO pin that is read by the supervisor. When the supervisor sees this pin transition from logic high to logic low, it waits 5 seconds and then removes power from the Linux computer.

The above sequence of events is bound or controlled by a number of parameters specified in the *prf_schedule.cfg* file. These parameters are grouped together within this file to form profile types. Each type of profile has a unique ID number. These profile types are then arranged together by ID into a comma separated list to form a pattern at the bottom the *prf_schedule.cfg* file. The *prf_schedule.txt* file is generated by expanding this pattern between a start and end date. The start and end date parameters allow the user to create multiple patterns that can run at later dates in the future. The parameters that make up a profile type are described here:

- id: unique profile identifier
- meta: profile description text
- type: 0=stationary, 1=oneway, 2+=yo-yo count
- direction: 0=down, 1=up, also initial direction for yo-yo
- interval: seconds between profile starts
- max_time: max profile duration in seconds
- shallow_depth: shallow stop in dbar
- shallow_window: shallow error window in dbar
- deep_depth: deep stop in dbar
- deep_window: deep error window in dbar
- slow_depth: begin ramp down starting at this depth in dbar
- slow_time: ramp down to half speed over *n* seconds
- pause_time: time in seconds to wait at top of yoyo profile

- •ramp_time: motor PWM ramp time in seconds
- •stall_timeout: if no dpdt in *n* seconds start backtrack
- •backtrack_time: seconds to drive in opposite direction
- •backtrack_count: number of times to perform backtrack
- •ctd_warmup_time: CTD warmup time in seconds
- •dpdt_threshold: minimum dbar/sec to be considered stuck
- •telemetry: 0=off, 1=on, initiate IM transfer to surface

D. Sensors

One of the original design criteria was that TOP should be able to drive up to the base of the ice floe and touch without damaging the sensors. It was also desired to improve the quality of down-going profiles; the quality of down-going ITP data are often degraded due to the location of the CTD sensor on the upper end cap that places the sensor in the wake of the ITP body on down-going profiles.

With these criteria in mind, it was decided to position the TOP sensor suite off the side of the upper end cap and to use sensors that would naturally allow flow past them in both profile directions. Side mounting lessens the probability of sensor damage when contacting the ice floe base. The design is such that the shallowest measurement is 15 cm below the ice-ocean interface. The next issue was how to protect the sensor, especially when pushing the profiler down through the 11" ice hole. A pair of (American) football helmet style U-shaped guards (Fig. 3) are used to protect the sensor suite during deployment without impeding flow past the sensors during profiling.

Research was conducted on availability of sensors, quality, availability, price, and most importantly a willingness to work with us on an new OEM style affordable sensor for expendable instrumentation.

Solumetrix was willing to enhance their existing conductivity cell design to withstand pressure to 300 dbar and also to develop a fast response temperature sting that could be used on a profiler. In addition, we planned to use a Keller i2c pressure transducer and wanted the pressure measurements to be integrated into the CTD output string along with conductivity and temperature. Here again Solumetrix was willing to work with us. The original sensor electronics package had a very quiet 18 bit ADC circuit. Today they are working on a 2nd generation quiet 24 bit ADC circuit.

In addition to Solumetrix, we have a new prototype Hybrid CTD from D-2, Inc., a transverse CTD from RBR, and a CT•Xchange™ Sensor from AML Oceanographic. These new sensors, fitted to separately designed upper end caps, are scheduled to be tested later this year.

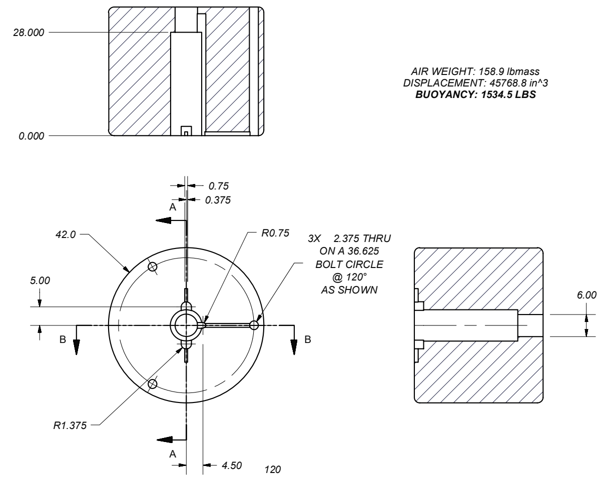

Fig. 7. ***TOP cylindrical buoy design***

E. Tether/Buoy

TOP uses a 200 meter length of 3/16" plastic jacketed wire rope similar to what is used for ITPs. Since one of the main design criteria for TOP was to be able to travel to the ice-ocean interface and bump the ice floe base, the ITP tether's upper potted section (which brought the IMM upper grounding plate into the water) needed to be eliminated. The wire rope termination that is bolted to the bottom of the surface package has a 4-pin pigtail where all 4 conductors are bonded to the steel strength member in the plastic jacketed wire rope and insulated from the water. A new way to bring the upper ground point for the IM circuit into the water was required. A grounding pole is the current solution to this problem. A new simple buoy design was created for TOP. The buoy is a 42" in diameter cylinder and 35" tall (Fig. 7). Near the circumference of the buoy is a 2.375" hole that acts as a drill guide for a 2" ice auger drill bit. Once the buoy is in place, a 2" hole is augered in the ice floe (Fig. 8 left) using this drill guide. A 1.5" OD x 12' long aluminum grounding pole with flange plate at top is placed through the drill guide hole in the buoy and down thru the ice floe (Fig. 8 right).

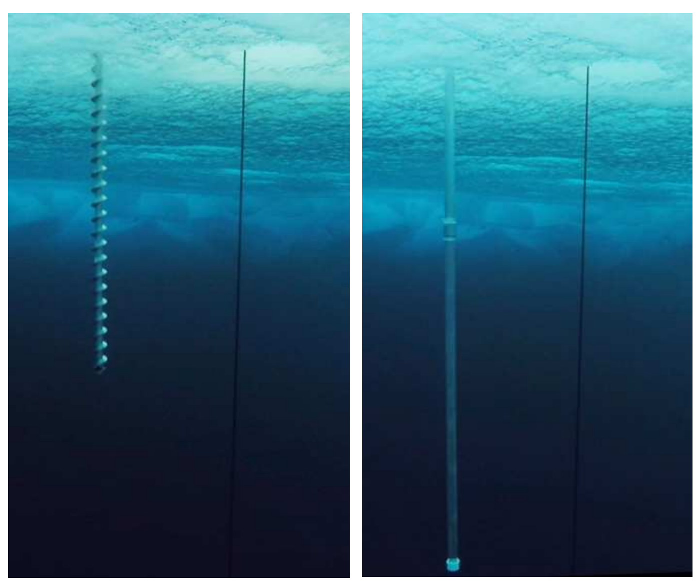

Fig. 8. ***Grounding pole auger (left) and installation (right)***

The upper flange is electrically connected to a re-designed 8 pin surface package communication cable that uses 4 pins for serial communication and opto-isolated wake signal. The other 4 pins are connected to the grounding pole. This grounding pole serves as the upper seawater ground for the inductive modem circuit while the bottom anchor termination serves as the lower grounding point. The grounding pole is assembled on ice from three 4' sections of 1.5" schedule 40 aluminum pipe connected with 2 aluminum pipe couplings. A plastic PVC cap is put on the bottom of the pipe to protect from sharp edges and 4.25" aluminum pipe flange is placed on the top of the pipe. The flange acts to keep the pole from dropping down into the water, provides some surface area to lag screw the pole to the buoy foam and serves as the electrical attachment point for an 8-pin pigtail that connects the grounding pole to the surface package communication cable. These are all COTS part easily available from any industrial supply website.

III. TOP Performance

The majority of TOP systems deployed to date were co-located with ITPs, allowing direct comparison of the profiling performance of these two instruments. Energy needed to profile up and down may be inferred from profile-averaged motor current plotted versus the drift speed of the buoy in (Fig. 9). In this example, data from TOP006 and ITP137 are highlighted, but for all collocated systems, significantly less motor current is used by the TOP to profile versus the ITP as the drift speed increases. While ITPs are rarely able to profile upward when the drift speeds exceed 30 cm/s due to motor electromagnetic decoupling at high amperage, TOPs have demonstrated the ability to reliably profile upwards in drift speeds exceeding 50 cm/s.

This advantage is presumably made possible by less drag from slower vertical speed through the water column and to a lesser extent from a more stream-lined shape. In addition to lower overall energy to profile, the TOP system shows less sensitivity to ice-floe drift speed and most importantly, improved ability to travel all the way up to the top stopping depth. TOP is able to reach its programmed upper depth at times of high ice floe drift speed due to its pinch roller drive system while the ITP often stalls during high drift speed events due to drive wheel slippage. An additional attribute of the TOP pinch drive system is the ability to profile when the tether has reduced tension such as when the end weight is sitting on the bottom. This may allow sampling over the continental slopes and shelves where ITPs have had limited success.

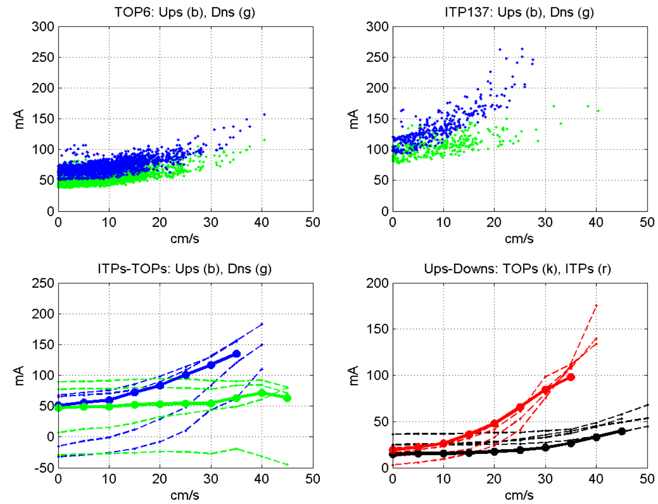

Fig. 9. ***Comparison of TOP and ITP drive system performance as a function of ice floe drift speed. Top left panel: mean motor currents versus drift speed for all up profiles (blue) and all down profiles (green) for TOP6; top right panel: same as top left panel for ITP137 (collocated with TOP 6); bottom left panel: difference of bin-averaged mean motor currents versus drift speed for each TOP from each collocated ITP for up profiles (blue) and down profiles (green); bottom right panel: difference of bin-averaged mean motor currents versus drift speed for down profiles from up profiles for TOPs (black) and collocated ITPs (reds). The solid thick lines with markers in the bottom panels indicate the TOP6/ITP137 pair.***

IV. Initial Scientific Results

As of this writing, a total of 7 TOP systems have been fielded in the Canada Basin sector of the Arctic (Fig. 10). The initial prototype TOP was deployed in fall 2019, followed by three each in 2021 and 2022. All were fielded in conjunction with the annual Beaufort Gyre Observing System (BGOS) / Joint Ocean Ice Study (JOIS) expeditions aboard CCGS Louis S. St. Laurent. In all but one case, TOPs were installed in ice floes adjacent to ITP systems and other instruments. TOP007 was deployed on its own in open water.

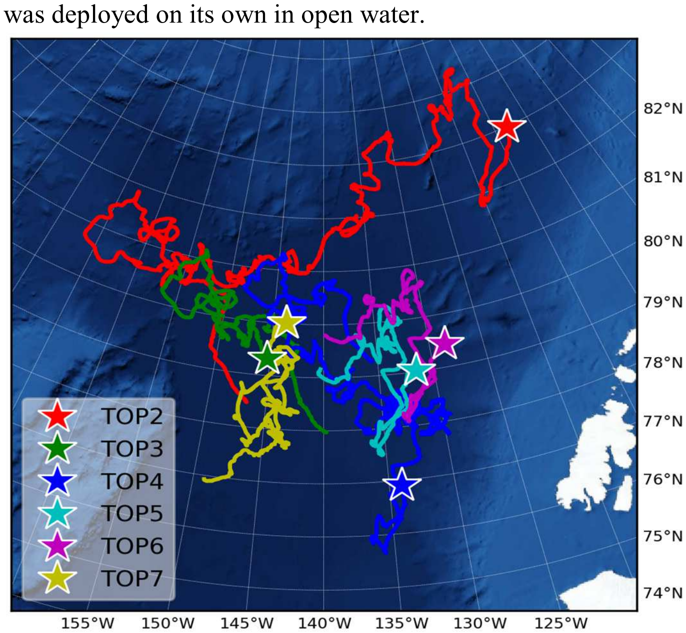

Fig. 10. ***Drift tracks of TOPs 2-7 deployed in the Canada Basin***

A. Thermohaline Variability

TOP004 was deployed on a 0.75 m-thick ice floe in the Beaufort Sea on September 4, 2021, at 79° 17.0' N, 135° 31.6' W. On the same floe, an Ice-Tethered Profiler (ITP122), a US Army Cold Regions Research and Engineering Laboratory (CRREL) Seasonal Ice Mass Balance Buoy (SIMB, 2021 #3) [3], and a Naval Postgraduate School Arctic Ocean Flux Buoy (AOFB48) were also installed. The TOP was initially programmed to occupy 6 two-way profiles from the surface to 200 m depth each day. After ~3 months, the programming was modified to alternately perform traverses from 200 m to the surface then down to 50 m, and 50 m to the surface to 200 m. The resulting data set yielded high horizontal- (~1 km) as well as vertical- (~5 cm) resolution sampling of the surface mixing layer and underlying transition zone. Following its deployment, TOP004 initially drifted to the NW, reaching north of 81° N on 145° E before returning back southeast to reach 78° N, 130° E after 1 year. The upper ocean temperature along the drift track (Fig. 11), shows the now characteristic Pacific Summer Water maximum around 50 m depth below a surface mixed layer that deepens from ~25 m to ~40 m over the course of the drift. Some of the deepening may be due to seasonal processes; note how the vertical gradient at the mixed layer base sharpens during the winter when enhanced surface mixing driven by brine rejection during ice formation can scour the mixed layer base. Another factor is that the TOP drifted closer to the center of the Beaufort Gyre anticyclonic gyre where Ekman convergence forces pycnocline deepening. Dramatic warming and restratification of the surface layer are seen in the final two months of the displayed time series with the temperature at 20 m depth increasing from ~-1.6° C to ~-1.25° C.

In November 2021, TOP004 sampled a 10 km-diameter anomalously warm anticyclone within the Pacific Winter Water layer, Fig. 11b, c. Some dozen profiles were obtained while the TOP transited this feature. While anticyclones are relatively common in the PSW layer [4,5], warm eddies at this depth so far from the continental shelf break, are among the rarer types of intra-halocline eddies observed in the Canada Basin. Looking at still finer scale (Fig. 11d), erosion of the eddy by double diffusive processes (diffusive layering and thermohaline intrusions) is seen to have been underway.

TOP002 also sampled a full annual cycle. It was deployed a year earlier on September 2, 2021, at 78° 34.9' N, 147° 15.5' W on a 0.85 m thick ice floe together with ITP127 and SIMB (2021 #2). Based on the CTD observations when the TOP was positioned at the ice-ocean interface, a time series of ocean temperature and the local freezing point was constructed (Fig. 12). Through the winter, the sea water in direct contact with the ice floe base is usually within a few m°C of the freezing point, but with occasional warmer episodes, possibly due to entrainment at the mixed layer base. With the arrival of spring and higher solar angle, the ocean warms, chiefly through short wave absorption in leads. Under ice water temperatures warm to around 1° C above the freezing point. With these data, basal ice melting rate could be estimated. The spike in freezing

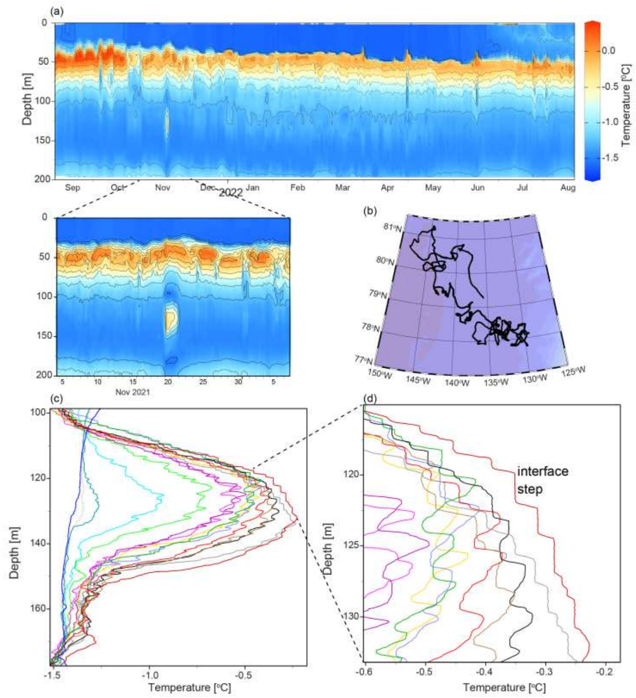

Fig. 11. Temperature sampled by TOP004. (a) Depth-time section over a full annual cycle (September 2021 - August 2022, over the drift track shown in (b)) showing the seasonal deepening of the mixed layer and some seasonal erosion of the warm Pacific Summer Water Layer centered around 50 m depth. The close-up portion shows a warm anticyclonic eddy, with core depth around 130 m, embedded in the Pacific Winter Water halocline sampled by TOP004 in November 2021. (c, d) Temperature-depth profiles through this warm-core eddy, estimated to have a diameter of about 20 km, showing the detailed temperature structure recorded by the TOP as it transected the eddy. Intrusions, characterized by temperature inversions, at the margins of the eddy transition to a staircase (with well-mixed steps and interfaces, labeled) overlying the warmest part of the eddy core

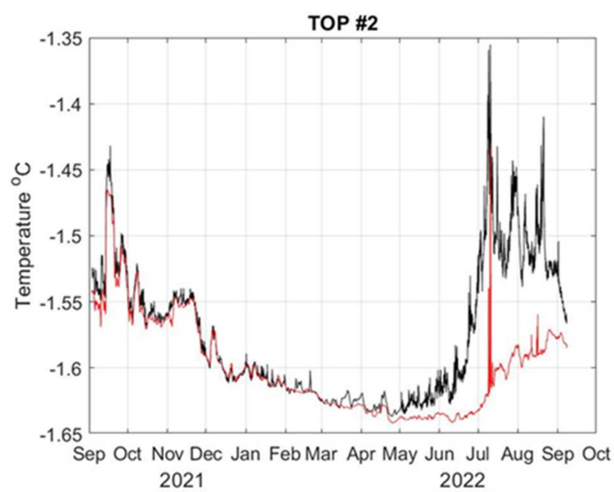

Fig. 12. Time series of the potential temperature sampled just below the ice-ocean interface by TOP002 (black curve). The red curve is the freezing temperature at the observed salinity and pressure of the shallowest observations from each one-way TOP profile. The spike in freezing point temperature in July 2022 reflects observations from a thin melt water pond that was sampled on a few profiles.

temperature seen July 2022 is a melt water pond sampled on just a few profiles before it was advected away by ice-ocean relative motion.

B. *Ice Draft Estimation*

A design goal for TOP was the ability to sample the ocean water properties in immediate contact with the supporting ice floe. This achieved by having the profiling vehicle travel up until impacting the base of the ice. An unanticipated benefit of this function is an estimate of the time-varying ice draft. Accurate ice draft estimation from TOP requires a correction for variations in atmospheric pressure. The high degree of correlation seen between the atmospheric pressure variations and minimum TOP pressures (Fig. 13) lends credence to the TOP estimates of ice draft.

As noted earlier, TOP002 was deployed alongside a Seasonal Ice Mass Balance Buoy that records snow thickness, the temperature distribution through the ice and changes in the depth of the ice-water interface [3]. TOP derived variation in ice draft agrees well with that determined by the SIMB during the fall and winter (Fig. 14). Note that the SIMB data are displayed on a vertical axis fixed with respect to the SIMB. In a frame relative to the sea surface, we would expect the floe to maintain relatively constant freeboard through the summer such that the SIMB ice draft would better agree with that derived from TOP.

Ice growth and melt, forces significant salinity change to the surface ocean. The seasonal cycle is nicely depicted by TOP temperature-salinity data at the ice water interface (Fig. 15). Observations show how between June and September, water at the ice-ocean interface in the Northern Canada Basin deviates from the freezing line, beginning in June when the temperature increases with relatively little change in salinity until freshening in July. By the start of September, water at the ice-ocean interface is at the freezing temperature.

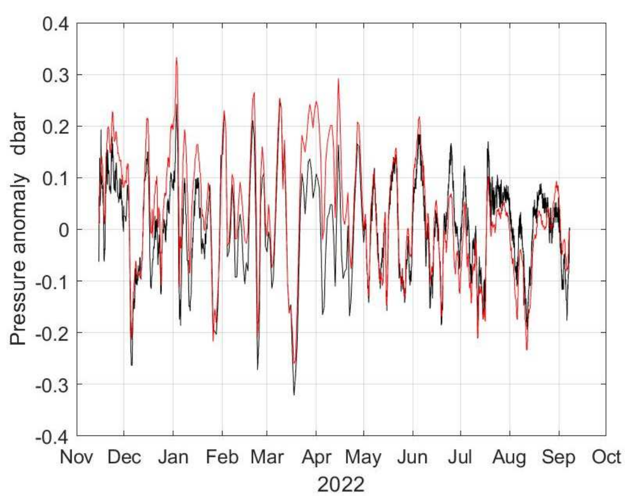

Fig. 13. ***Time series of minimum pressure sampled on each TOP002 profile (black) and the anomaly of atmospheric sea level pressure (SLP) from a long-term average sampled by the SIMB deployed adjacent to the TOP (red). The TOP pressure data were high-pass filtered with cutoff period of 10 days.***

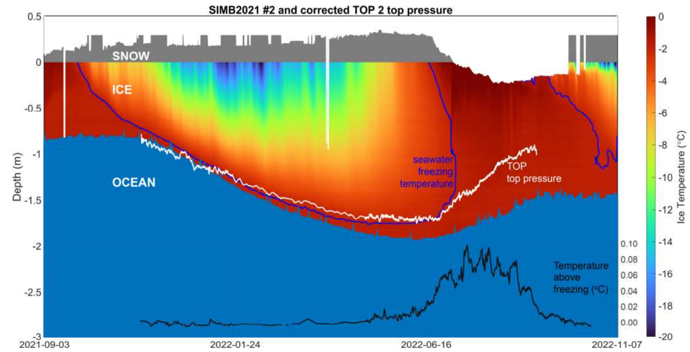

Fig. 14. ***Observations of snow (gray) and ice thickness (red to blue color transition) from Seasonal Ice Mass Balance Buoy 2021-2 together with estimates of the sea ice draft from TOP002 (white curve) after correction for variations in atmospheric pressure. The blue line contour marks the location where the ice is at the freezing temperature. The black curve at the bottom is departure of the sea water temperature from the freezing point at the ice-water interface.***

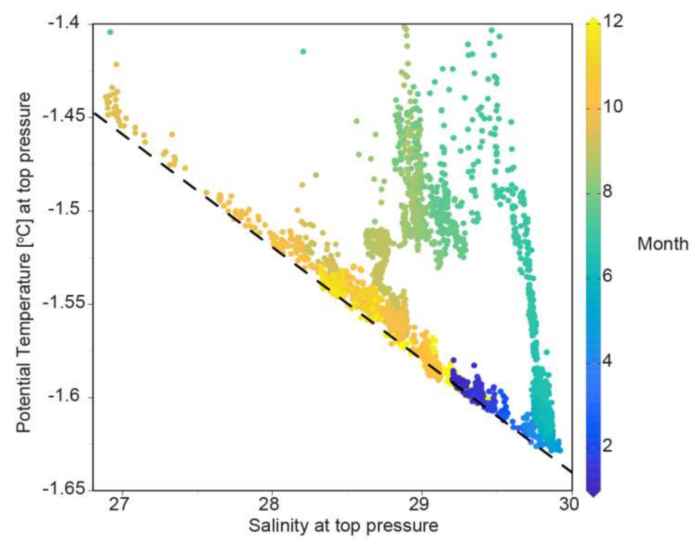

Fig. 15. Potential temperature vs. salinity at the ice-ocean interface (the shallowest measurement) sampled by TOP002 over a full annual cycle (September 2021 to October 2022). The color indicates the month of the year, and the dashed line is the freezing line

These and other areas of research will be pursued in the coming years as more TOP data are obtained.

V. Future Plans

It is hoped that the ITP/TOP sampling program will be renewed for another 5-year period. In support of regular deployment of systems and the collection and distribution of under-ice water property observations, the buoy technology will be evolved. A primary focus of this work will be to merge the ITP and TOP designs to a device able to sample the ocean from the ice-ocean interface down to ~800 m depth.

ACKNOWLEDGMENT

Development, testing, and operational deployments of TOP systems have been funded by the Arctic Observing Network program of the National Science Foundation. Mechanical Engineering by Chris Rauch, Todd Gregory. Sensor Suite by David Harmer, Jim Hearne, Solumetrix. Tether by James Ryder, Jeff Pietro. SIMB Data by Donald Perovich, Cameron Planck. Thanks to Joint Ocean Ice Study (JOIS) and Beaufort Gyre Observing System (BGOS). Special thanks to crew of Canadian Coast Guard Heavy Ice Breaker Louis. S. St. Laurent (CCGS LSSL). Photos by Gary Morgan CCGS LSSL

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