IceNode: a Buoyant Vehicle for Acquiring Well-Distributed, Long-Duration Melt Rate Measurements under Ice Shelves

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Abstract— **Antarctic ice shelves buttress the Antarctic Ice Sheet from sliding into the ocean and significantly raising global sea level. However, the accelerating dynamics of ice shelf melt in a warming environment are poorly understood, and the collapse of Antarctic ice shelves remains one of the largest sources of uncertainty in global sea level rise projections. The cavities below Antarctic ice shelves are notoriously difficult to access, making model-based hypotheses about the relationship between ocean warming and greater ice shelf melting difficult to verify because of a lack of in-situ data to constrain model parameters and examine key assumptions. We present early progress on IceNode, a novel vehicle under development at the NASA Jet Propulsion Laboratory designed to acquire well-distributed, concurrent, long-duration melt rate measurements under ice shelves. IceNodes are deployed as an array from a ship at the shelf edge, and use variable buoyancy to ride melt-driven exchange currents far into the cavity. Once underneath their target landing area, they release a ballast weight to gain high positive buoyancy and attach to the underside of the ice shelf, where they acquire in-situ measurements of basal melt rate directly at the ice-ocean interface for a year or more. Finally, IceNodes detach from their landing structure and use variable buoyancy to ride melt-driven exchange currents back to open water, where they surface and transmit their mission data home. IceNodes are designed to be relatively low-cost, expendable, and have simple logistics, enabling scientists to deploy scalable arrays that acquire simultaneous, distributed measurements of co-varying ice shelf melt and ocean conditions over large spatial areas, thereby providing an unprecedented view of ice shelf melt rate variability and its drivers.**

Keywords— ***icenode, ice shelf, ice shelves, grounding zone, melt, sea level rise, climate change, underwater vehicles, oceanic instrumentation, sensors, robotics, autonomous, vehicle design, buoyant lander, profiling float, oceanography***

I. INTRODUCTION

A. Motivation

By the end of the century, the collapse of Antarctic ice shelves could trigger a meter or more of sea level rise, with profound effects for hundreds of millions of people worldwide [1]. These ice shelves serve as “corks in the bottle” that buttress the Antarctic Ice Sheet and prevent it from sliding into the ocean. Collectively, they hold back more than 50 meters of global sea-level rise equivalent in total [2]. Lack of understanding about how ocean warming will further accelerate the disintegration of Antarctic ice shelves remains one of the largest sources of uncertainty in global sea level rise projections. Current model-based hypotheses linking ocean warming to greater ice shelf melting are difficult to test owing to the dearth of concurrent and coincident in situ ocean and melt rate observations, especially near critical locations such as ice shelf grounding zones. Present methods for measuring in situ cavity melt for ice shelves require deploying instruments through boreholes drilled through the ice, which can be many hundreds of meters thick. Drilling operations are logistically complex and expensive, are precluded from accessing critical locations such as the grounding zone due to surface crevassing, and only yield data at a small number of proximate sites for relatively short durations. What is needed is an instrument platform capable of acquiring long-duration measurements of melt rate directly at the basal ice-ocean interface, which is logistically simple to deploy and cost-scalable to capture the distribution of melt rate variability across multiple measurement locations under the shelf.

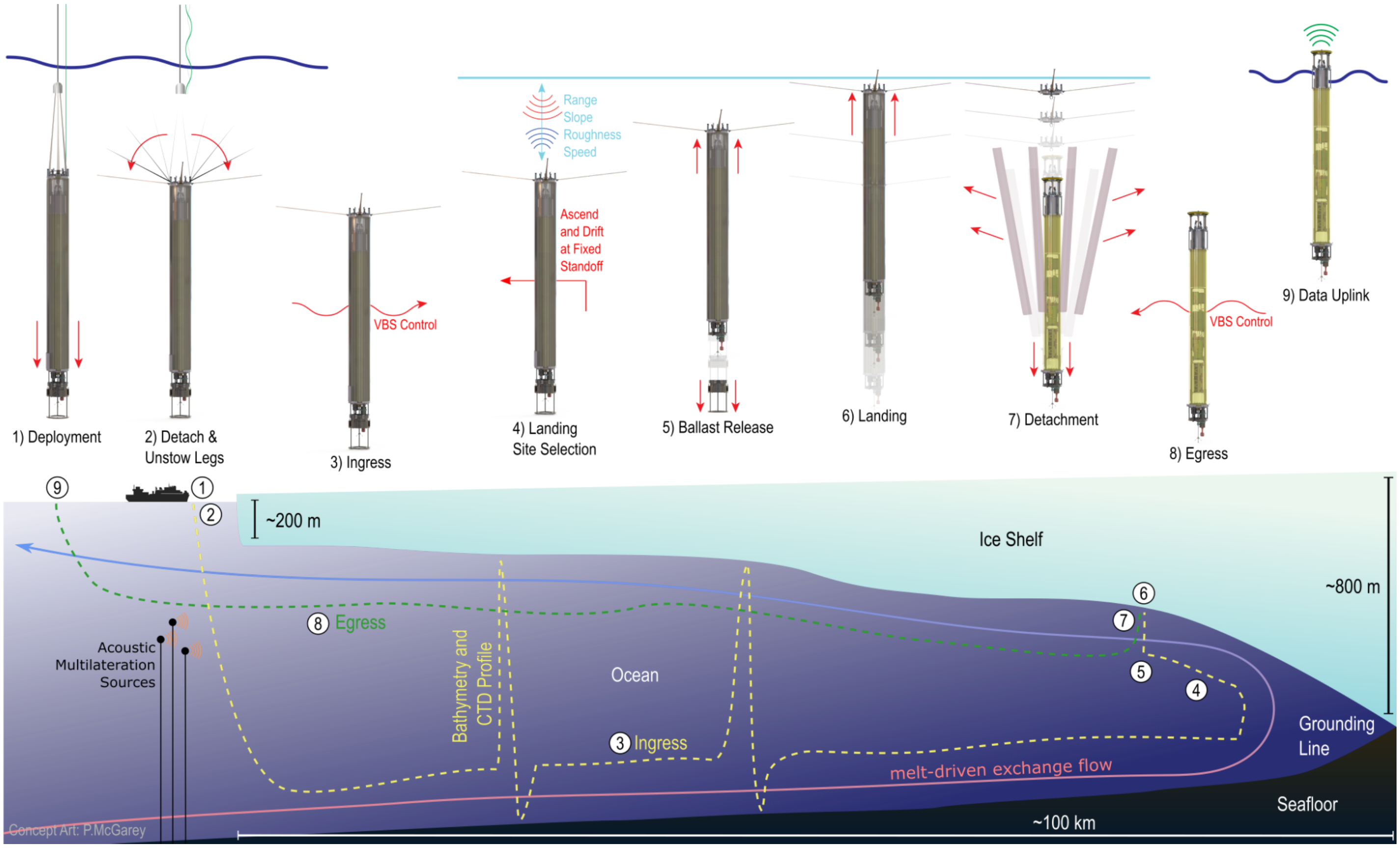

Fig. 1. IceNode Concept of Operations (CONOPS). Multiple IceNodes are deployed at once by an icebreaker at the ice shelf edge, then drift under the shelf on melt-driven exchange currents to form an array of concurrent, long-duration basal melt rate observations over a large spatial area. IceNodes may optionally also be deployed down a borehole ≥ 25 cm in diameter.

B. *System Description and Concept of Operations*

We present early progress on IceNode, a novel vehicle under development at the NASA Jet Propulsion Laboratory designed to acquire well-distributed, concurrent, long-duration melt rate measurements under ice shelves. IceNodes employ a variable buoyancy system (VBS) and a series of releasable ballast and float mechanisms to control their buoyancy in the water column throughout various stages of their mission. IceNode is deployed by a ship at the shelf edge with near neutral buoyancy (Fig. 1, phases 1 and 2) then uses its VBS to descend and embed itself in deep inflowing melt-driven exchange currents to be swept underneath the shelf. During ingress, IceNode performs vertical profiles to measure water column properties using its Conductivity, Temperature, and Depth (CTD) probe, and gathers bathymetric point data by logging the depth of the seafloor and underside of the ice shelf when it encounters them (either by physically bumping into the seafloor, or detecting the ice with Doppler Velocity Log (DVL) ranges) (phase 3). Once below its target landing area, IceNode ascends and drifts at a fixed standoff from the ice, using its DVL to wait for a suitable moment to land based on ice surface slope, roughness, and drifting speed (phase 4). When a suitable landing location is found, IceNode releases a ballast weight to gain high positive buoyancy to land on the underside of the ice and acquire melt rate measurements directly at the basal melt interface for a year or more (phases 5 and 6). When finished, IceNode jettisons its landing legs and syntactic foam to regain near neutral buoyancy (phase 7) and uses its VBS to embed itself in shallow outflowing currents and be swept back to open ocean (phase 8). Finally, IceNode uses its VBS to ascend to the surface and transmit its mission data home over the Iridium network (phase 9). Throughout its mission, IceNode localizes itself using multilateration based on ranging signals from a set RAFOS acoustic moorings installed at the shelf edge. With relatively low cost, IceNodes are intended to be expendable, and are not intended to be recovered after their mission. Due to their low cost and relatively simple deployment logistics, many IceNodes can be deployed at once to form an array that that acquires simultaneous, distributed measurements of co-varying ice shelf melt and ocean conditions over a large spatial area, including near grounding zones, thereby providing scientists with an unprecedented view of melt rate variability and its drivers. IceNodes will provide concurrent, well-distributed, long-duration ground-truth melt rate and ocean variability data that will enable scientists to 1) validate and improve ice shelf melt parameterizations and coupled ocean / ice sheet climate models and 2) validate estimates of ice shelf melt that are inferred from remotely-sensed ice shelf and ocean data. IceNode will also be deployable down a 25 cm operational diameter borehole to enable partnerships of opportunity and targeted deployment to specific scientific features of interest.

C. *Related Work*

The cavities underneath ice shelves are notoriously difficult to access and return safely from, and are cut off from communication with the outside world by up to a thousand meters of ice overhead. Due to the difficulty of access, relatively few in-situ observations have been acquired in these environments to date, and many active hypotheses about the dynamics of these environments are hampered by a basic lack of observational data. Generally speaking, there are two methodologies for accessing the ocean cavity beneath an ice shelf - using boreholes drilled through the ice from the top surface of the shelf to the ocean below, and using a ship (an ice-breaker, in the case of remote Antarctic Ice Shelves whose fronts are obstructed by sea ice) to deploy mobile assets in open water at the shelf edge, which then make their way under the shelf and back out again either under their own power or by taking advantage of naturally occurring ocean circulation patterns.

Direct in situ measurements of melt rate inside ice shelf cavities have historically been limited to point measurements taken by dedicated borehole-deployed instruments such as [3] and [4], but such measurements are few and far between. Tethered ROVs and HROVs such as Moss Landing Marine Lab's SCINI [5] and Deep-SCINI [6], Stone Aerospace's ARTEMIS [7], and Georgia Tech's Icefin [8] have also been deployed down boreholes drilled in ice shelves or sea ice. These vehicles have captured data on water column properties, collected water samples, and taken imaging and sonar-based data. However, such missions have typically been short-range (hundreds to a few thousand meters from the borehole) and short-lived (hours) due to limitations with tether logistics, battery life, and borehole freeze-over, especially in the case of deep ice shelf boreholes. Boreholes generally cannot be safely implemented in close proximity to active grounding zones or other high interest areas with complex surface topography due to heavy surface crevassing. In addition, boreholes typically have complex logistics, high costs, and short operational lifetimes, making them ill-suited as a scalable access solution for long-duration distributed multi-measurement campaigns.

In ocean-based missions, assets are deployed in open water at the ice shelf edge by an icebreaker, then traverse underneath the cavity to acquire data and back out again to return it, either through physical recovery of the vehicle or transmission of the data over Iridium link. Notable missions include the British Antarctic Survey's Autosub 3 at Pine Island Glacier [9] and Autosub Long Range at the Filchner and Ronne Ice Shelves [10], which collected multibeam sonar, CTD, and water column turbulence microstructure data, and the Applied Physics Lab at the University of Washington's (APL-UW) Seagliders and EM-APEX floats under Dotson Ice Shelf, which collected CTD profiles, current speed data, and bathymetric touches [11]. IceNode's concept of operation draws especially heavy inspiration from APL-UW's successful EM-APEX campaign, which pioneered the use of variable buoyancy to exploit melt-driven exchange flows as a natural transport mechanism in and out of the cavity (deep inflow, shallow outflow) and successfully returned four out of four EM-APEX floats back to open water where they could transmit their data home after spending multiple months and collectively travelling hundreds of kilometers under ice (the floats were not physically recovered) [12].

While each mission to date has been successful in its own right, importantly, no ocean-deployed asset has had the capability to physically interact with the ice-ocean interface or directly take measurements of basal melt rate, they have only collected data from the water column below. Additionally, none of the borehole-deployed assets have been easily scalable due to the intrinsic limitations of boreholes. The IceNode concept will allow for cost-efficient arrays of long-duration, concurrent, well-distributed direct melt rate measurements deployed from the shelf front, enabling scaling of this critical measurement by reducing the cost of each additional measurement platform from the cost of a borehole (several $M) to the cost of a single additional vehicle (~$130K). This will enable scientists to acquire unprecedented panoramic datasets elucidating melt dynamics directly at the basal melt interface of major ice shelves.

II. Mission Architecture Study

The mission architecture for an IceNode array to acquire concurrent, distributed, long-duration melt rate measurements is significantly different from any previous instrumentation attempts made inside an ice shelf cavity in terms of both scalability and CONOPS. In order to investigate the viability of an IceNode array to achieve in-situ characterization of distributed basal melt rate under Antarctic ice shelves, we utilized a state-of-the-art ocean model of the cavity beneath Pine Island Glacier (PIG), Antarctica [13] to study the expected performance of the array as a function of different mission designs. The model simulates ice-ocean interaction using the MIT General Circulation Model (MITgcm), which includes a dynamic / thermodynamic sea-ice model as well as an explicit representation of freezing/melting processes in the sub-ice-shelf cavity. The model uses a horizontal grid spacing of ~280m, vertical grid spacing of 5m, and provides hourly output (computed on a 3 second timestep), which is an unprecedented resolution for modeling ocean processes of the PIG cavity and of Antarctic ice shelf cavities in general. The initial and boundary conditions are taken from a coarser model set up of the Amundsen Sea Embayment. Although the model encodes the main processes of the sub-ice shelf cavity, it does not necessarily represent the sub-mesoscale variability at a specific time in the real world.

The first science objective of a future Antarctic IceNode campaign is to characterize the mean and temporal variability of in situ ice-shelf basal melt rate at IceNode landing locations for a full seasonal cycle (365 days). Success for this objective is directly addressed by IceNode acquiring at least once-daily melt rate measurements at the basal melt interface. However, one detail that must be quantified is the observation duration required to characterize the true mean as opposed to higher frequency noise. Using standard statistical methods, and assuming one independent melt rate measurement per day, we determined the time needed to predict the mean melt rate to within 10% of the true value with 99% confidence at all locations on the ice shelf, which is shown in Fig. 2. In most places, the true mean could be discovered on the order of days, although in some regions of the shelf it takes months due to extremely low melt rate making the signal harder to pick up against background noise. Considering that each IceNode is designed to acquire data for a year in its landed science phase, the first objective is highly achievable.

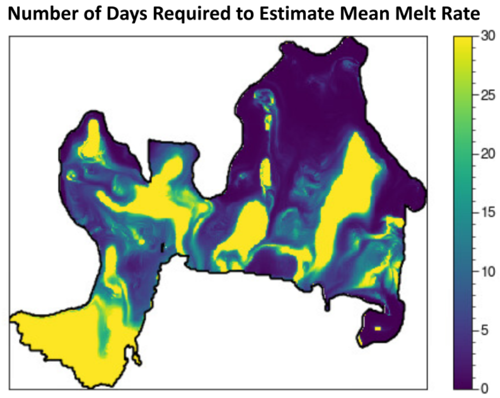

Fig. 2. Top-down view of Pine Island Glacier, Antarctica, showing the number of days required at each location to estimate mean melt rate to +/- 10% of the true value with 99% confidence, assuming measurement uncertainty of 0.1 m yr^{-1}.

The second science objective is to estimate the basal melt rate variability – specifically the time series of melt rate anomaly – at various regions under the shelf which may not be directly observable by the IceNode array. We do this by combining the localized data collected at the IceNode landing locations with knowledge of statistical melt covariations predicted by the numerical cavity model to infer melt rate at a number of science targets where IceNodes may have difficulty landing and observing directly. In the interest of brevity, we will discuss only results for the grounding zone here, as the grounding zone is thought to be a primary driver of ice shelf melt dynamics, and the results for the other science targets were qualitatively similar.

In order to study the achievability of the second objective, we conducted an Observing System Simulation Experiment (OSSE) to characterize the performance of the IceNode array as a function of number of IceNodes, IceNode placement under the shelf, measurement accuracy, frequency, duration, and frequency band of the target signal to be reconstructed. Different numbers of simulated IceNodes were placed randomly underneath the ice shelf (not including the area they were meant to infer) and sampled synthetic melt rate data drawn from the model, plus added noise, with a given frequency and duration. Gauss-Markov estimation was used to estimate the time series of melt rate using the synthetic measurements, expected measurement error, and statistics of the melt rate field derived from the numerical cavity model for three different frequency bands: seasonal variability (56 day lowpass filter), monthly variability (14 – 56 day bandpass filter), and weekly variability (7 – 14 day bandpass filter), meant to help tease out the effects of different geophysical forcing mechanisms that operate on different timescales. The experiment was repeated for 100 trials for each combination of number of IceNodes, measurement uncertainty, measurement frequency, and landing duration.

The OSSE analysis found that even without landing in the grounding zone, relatively small IceNode arrays are sufficient to estimate seasonal and monthly melt rate variability at the grounding zone using melt measurements at the IceNode landing locations with one measurement per 13 hours and measurement uncertainty of 0.1 m/yr (expected performance).

Specifically, an array of 9 IceNodes randomly distributed under the (non-grounding zone) shelf has a 99.7% chance of achieving greater than 75% of the explained variance in the seasonal grounding zone melt rate signal, and larger or better-targeted arrays can capture close to all the explained variance with very high probability. Characterizing the seasonal cycle of melt rate variability would represent a significant step forward in knowledge about grounding zone dynamics. Capturing significant amounts of the monthly signal is harder but still probably feasible – an array of about 30 randomly distributed (non-grounding zone) IceNodes would have an approximately 50% chance of capturing greater than 75% of the explained variance of the monthly signal. Characterizing the monthly variations at the grounding zone would provide a powerful constraint on numerical models and represent an unprecedented ground-truth dataset for next-generation remote sensing assets. Achieving similar levels of explained variance for the weekly variability signal requires significantly larger IceNode arrays due to higher noise levels at these frequencies, and is probably not practical. Fig. 3 shows the reconstruction of grounding zone melt rate anomaly over the course of one year for the seasonal and monthly frequency bands with an array of 20 IceNodes.

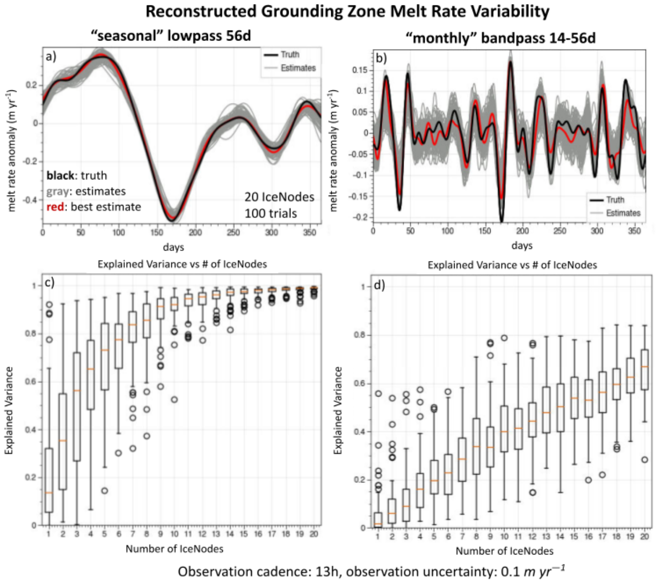

Fig. 3. a) and b): Reconstructions of grounding zone melt rate anomaly for seasonal and monthly frequency bands using an array of 20 IceNodes randomly distributed outside the grounding zone (100 trials). c) and d): Performance of the IceNode array across 100 trials as a function of number of IceNodes. Boxes represent +/- 1 σ and whiskers represent +/- 2.7 σ from the center of gaussian fit to the distribution of runs (orange line).

These studies do not take into account the successful return rate of the data from underneath the shelf. Due to the autonomous nature of the mission, long duration, and large distances traveled, presumably some of the IceNodes will fail to reemerge from underneath the shelf and transmit their data home, and that data will be lost. Although the true loss rate of IceNodes is hard to predict, some anecdotal evidence can be gleaned from the APL-UW campaign conducted under the Dotson Ice Shelf with four EM-APEX profiling floats during the 2018-2019 field season, which used a similar navigational approach to IceNode using variable buoyancy to embed the floats in melt-driven exchange currents for transport in and out of the cavity. Notably, all four floats reemerged from underneath the shelf to transmit data home after spending several months and traversing hundreds of kilometers inside the cavity [12]. In addition, simulated results from a novel stochastic guidance technique summarized in a later section of this paper suggest that reliable guidance of IceNodes to specific targets is possible by strategically exploiting probabilistic patterns in current directions at different depths, and it may even be possible to directly target landing locations in the grounding zone itself. The combination of these two factors suggest that a successful data return rate of 50% is feasible for an IceNode campaign, as is the upper half of the IceNode array performance regime shown in Figs. 3c and 3d. Baselining an IceNode array size of 40 (targeting successful return of 20 IceNodes as informed by the OSSE analysis, and assuming 50% return rate), preliminary cost studies indicate that an IceNode campaign could be conducted at Pine Island Glacier or similar ice shelves for low single-digit millions of dollars, which is within the funding cap of several relevant NASA and NSF funding programs and represents a high science value return on investment.

III. VEHICLE DESIGN AND DEVELOPMENT

A. Onboard Instrumentation and Mechanisms

IceNode carries onboard a suite of instruments and mechanisms necessary to carry out its scientific mission. The most important components and their locations on the vehicle are shown in Fig. 4. The primary scientific instrumentation onboard IceNode is the Ocean Turbulence Flux Package (OTFP). The design and functionality of the OTFP is comparable to the instrument package used in [3], but has been adapted for integration on the IceNode vehicle. The OFTP consists of three instruments 1) an Acoustic Current Meter (ACM), which precisely measures the 3D water velocity vector in a 10 cm cube with fixed 2.75 m standoff from the ice using two-way doppler travel time across four different acoustic paths, 2) a fast response Conductivity, Temperature, and Depth sensor (CTD), and 3) a high-rate inertial measurement unit (IMU) used to cancel out instrument motion and tilt. These three instruments together allow the vertical turbulent fluxes of heat, salt and momentum to be determined by direct eddy-correlation methods. As the ice melts, temporally integrated salt flux measurements near the ice base allow the rate of injection of freshwater into the boundary layer to be calculated, and the local melt rate of the ice shelf base to be estimated.

In addition to the OTFP as the primary science instrumentation, IceNode carries onboard a number of other instruments necessary to perform required mission behaviors. A list of major components and their purposes is shown in Table 1.

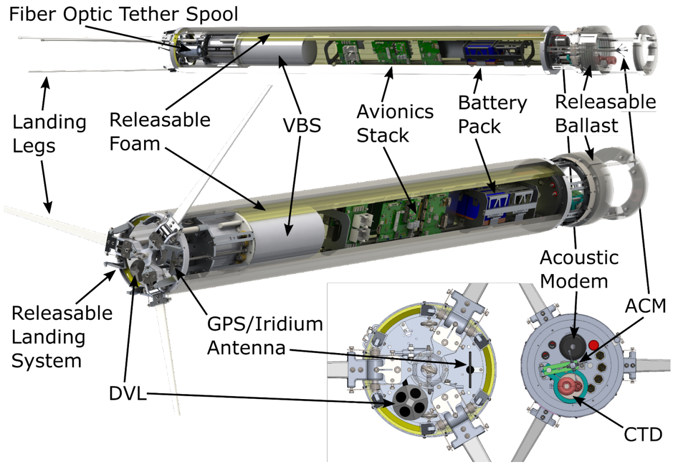

Fig. 4. Locations of primary components on the IceNode vehicle

Component	Purpose	Model
Acoustic Current Meter (ACM)*	Measure 3D water current velocity in fixed volume at ice-ocean boundary layer for OFTP melt rate estimation	Adaptation of custom instrument used in [3]
Conductivity, Temperature and Depth Probe (CTD)*	Measure water column properties for OFTP melt rate estimation, and during bathymetric profiles during ingres	RBR Brevio 3
Inertial Measurement Unit (IMU)*	Tilt and motion correction for ACM water velocity vector, collision detection for bathymetric profiles, landing detection	Lord Microstrain 3DM-CX5-25
Acoustic Modem	Receive commands and communicate telemetry during deployment and testing	Teledyne Benthos ATM 900
Avionics Stack	Control computer and power / electronics interfacing with instruments and mechanisms	Custom JPL designed PCB stack
Ballast/Float Severance Actuator	Triggerable severance mechanism for separating vehicle from ballast and releasable float / landing leg system	Kirintec KT-600-0392-00 M K-cutter
Battery Pack	Onboard power source for all mission stages	Custom Lithium Thionyl Chloride primary pack using SAFT LSH20 cells
Doppler Velocity Log (DVL)	Detect underside of ice, measure ground speed, slope, and surface roughness of underside of ice for approach, constant standoff drifting, and landing	Waterlinked A50
Fiber Optic Tether Spool	High bandwidth communications for supervised operation (e.g. testing)	Depends on application
GPS/Iridium system	Localize vehicle at the end of the mission, communicate mission data back to operators	GPS chip: u-blox NEO M8 Iridium Modem: Iridium 9523 Shared antenna: MRV Systems 920036
RAFOS receiver	Receive ranging pings from moored sound sources for acoustic multilateration	TBD
Releasable Ballast	Gain high positive buoyancy when jettisoned for stability in landed phase	Custom JPL design
Releasable Foam	Offset ballast release when jettisoned, to regain near neutral buoyancy in egress phase	Custom JPL design
Releasable Landing System	Absorb landing impact, provide wide base for stability in landed phase	Custom JPL design
Variable Buoyancy System (VBS)	Depth control in the water column	Custom design by MRV Systems
*These instruments are collectively used to estimate melt rate as part of the Ocean Turbulence Flux Package sensor fusion (OTFP)		

Table 1. Purposes and models of IceNode primary components

B. System Analysis and Generative Design

The design of the IceNode vehicle was challenging in several aspects. First and foremost, IceNode's CONOPS represent an unattempted mission architecture, which requires the IceNode vehicle to support several novel capabilities, in an environment that is not well characterized. As such, there were many initially unknown design variables and system requirements which resulted in a large and poorly understood preliminary design space.

The primary objective for an individual IceNode vehicle is to land buoyantly on the underside of an ice shelf and take melt rate measurements directly at the ice-ocean basal melt interface for at least a year (in order to observe a full annual cycle of geophysical forcing on melt dynamics). As a result, the majority of the IceNode design effort centered around making sure the vehicle could successfully achieve this objective over as wide as possible of a range of environmental conditions it may encounter. Practically speaking, this resulted in two primary but conflicting design drivers: buoyant stability vs battery life.

First, IceNode must provide a stable buoyant platform for the OTFP, even in the presence of uneven or sloped landing surfaces and destabilizing horizontal forces from currents. Because the vertical velocities of turbulent eddies transporting salt through the boundary layer are very small compared to the horizontal component created by boundary layer current under the ice shelf, the OTFP measurement is sensitive to mechanical movement of the 10 cm cube ACM sample volume at the base of the IceNode instrument stalk. Low magnitude instrument movements can be mitigated by subtracting 3D instrument velocities measured by the IMU from the 3D velocity vector measured by the ACM and using spectral covariance methods in the heat and salt flux calculations, but high magnitude movements cannot. Consequently, it is important to have a stable mechanical design with minimal flow-induced motions (e.g. transverse slip, tilt, or vibration).

Second, IceNode must carry enough batteries onboard to complete its year-long landed science objective , as well as the ingress, egress, and data transmission phases of its mission. This design driver is in direct conflict with the buoyant stability design driver because the leading factor in IceNode's stability is its net positive buoyant force in the landed configuration Any onboard batteries subtract from this buoyancy, given they are much denser than water and exist inside the pressure hull, where they don't contribute to volumetric displacement of seawater.

An additional constraint which significantly influenced IceNode's design was the self-imposed requirement to fit down a 25 cm borehole in order to diversify IceNode's ice shelf cavity access methods, allow precise targeting of landing location, and facilitate future Antarctic partnerships through borehole deployments of opportunity. This requirement exacerbated the difficult coupling of dimension and mass design constraints on IceNode, as ultimately the vehicle must 1) be highly positively buoyant in the landed configuration, but be near neutrally buoyant in both ingress and egress configurations, which translates to tight dimension and mass constraints to achieve net vehicle density very close to seawater, and 2) it must be both wide enough to fit all necessary components, but also narrow enough to fit down a 25 cm borehole.

Since IceNode's primary design drivers are coupled and conflicting and their performance also depends on variable environmental factors present at IceNode's eventual landing location (e.g. landing slope, current speed, landing leg / ice coefficient of friction), it was not intuitive or known in advance which designs would prove to have high performance. In order to facilitate exploration of the design space, we implemented a custom physics-based systems analysis framework which could automate analysis such as resource budgeting, mission simulation, mass and buoyancy balancing, and static landing stability analysis given an IceNode design configuration and an environmental configuration (both defined as a dictionary of various design and environmental parameters and their values). Using this framework, we discovered which design parameters had the largest effects on design success by manually introducing a diversity of designs and environmental parameters, and paying close attention to the success or failure of each design and its root causes. With the primary design "knobs" known, we conducted a generative design study in which we programmatically varied a handful of the most important design parameters to generate 1540 different design candidates and tested them across 160 different environmental scenarios. By extensively iterating across the entire range of viable values for the most important design parameters and comparing the resultant designs' success or failure against a range of environments, we characterized the boundaries of the environmental envelope in which the IceNode design problem is solvable. Finally, we conducted a trade study to down select a single design candidate with which to proceed into detailed design for the IceNode vehicle prototype.

The system analysis framework enabled rapid numerical prototyping and critical analysis of candidate designs, as well as automated and extensive exploration of the large IceNode design space which greatly accelerated the maturation of the IceNode concept from napkin sketches to preliminary design. The results of the trade study gave us confidence that we were moving into the detailed design stage with a high-performance preliminary design. Furthermore, once the chosen design candidate was down selected, it was easy to continuously update and maintain the system analysis framework and configuration such that we could quickly conduct new analyses and maintain predictions for system performance as the design matured. A more detailed discussion of the systems analysis and generative design framework used to develop the preliminary design for IceNode can be found in [14].

C. Detailed Design

While the systems analysis framework and generative design study served to identify a well-performing set of high-level design parameters with which to proceed, it was not suitable to engage in detailed subsystem design of the vehicle. Solutions to several specific major engineering challenges were required for IceNode's functionality, detailed in the sections below. A table summarizing the key specifications for the IceNode vehicle is shown in Table 2.

Component Packing: Component packing for the releasable systems proved to be one of the most challenging design problems because the systems had to release and separate cleanly from the vehicle without risk of snagging or damaging sensitive instrumentation housed on the top and bottom pressure vessel caps. In addition, in order to achieve the large net buoyancy change from neutral buoyancy in ingress phase to high positive buoyancy needed for stability in landed phase, the releasable ballast had to have significant mass. To offset this mass loss back to neutral buoyancy in egress phase, the releasable leg and float system had to have low density and high volume, which made it too large to include above the pressure vessel top cap due to instrument interference and increased vehicle length. In order to solve this issue, we packed syntactic foam pieces around the circumference of the pressure vessel which are pinned by the landing leg system but float away upon its release. This allowed a significant amount of floatation to be included with minimal interference with the rest of the vehicle's physical structure. The placement of instruments, mechanisms, and penetrators on the top and bottom pressure vessel caps also proved challenging, as space was extremely limited and some instruments could not be obstructed due to water flow or line of sight requirements. The packing solution eventually settled on is visible in Fig. 4. In cases of conflicting placement considerations between components, priority was given to scientific instruments according to their criticality to mission success.

Ballast and Bottom Release System: The releasable ballast system mounted at the bottom of the IceNode vehicle serves several purposes. First and foremost, its function is to provide a large jettisonable mass, such that when released from the neutrally buoyant vehicle, IceNode becomes highly positively buoyant to be able to and maintain landed stability during the primary science phase of the mission. To serve this purpose, the adjustable mass of the ballast system consists of three sections of arc-shaped stackable stainless steel weights (ranging from 100 to 500g each) arranged around the circumference of the subsystem. Fine tuning of the ballast mass may be achieved by adding or removing weights until neutral buoyancy is achieved, and trimming of the vehicle (if the long axis does not align with gravity) may be achieved by using an asymmetric distribution of weights across the different sections. A secondary function of the releasable ballast system is to shield the fragile OTFP instruments from inadvertent contact with the seafloor or other physical objects during deployment and ingress. As such, the releasable ballast system creates a protective enclosure which is designed to prevent the instruments from being bumped from the side or from below. This enclosure is strong enough to withstand downward collisions at maximum 0.2 m/s downward profiling speed with up to 0.1 m/s horizontal current, while still allowing relatively unobstructed flow of water for taking CTD measurements while performing vertical profiles (downcast preferred). The ballast release system consists of a spring loaded v-band clamp, which secures the ballast to the rest of the vehicle. The sheet metal band springs open when an M3 bolt is cut with a pyrotechnic device, effectively releasing the v-grooves and allowing the ballast to fall away vertically under the force of gravity. To prevent the ballast from hitting the OTFP during the release, the instruments are placed in a 12 degree cone-shaped safety region, such that the ballast system may fall away at an angle of up to 12 degrees with respect to the long axis of the vehicle. For additional safety, IceNode's software landing logic will not allow the ballast release if it detects that the vehicle is tilted more than 12 degrees. A close up view of the ballast and ballast release system is shown in Fig. 5 and the ballast release and landing sequence is shown in Fig. 1, phases 4 through 6.

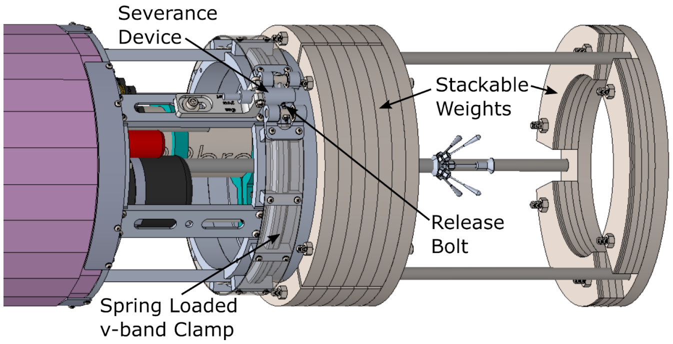

Fig. 5. Bottom release system.

Landing Legs and Top Release System: The releasable float and landing leg system performs multiple functions. 35 liters of syntactic foam provide large positive buoyant force during the landed stage of the mission and three deployable legs prevent the vehicle from tottering or tipping due to local ice slope, surface undulations, drag induced by the melt driven current, and vortex induced vibrations. During the landing the vehicle experiences a sudden deceleration as it impacts the ice. We designed the material and form of the landing legs to elastically deform during landing then return to straight and rigid after the impact energy dissipates. During initial deployment the vehicle is lifted by a hoist ring at the top of the landing system and the legs are folded up above the vehicle to allow them to fit within a 25 cm borehole. When the vehicle is released, the leg deployment is started by light kickoff springs and is carried through by the weight of the legs. A hardstop prevents the legs from rotating past the deployed position during deployment and while supporting the landed vehicle. The next function of the system is that it must be jettisonable at the conclusion of the landed phase so that the vehicle returns to near neutral buoyancy for the egress phase and to separate from the landing legs which may become embedded in the ice. This is accomplished by connecting the landing system to the main vehicle body with a pretensioned wire rope. To sever the connection, the vehicle fires two (redundant) pyrotechnic wire rope cutters. Kick off springs aid in separation and ensure that the syntactic foam segments are separated from the pinning features which hold them against the pressure vessel. Finally, the landing system must protect the instruments and antenna at the top of the vehicle without hindering their function. The upward looking Doppler Velocity Logger (DVL) and Iridium/GPS antenna are nested within the landing system to protect them from interactions with the ice surface during all phases of the mission.. The DVL field of view looks through an opening in the landing system which gives it a clear view for selecting a landing location. After the landing system has been jettisoned, the Iridium/GPS antenna becomes unobstructed for improved Iridium data connection during the data uplink phase. The support structure which stays with the vehicle after the landing system has been jettisoned is optimized for minimum volume to maximize the height of the GPS/Iridium antenna above the water for improved Iridium transmissibility when IceNode is floating at the ocean surface during the transmit stage. The details of the top release system are shown in Fig. 6, and the release, separation and liftoff sequence is depicted in Fig. 1, phases 6 and 7.

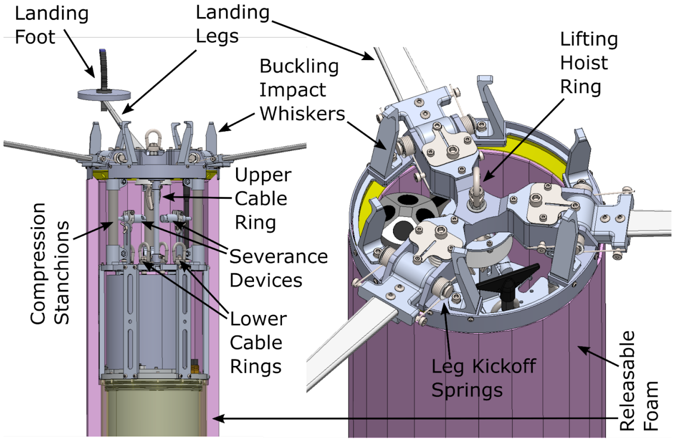

Fig. 6. Top release system. Pretensioned wire rope is not modeled, but feeds from the lower cable rings through the severance devices to the upper cable ring.

Severance Devices: A trade study was conducted to identify severance devices that could enable the release of the ballast system and the landing and float systems whilst fulfilling other key requirements, namely: surviving a corrosive seawater environment for more than a year at pressures up to 1500 psi, and allow for fast actuation for precision landing after a suitable landing location is identified above the IceNode vehicle in the landing site selection phase. Secondary requirements were also taken into account, including small mass and volume, low power and cost, ability to withstand high loads or be removed from the load path, and test safety throughout the development of a prototype vehicle. A number of options were considered: high torque motors, shearing bolts, thermal fusible links, galvanic erosion links, cord burners, and pyrotechnic cord cutters. Although high torque motors can hold high loads and have significant heritage in underwater applications, they are bulky items that consume large amounts of power. Shearing bolts were considered to be too expensive, and cord burners and thermal fusible links would require a custom development that might lack reliability. Galvanic erosion links are commonly used for mooring applications, and work reliably in seawater. However two main concerns emerged: First, the stronger the erodible link would have to be to hold high loads, the longer it would take to sever the link and deploy the subsystem, which is especially problematic in the case of the ballast release, where the vehicle would continue to drift for minutes before ballast release after having identified a suitable landing spot. Second, galvanic erosion links do not work in freshwater, which would limit field testing venues, especially those with ice covered surfaces. Although to the best knowledge of the authors pyrotechnic cord cutters have not been used in deep sea applications, they have been used for explosive ordnance disposal in marine environments up to 100 m depth and the manufacturer did not identify any theoretical failure modes up to 1000 m depth as the cutters have no internal voids. They are lightweight and compact, low cost, can be removed from the load path (instead carried by a strong metal wire or bolt), and actuate on the order of milliseconds. Another advantage is that they can be tested in a dry, freshwater, or saltwater environment (granted they can survive corrosive conditions). This can be achieved by careful selection of materials such as ceramic blades, anodized aluminum and reducing the amount of dissimilar metals. Although they are technically explosive devices, they represent minimal danger to personnel during operation, as they only create a mild clicking sound when fired and are safe to operate in the palm of one's hand. As a result, Kirintec KT-600-0392-00 M K-cutter pyrotechnic cord cutters were selected as the severance device for IceNode - one to shear an M3 bolt to release the ballast system, and two to simultaneously sever a stainless steel cable restraining the releasable leg system and float (for redundancy, since these cutters have to sit in sea water for more than a year until the landed science phase is complete, and also to minimize whiplash of the tensioned severed cable near sensitive instruments). The placement of the cutters is visible in Figs. 5 and 6. The cutters will be tested to full operational depth during physical vehicle checkouts.

Landing Feet: IceNode's landing feet serve as the physical interface between the vehicle and the underside of the ice shelf. Because movement of the ACM head must be minimized during landed OTFP measurements, the vehicle must not slip laterally across the surface of the ice even in the presence of currents exerting horizontal force on the body of the vehicle. To maximize stability, the landing feet needed to have a high static coefficient of friction with the ice. The foot contact pad is made from an elastomeric fiber composite proven to have excellent traction characteristics, with a static coefficient of friction up to 0.3 on wet ice [15]. The landing surface may also be locally uneven—camera images of the basal surface of ice shelves often exhibit scalloping and other irregular topography [6], [8]. For this reason, the foot contact pad is hinged using a cotter pin and has +/- 32 degrees of swivel to conform to the local terrain. Because the underside of the ice shelf can be actively melting at a rate up to 6 cm / day [3], the landing surface will be constantly ablating away from above the vehicle, and the swivel mechanism will help the contact foot track the local topology as it changes. There is also a possibility that because IceNode's body sticks down into the (relatively) warmer water column below the ice, and there exists a metallic thermal pathway between the feet and the rest of the vehicle, the feet will melt into and physically embed in the ice over time. Next in line with the footpad is a toothed stainless steel foot piece designed to facilitate this melt-embedding. Once the feet are embedded, IceNode will create a much more solid connection with the ice from the standpoint of OTFP stability. However, if the melt-embed process is allowed to continue indefinitely, eventually the vehicle body itself would become embedded in the ice, and IceNode would not be able to escape during egress to complete its mission. For this reason, the final feature of the landing feet is a large surface area disk covered with insulating marine grade rubber designed to impede the landing legs from embedding any farther than the top plane of the disk. Fig. 7 shows the design of the landing feet in detail.

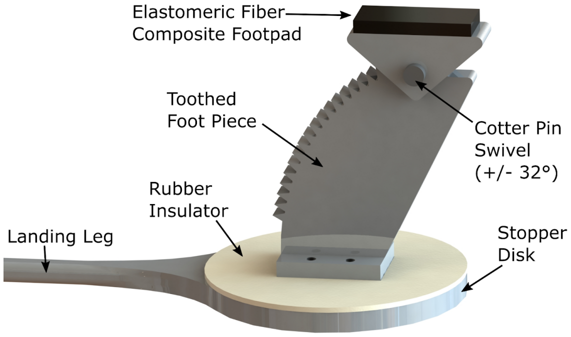

Fig. 7. Landing foot.

Drift and Ascent Stability: It is important that IceNode stay vertically oriented in the water column during all stages of its mission. In order to achieve static stability during the drifting stages, the center of mass was placed below the center of buoyancy and the metacentric distance between the two points was maximized, within other design constraints. When IceNode releases its ballast weight to gain high positive buoyancy for the landed stage of the mission, it reaches a terminal velocity of approximately 1 m/s within hundreds of milliseconds. During the ascent, it is important that IceNode stay hydrodynamically stable and not tumble and flip over before landing. This is hindered by the fact that the center of mass of the vehicle shifts upwards when the significant ballast mass is released from the bottom of the vehicle, thus reducing the metacentric height and thus the attitude stability of the vehicle. A rudimentary drag model was developed to assess the stability of IceNode during ascent, and determined that the center of mass of the vehicle needs to be located below 63% of the pressure vessel length to return to a stable vertical state after a perturbation in vehicle tilt. However, the model had uncertainty in the drag force point of application and its magnitude, which is especially difficult to estimate in the transition flow that IceNode operates during this rapid ascent (Reynolds number $\propto 10^5$—10^6). As a risk mitigation measure, stabilizing drag flaps were designed near the bottom of the pressure vessel cylinder to increase drag (also reducing the ascent velocity) and move the drag force application point further down the body of the vehicle. A secondary benefit of the drag flaps is that they will mitigate tipping of the vehicle due to wave action when floating at the surface during the data uplink phase. The final dimensions of the drag flaps will be determined through physical testing of ascent and surface floating stability of the IceNode prototype. More details of the ascent stability model are available in [14].

Length	With legs stowed: 3.8 m With legs deployed: 3.0 m ACM sensor volume to ice standoff: 2.75m Pressure Vessel length: 1.8m Individual landing leg length: 1.0m
Diameter	With legs stowed: 0.25 m With legs deployed: 2.25 m
Mass	Total: 105.5 kg Bottom releasables:22.1 kg Top releasables: 19.4 kg
Volume	Total: 0.137 m^3 Bottom releasables: 0.0019 m^3 Top releasables: 0.0371 m^3
Max Rated Depth	1000 m
Endurance	1 year of landed science operations, plus 1.5 months each for ingress and egress and power for mission data transmission over Iridium
Communications	Acoustic modem Iridium antenna Optional fiber optic tether
Localization	Multilateration using RAFOS sources at shelf edge. Anecdotally estimated at ~2.5 km position uncertainty based on [12]
Guidance	APL-UW EM-APEX fixed depth fraction approach [12] or QMDP-based stochastic ocean model guidance [16]
Sensors	Custom Ocean Turbulence Flux Package (ACM, CTD, IMU) Upward looking DVL RAFOS acoustic receiver
Science Products	Turbulent heat, salt, and momentum fluxes time series Basal melt rate time series Basal surface roughness CTD water column profiles Top and bottom bathymetric point measurements (x, y, z coordinates)

Table 2. Summary of key specifications for IceNode

IV. AUTONOMOUS GUIDANCE

The effectiveness of an IceNode array to gather valuable science results depends largely on two factors related to guidance and navigation—the IceNodes' ability to successfully traverse far beneath the shelf and back out again to uplink their mission data (the vehicle return rate), and the individual landing locations of the IceNodes underneath the ice shelf. A reliable technique to safely guide IceNodes under the shelf is crucial to mission success, and the more accurate the technique is at placing IceNodes in landing locations of high scientific interest, the greater the science return will be.

The simple and effective guidance algorithm used by APL-UW EM-APEX floats during their 2018-2019 Dotson Ice Shelf deployment provides a viable baseline technique for traversing IceNodes under ice shelves. Beneath warm (melting) ice shelves, cavity current circulation is reliably driven by melt-driven exchange flow such that warm, bottom-trapped inflow is sucked into the cavity at depth, and colder, fresher, shallow ceiling-trapped outflow is expelled from the cavity along the bottom side of the shelf. The EM-APEX floats exploited this geophysical phenomenon as a natural transport system in and out of the cavity. After deployment at the shelf edge by an icebreaker, the EM-APEX floats used their variable buoyancy systems to descend into the inflow currents and be swept underneath the cavity. Periodically, the floats determined the top and bottom bathymetry of the cavity by performing a vertical profile and physically bumping the seafloor below and ice shelf above. For the rest of the time during ingress, the floats drifted at a deep fixed percentage of the cavity depth (e.g. 75%) designed to stay embedded in the inflow currents. Once a pre-set timer elapsed and it was time to return to open water, the floats switched to maintaining a shallow fixed percentage of the cavity depth (e.g. 25%) in order to embed themselves in outflow currents and be carried out from beneath the shelf. Periodically, the floats received and recorded the timing of acoustic ranging signals from well-localized moored RAFOS sources installed at the shelf edge, so that their positions over time could be post-processed using multilateration (the floats did not perform localization calculations onboard). Using this technique, APL-UW successfully guided four EM-APEX floats tens of kilometers past the ice terminus into the Dotson Ice Shelf cavity, traversed hundreds of kilometers and many months under ice, and successfully returned all four vehicles to open water where they transmitted their mission data home. A straightforward extension of the APL-UW EM-APEX approach for IceNode is to move the localization calculations onboard, and trigger landing if IceNode finds itself under a predefined target area, or a timeout elapses. This is likely the baseline guidance technique that IceNode will use to access the cavities under ice shelves.

Although not strictly necessary to achieve IceNode's mission objectives, a more sophisticated guidance algorithm with better control over IceNode's drifting trajectory could increase IceNode array efficiency (returned science value vs number of IceNodes) by enabling higher vehicle return rate, more accurate targeting of IceNode landing locations, and faster and more directed traverses. The benefits would be three-fold: 1) the higher return rate of vehicles would mean less vehicles are lost under the shelf so more data is returned for a given array size, 2) the ability to selectively access areas whose melt rate is well correlated with target signals of interest would allow the IceNode array to achieve the performance regime near the top of the whiskers in the IceNode array performance vs size plots show in in Figs. 3c and 3d, and 3) less wasted traverse time during ingress and egress phase would leave more battery power for the landed science phase.

In order to investigate the feasibility of a more advanced guidance algorithm, we developed a Q-function Markov Decision Process (QMDP) based guidance technique and tested it in simulation using the same ice shelf cavity circulation model used in the mission architecture study. The MDP technique performs probabilistic planning utilizing statistical knowledge of stochastic circulation dynamics encoded within the cavity model to exploit advantageous circulation patterns at different depths in the water column. The algorithm identifies the probabilistically best drift depth to reach a given target area for each x, y location under the shelf, then commands IceNode to move to that depth using its VBS. The QMDP approach is especially suited to IceNode guidance because it can natively represent stochastic state transitions due to uncertain currents, and the QMDP policy may be computed offboard ahead of time then stored as a lookup table on the vehicle, requiring minimal computational expense or power usage during online mission operations. Results in the simulation showed that the QMDP guidance technique can deliver up to 88.8% of vehicles to the grounding zone of Pine Island Glacier from the shelf edge, representing a 33% improvement over the baseline EM-APEX guidance technique, and do so 21% faster, leaving more battery available for landed science operations. More details of the methodology and results are available in [16].

V. FUTURE PLANS

The IceNode prototype vehicle is currently undergoing fabrication and subsystem testing, with full system integration expected near the end of 2021. Moving into 2022, IceNode will undergo a series of field tests to demonstrate functionality of all system performance requirements. Once functionality has been demonstrated and the prototype is mature, the technology will be licensed to a third party company with experience in mass manufacturing of commercial profiling floats. This will allow a fleet of IceNodes to be constructed for future JPL-led Antarctic IceNode campaigns, and will also make the IceNode technology available to other scientists and institutions who may find use in the IceNode platform. If initial IceNode campaigns are successful, our hope is that IceNode technology could become widely adopted by multiple institutions and used to instrument a representative selection of critical ice shelves across Antarctica. These unprecedented in-situ datasets from IceNode, combined synergistically with results from remote sensing, modeling, and other specialized in situ assets, could lead to much more detailed understanding of ice shelf melt dynamics and the resultant ramifications for global sea level rise. With less uncertain sea level rise projections, policy makers will be able to make better informed decisions on this important climate threat with direct impact on the lives of hundreds of millions of people worldwide.

ACKNOWLEDGMENT

Part of this work was carried out at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004). We gratefully acknowledge support from the NASA Cryospheric Sciences Programs. High-end computing resources were provided by the NASA Advanced Supercomputing (NAS) Division of the Ames Research Center. ©2021. All rights reserved.

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