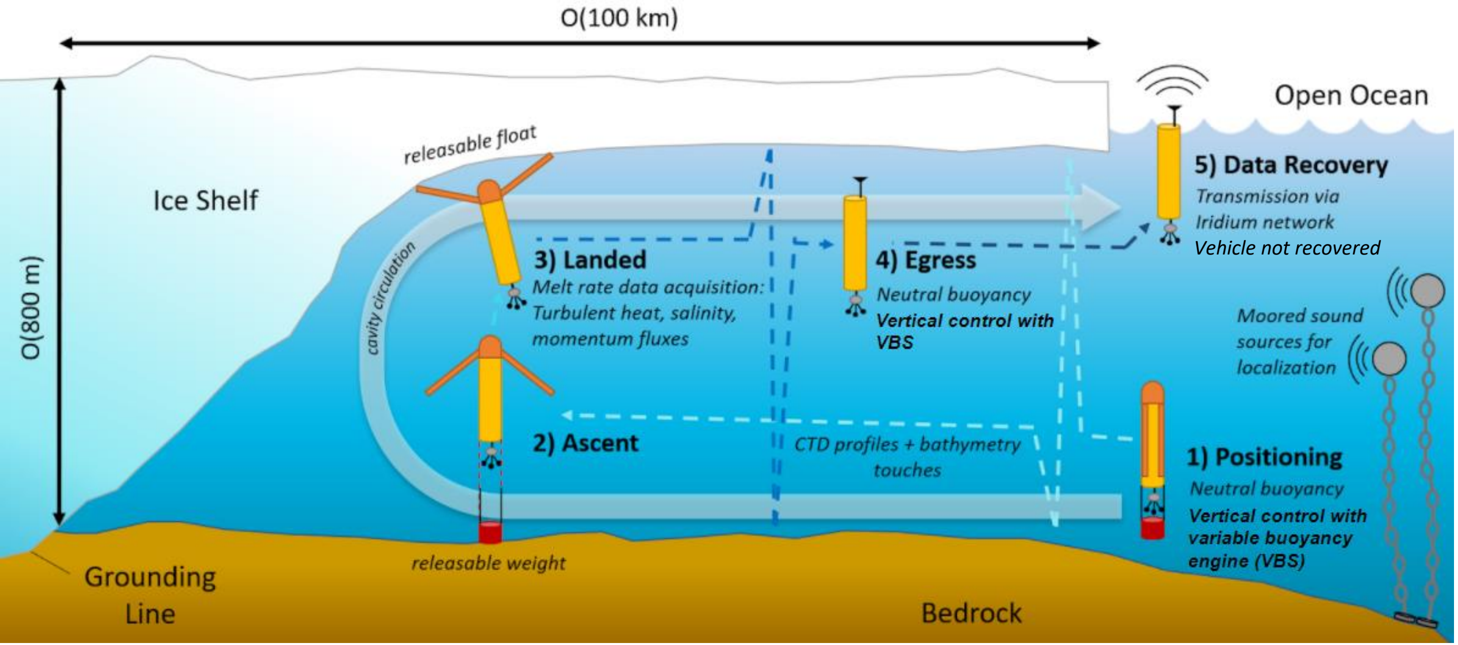
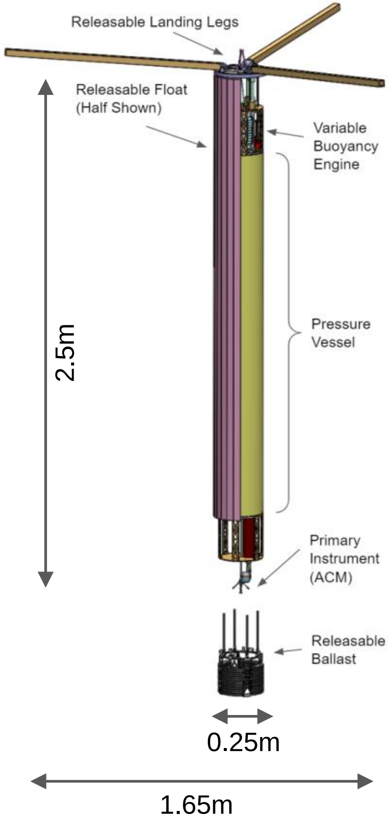




Virtual Research Presentation Conference

IceNode: A Buoyant Vehicle for in-situ Measurement of Melt Rates beneath Ice Shelves

Principal Investigator: Evan Clark (397K)
Co-Is: Andrew Branch (397), Dane Schoelen (347), Ian Fenty (329) Michael Schodlok (329),
Eric Rignot (334), Daniel Limonadi (8000), Tim Stanton (Moss Landing Marine Labs)

Assigned Presentation # RPC-058
Program: Topic

Jet Propulsion Laboratory
California Institute of Technology

Abstract

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. These ice shelves hold back more than 50 meters of sea-level rise equivalent in total [1].

However, a lack of detailed understanding about how ice shelves will behave in a warming climate remains a primary obstacle to accurate sea level rise projections.

Predictive numerical melt models require better constraining ground-truth data of basal melt rate, but the field suffers from a dearth of in-situ measurements because these extreme environments are difficult to access and cut-off from communication with the outside world.

FY17-19 8X Strategic RTD R.17.231.068 Under Ice Exploration identified well-distributed, concurrent, long-duration measurements of melt rate at the basal ice-ocean interface to be among the most critical in-situ measurements to constrain physical ice shelf melt modeling.

Existing borehole-based approaches of acquiring basal melt rate are not scalable due to the high cost and short operational lifetime of boreholes and limitations in their placement due to safety and logistics constraints on the surface [2].

Development of the IceNode platform will enable scaling of this critical measurement by allowing deployment of a fleet of IceNode vehicles from open ocean at the ice shelf front, reducing the cost of each measurement from the cost of a borehole (several $M) to the cost of a single additional vehicle (~$80K).

IceNode will represent a unique strategic asset positioning JPL to win future external proposal calls targeted towards climate change induced effects on the Antarctic continent, including NASA ROSES and Earth Ventures Suborbital (EV-S) awards.

Acknowledgements

IceNode Team: Evan Clark (PI) (397K), Andrew Branch (397K), Ian Fenty (329C), Ara Kourchians (347A), Daniel Limonadi (8000), Gauri Madhok (397K - intern), Flora Mechentel (355L), Tyler Okamoto (347C), Eric Rignot (3340), Federico Rossi (347N), Brendan Santos (397K - intern), Justin Schachter (313F - co-op), Michael Schodlok (329C), Dane Schoelen (347C), Xavier Zapien (347A), Christine Gebara (355L), Tim Stanton (Moss Landing Marine Labs)

MRV Team (VBS subsystem design + underwater engineering expertise): Theresa Friske, Fritz Stahr, Ian Culhane, Christian Sarason, Ronnie Nigash, and David Faust

JPL Underwater engineering SMEs (tabletop reviews): Chris Yahnker, Matt Gildner, Jackie Sly, Justin Koch, Russell Smith, Gail Woodward, and Rebecca Castano

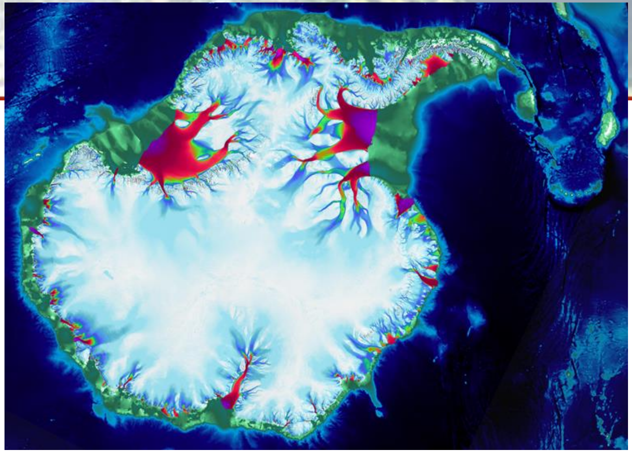
APL-UW (advice/support): James Girton, Craig Lee

Upper Management (support and guidance): Mark Simons and Cinzia Zuffada (OCSCT), Duane Waliser and Jason Hyon (8X)

This project would not have been possible without the contributions of all these people. Thank you!

Problem Description

- Antarctic ice shelf collapse could contribute 1m+ of global sea-level rise by 2100, severely impacting 100M's people worldwide
- Antarctic Ice Sheet contains 50m+ of sea-level rise equivalent
- Represents single largest source of uncertainty in sea-level rise projections
- Ice shelf numerical models need well-distributed, concurrent, long-duration, basal melt rate data to constrain projections
- But no scalable instrument platform currently exists capable of taking these measurements

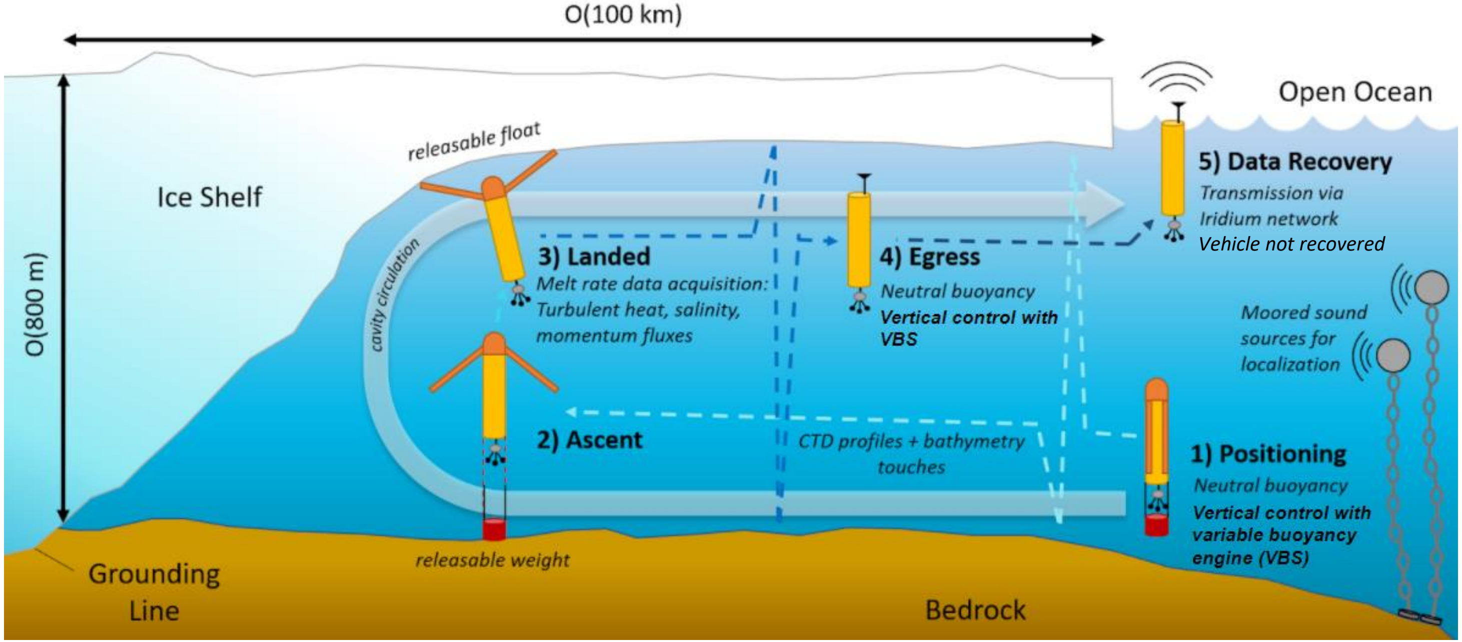


Ice shelves fringe ~75% of Antarctic margin and the regulate rate of ice discharge into the ocean (figure credit Fernando Paulo)

Broken-off piece 2x the size of Luxembourg

Larsen C Ice Shelf rift, 2018

Approach – Concept of Operations (CONOPS)



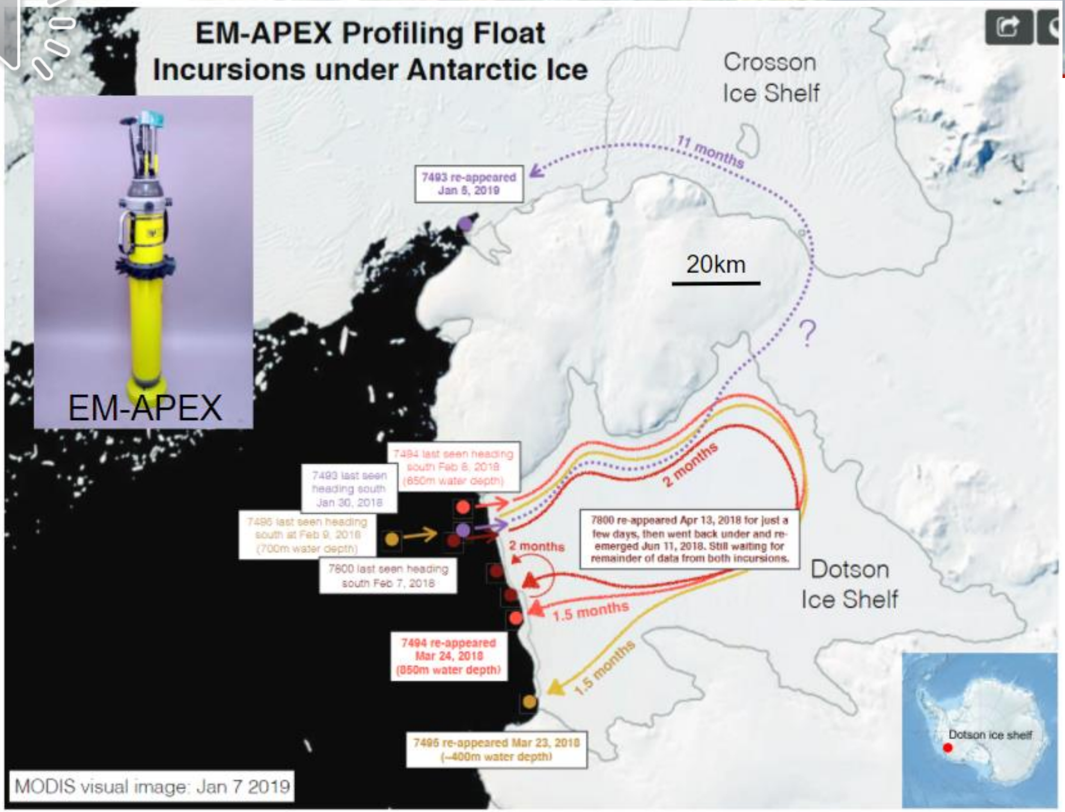
Mission Phases:

1) Positioning: Use VBS to drift on prevailing currents underneath shelf cavity
2) Landing: Release ballast, deploy landing legs, and land buoyantly on underside of ice shelf
3) Landed: Take stable, long-duration in-situ basal melt rate measurements for 1 year
4) Egress: Release buoyant landing system, use VBS to drift on prevailing currents to open ocean
5) Surface and transmit date home over Iridium network. Vehicle is not recovered

An icebreaker at the ice shelf edge deploys a fleet of inexpensive (~$80K), expendable IceNodes to form an in-situ melt rate observation array. IceNodes may also be deployed down a 25cm borehole of opportunity

Related Work

- CONOPS surprisingly not as crazy as it sounds
- Based on successful APL-UW Dotson EM-APEX campaign [3]
- 4/4 vehicles reemerged to return data after months, 100+ kms of travel under shelf
- EM-APEX could not land - only measure water column properties
- IceNode novel contribution is the ability to land / directly measure basal melt rate



(Girton et al., 2019)

Methodology Overview

Objective of FY20 (Year 1): Determine if the IceNode concept is viable to accomplish the mission objectives in terms of technical feasibility, scientific viability, and cost

Initiative 1: Platform Feasibility: determine if it is technologically feasible to design and develop a vehicle capable of landing and acting as a stable platform for acquiring in situ melt measurements at the basal melt interface

Initiative 2: Scientific Viability: establish whether or not an array of IceNodes deployed from an icebreaker at the shelf edge is a viable concept for in-situ characterization of distributed basal melt rate under Antarctic ice shelves in terms of science return and cost

Initiative 3: Autonomous Navigation: identify and prototype autonomous navigation algorithms to assist IceNode to reliably ingress and egress from beneath the ice shelf by utilizing flow circulation patterns inside the cavity

Methodology: Platform Feasibility

Initiative 1: determine if it is technically feasible to design and develop a vehicle capable of landing and acting as a stable platform for acquiring in situ melt measurements at the basal melt interface

Challenges:

- Accommodate all the required subsystems and battery capacity needed for a year long mission within limited mass and volume constraints
- Have enough landed stability due positive buoyant force to minimize motion of the melt rate sensor suite due to currents and on potentially sloped landing surfaces

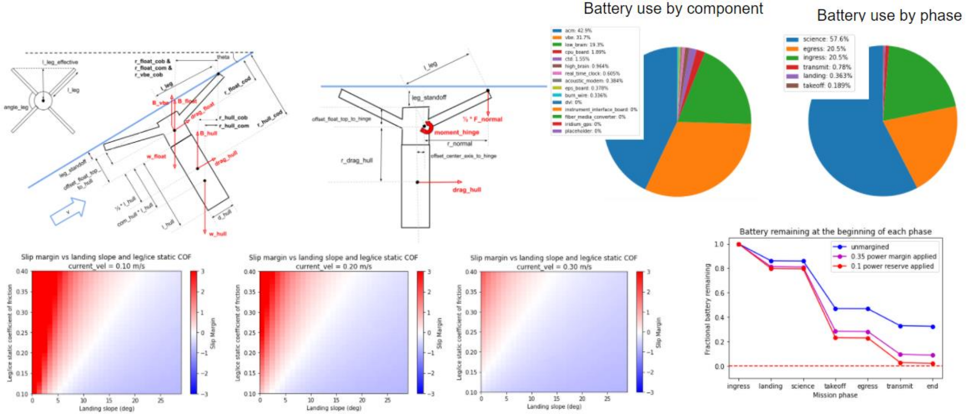
Approach:

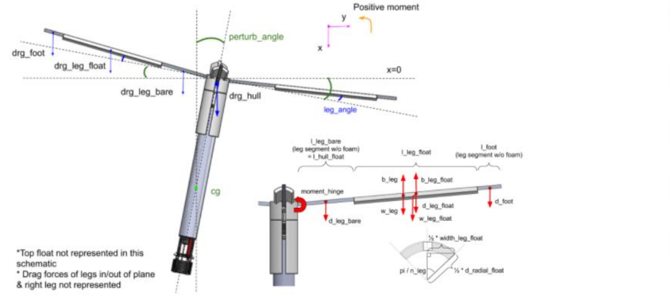
- Developed a Science Traceability Matrix (STM) in consultation with science team to identify and flow down mission objectives into system and subsystem level performance requirements
- Developed physics-based design validation software to verify or reject proposed designs on paper
- Used generative design (1540 designs) to identify boundaries of solution space
- Conducted trade study to downselect design candidate to proceed with vehicle prototype design
- Developed point designs for all subsystems, incorporated into integrated vehicle prototype design

Results: Platform Feasibility

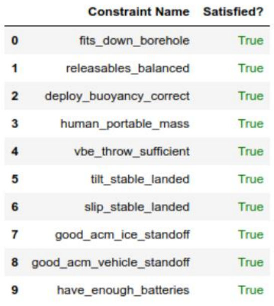
Design Validation Software

- Buoyant platform can satisfy mission requirements ✓
- Key design variables and tradeoffs identified
- Key environmental hurdles understood





*Top float not represented in this schematic
* Drag forces of legs in/out of plane & right leg not represented



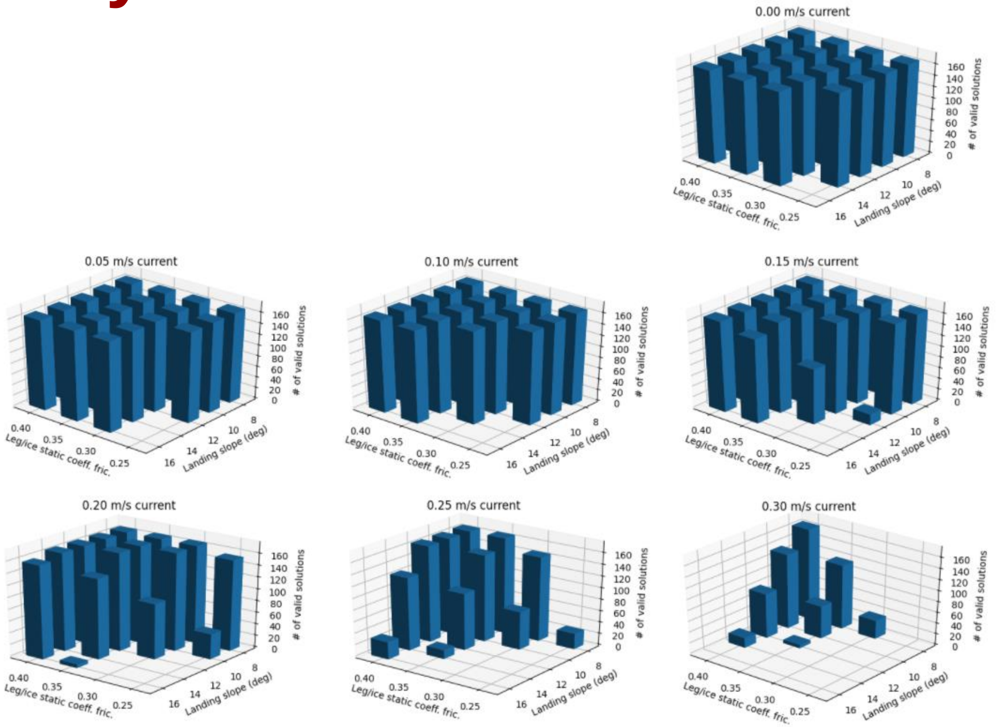
	Constraint Name	Satisfied?
0	fits_down_borehole	True
1	releasables_balanced	True
2	deploy_buoyancy_correct	True
3	human_portable_mass	True
4	vbe_throw_sufficient	True
5	tilt_stable_landed	True
6	slip_stable_landed	True
7	good_acm_ice_standoff	True
8	good_acm_vehicle_standoff	True
9	have_enough_batteries	True

Selected sample output from the IceNode design validation software which helps verify or reject paper designs given input design parameters and environmental conditions

Results: Platform Feasibility

Characterization of Boundaries of Design Solution Space

- Programmatically generated and tested 1540 different designs across swath of environmental scenarios we might encounter under the shelf
- Characterized the boundaries of the valid design solution space

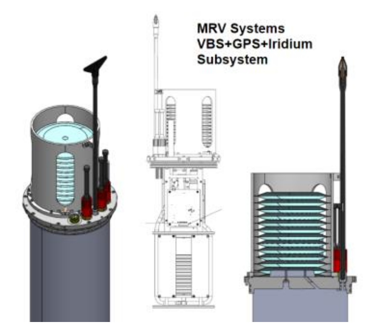


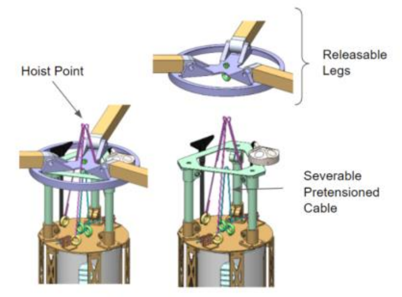
Number of valid solutions among 1540 programmatically generated designs as a function of current speed, landing slope, and ice/foot static coefficient of friction

Results: Platform Feasibility

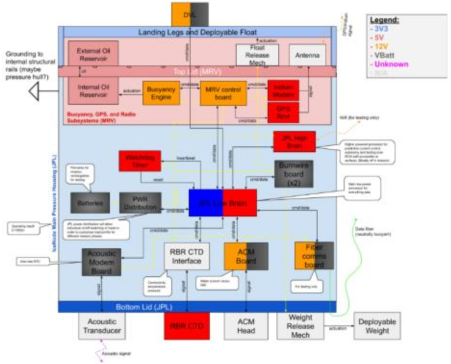
Prototype vehicle design

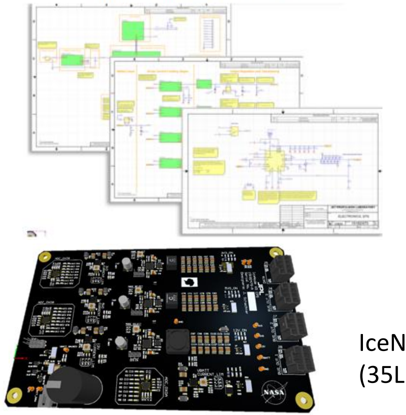
- Conducted trade study to downselect design candidate from generated designs
- Prototype vehicle design developed
- All major sub-systems incorporated without interference
- Cost estimate developed (~$80K w/ margin)
- **Primary feasibility concerns retired** ✓

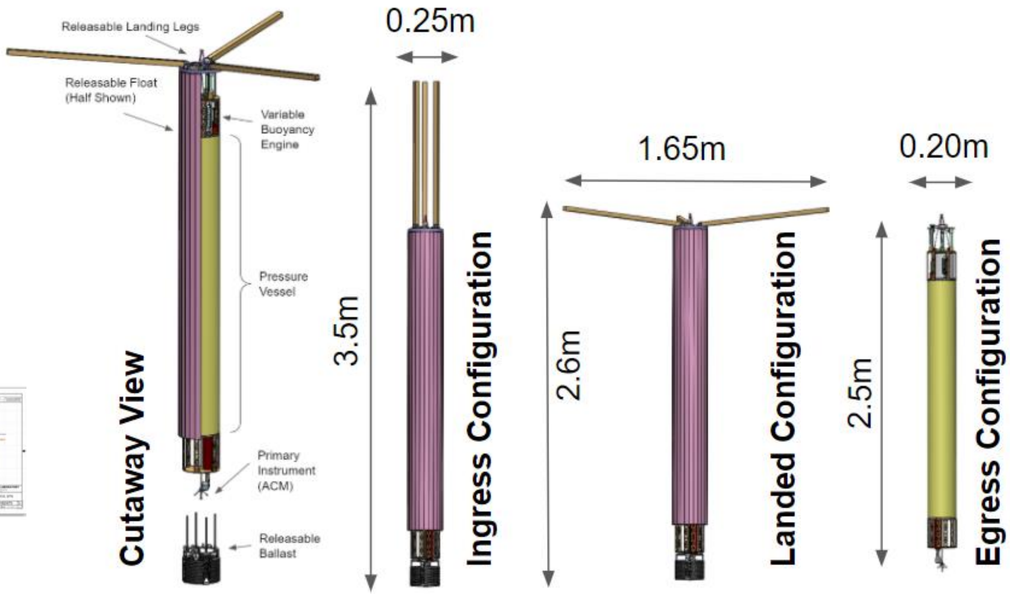




Release System


IceNode v3 System Diagram


Avionics Board Development



IceNode prototype design. Mass: body 60kg, releasable ballast 16 kg, releasable floats/legs 25kg (35L). Wet weight: ingress +5N (VBS adjustable), landed -160N, egress +5N (VBS adjustable)

Methodology: Scientific Viability

Initiative 2: establish whether or not an array of IceNodes deployed from an icebreaker at the shelf edge is a viable concept for in-situ characterization of distributed basal melt rate under Antarctic ice shelves in terms of science return and cost

Approach:

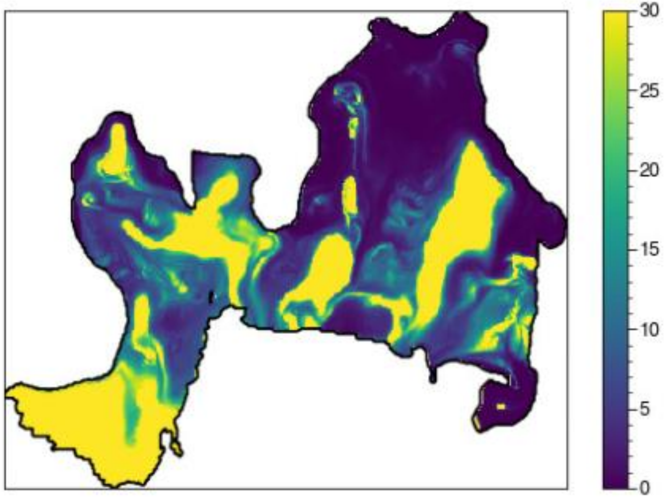
- Used a state-of-the-art ocean model of the cavity beneath Pine Island Glacier (PIG), Antarctica [4] to study the expected performance of an IceNode array as a function of different mission designs
  - **Science Objective 1: Characterize the mean and temporal variability of ice-shelf basal melt rate *in situ* at IceNode landing locations for a full year**
    - Used standard statistical methods to determine 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 using daily IceNode measurements.
  - **Science Objective 2: Infer the basal melt rate variability at various regions under the shelf that may not be directly observable by the IceNode array (e.g. the grounding zone)**
    - Used Gauss-Markov estimation to combine localized IceNode melt data with knowledge of statistical melt covariations predicted by the numerical cavity model to predict melt rate anomaly at unobserved science targets
    - Conducted an Observing System Simulation Experiment (OSSE) to characterize IceNode array performance as a function of number of IceNodes, placement, measurement accuracy, frequency, duration, and frequency band of the target signal to be reconstructed.

Results: Scientific Viability

Science Objective 1: Characterize the mean and temporal variability of ice-shelf basal melt rate *in situ* at IceNode landing locations for a full year ✓

- Prototype vehicle design supports enough batteries for a year’s worth of landed operations with twice daily melt measurements
- Mean melt rate at landing sites can be characterized in O(days) in most locations
- Some locations require O(weeks) due to smaller signal to noise ratio

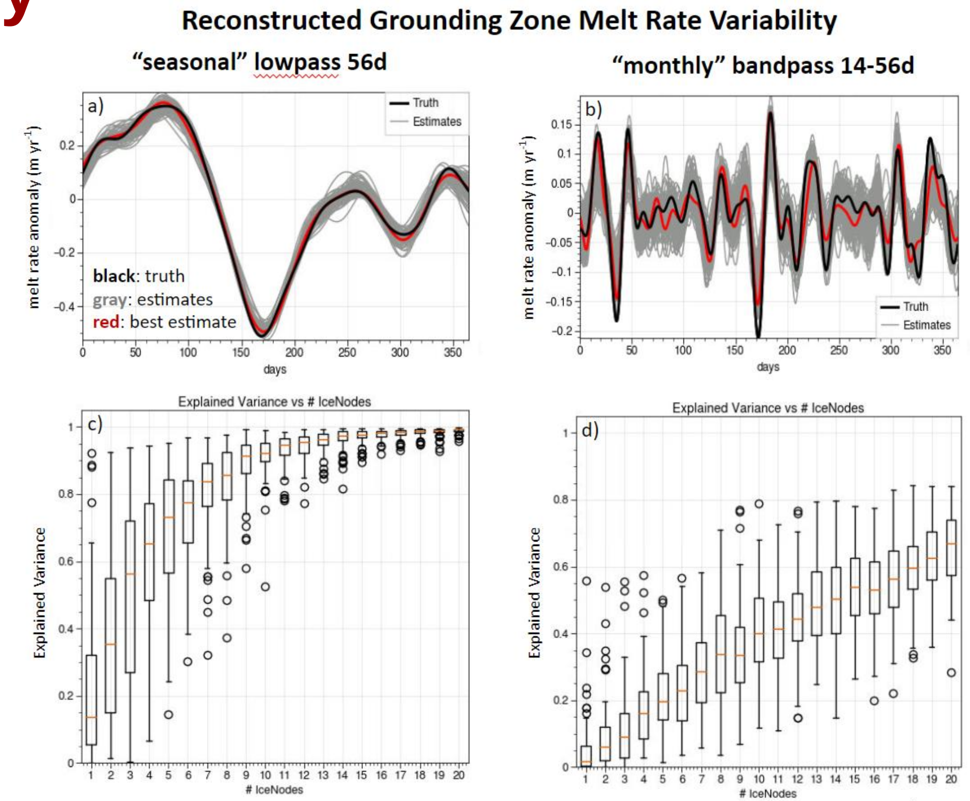
 # days required to estimate mean melt to +/- 10% of true value at 99% confidence



Results: Scientific Viability

Science Objective 2: Infer the basal melt rate variability at various regions under the shelf that may not be directly observable by the IceNode array (e.g. the grounding zone) ✓

- Relatively small IceNode arrays are sufficient to gain significant insight into seasonal and monthly melt variations
  - 9 randomly distributed IceNodes gives 99.7% chance of capturing >75% of the explained variance in the seasonal melt rate signal
    - Characterizing the seasonal cycle of melt rate variability would represent a significant step forward in knowledge about grounding zone dynamics
  - 30 randomly distributed IceNodes gives ~50% chance of capturing >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.
- Larger arrays can capture more of the explained variance
- Selective IceNode placement is not required to achieve science objectives
  - But it does increase the efficiency of the array, especially for smaller arrays



Reconstructed Grounding Zone Melt Rate Variability

"seasonal" lowpass 56d

"monthly" bandpass 14-56d

20 IceNodes, observation cadence: 13h, observation uncertainty: 0.1 $m\ yr^{-1}$

Methodology: Autonomous Navigation

Initiative Objective: identify and prototype autonomous navigation algorithms to assist IceNode to reliably ingress and egress from beneath the ice shelf by utilizing flow circulation patterns inside the cavity

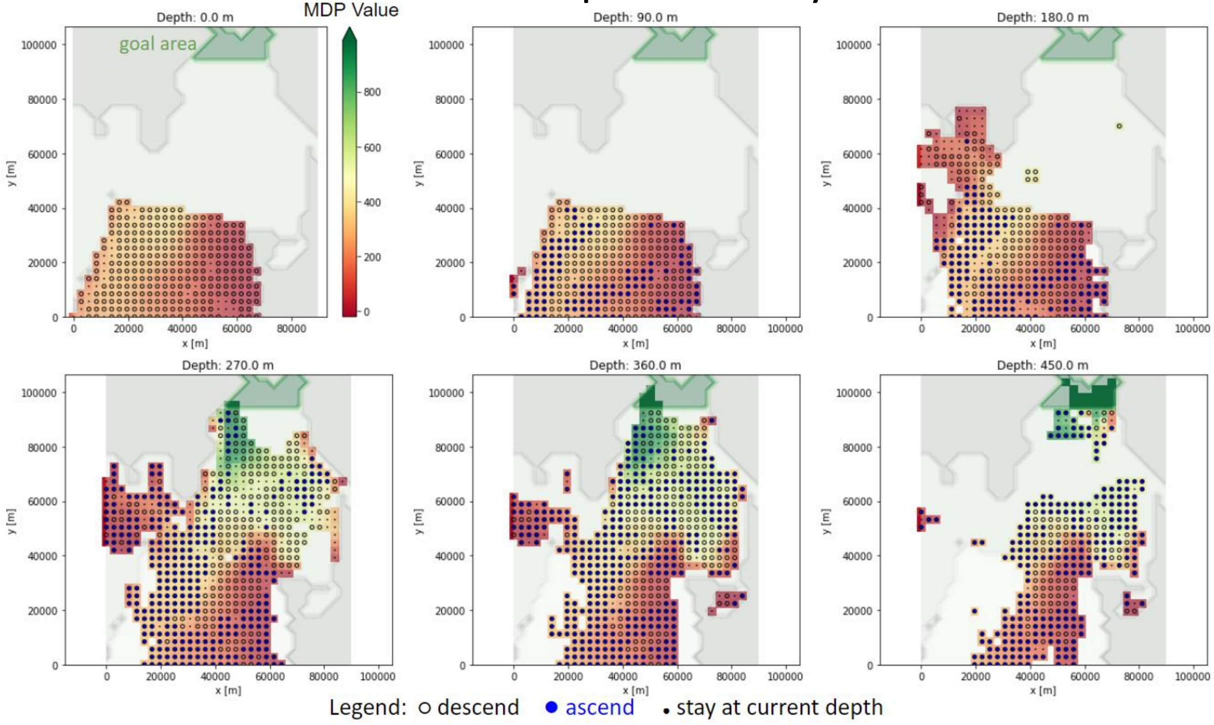
Approach

- Improved navigation algorithms (compared to EM-APEX baseline) could unlock better array performance regime and increase the reliability of IceNodes to return mission data
- Implemented IceNode navigation in simulation on cavity model using Markov Decision Process (MDP)
  - Natively represents stochastic state transitions due to uncertainty in currents
  - Inexpensive onboard execution – pre-compute computationally expensive policy offline
  - MDPs have JPL heritage and success in analogous problems (e.g. balloon path planning in Titan and Venus wind fields)
- MDP Formulation:
  - **States**: state values, policies are computed at discretized (x,y,z) locations
    - 3km horizontal stride, 30m vertical stride. Underlying dynamics are *continuous.* For non-grid states, value and policies are *interpolated*
  - **Actions**: “go to depth *d*” (limited by maximum ascent/descent rate in fixed timestep)
  - **Transitions**: lagrangian tracer dynamics built up from uniformly randomly sampling timeslices out of the cavity model
  - **Rewards (costs)**: time penalty, energy penalty for ascending
  - **Final states**: desired landing zone (++), outside of model boundaries (-)

Results: Autonomous Navigation

- Preliminary MDP optimal policy computed
- Gives probabilistically best action + MDP Value (“how easy is it to get to goal”) at each location under shelf
- Anecdotally, several features which makes us believe it is working correctly:
  - Directs IceNode around obstacles – dives at surface, ascends near cavity-spanning ridge @ 450m depth, dives when trapped in bubbles under thin ice @ 180m depth
  - Better MDP scores are biased towards left side of cavity, where strongest inflow currents exist due to Coriolis effect

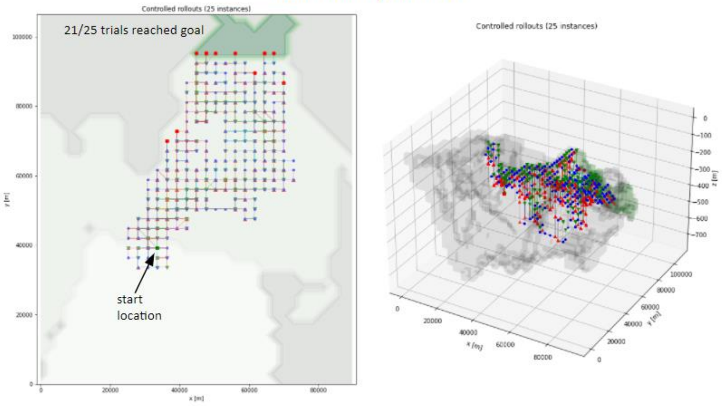
MDP Optimal Policy



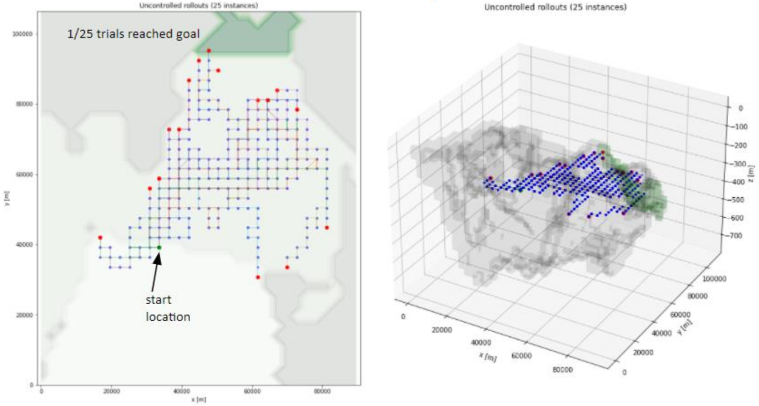
Results: Autonomous Navigation

- Rolled out MDP policy on MDP transition model
- Performs active control – 21/25 trials reach goal area
- Does better than naïve uncontrolled policy which keeps constant depth when released into inflow – 1/25 trails reach goal area
- More work to come

MDP Policy Rollout



Uncontrolled Policy Rollout



Legend: ▲move up ● hold depth ▼move down ● terminal condition

Future Plans

FY21 (Year 2):

- Prototype development and baseline functionality testing
    - Fabrication of IceNode prototype
    - Subsystem integration testing
    - Pressure tank testing and
    - Tank basic functionality testing
    - Mock mission ocean testing
- Further development of autonomous navigation techniques in simulation
    - MDP rollout on model dynamics
    - Quantitative metrics of navigation performance
    - Investigate effect of MDP resolution
    - Performance comparison against baseline EM-APEX Dotson algorithm

FY22 (Year 3):

- Advanced functionality demonstrations up to Technology Readiness Level (TRL) 6 (ready for deployment in the Antarctic Environment)
    - Mock mission demonstration in relevant under-ice environment
    - RAFOS localization demonstration

Significance of Results

- FY20 results are extremely promising for IceNode
    - Retired main system-level design risks
    - Shown IceNode is technically feasible to build
    - OSSE analysis shows that a relatively small IceNode array can efficiently achieve the science objectives
    - Prototyped autonomous navigation technique with encouraging early results to reliably target landing zones and egress to open water
    - Cost estimate shows IceNode array is within cost cap of several promising external funding sources
        - NASA ROSES Salinity
        - NASA Earth Ventures Suborbital – as one in-situ asset in a portfolio of observation platforms
- IceNode dataset directly addresses KISS [5] and most recent NASA Earth Science Decadal Survey [6] recommendations
    - No other measurement platform exists capable of acquiring distributed, long duration melt rate measurements needed by scientists
    - Will greatly improve understanding of melt dynamics, help ground-truth airborne and spaceborne remote sensing data, constrain numerical model parameters for predicting future ice shelf melt, collapse, and sea-level rise
- Development strategically positions JPL for future external polar science funding and strengthens portfolio/expertise in under-ice exploration technologies for future Ocean Worlds missions
- Project directly supports JPL Quest 1: “Understand how Earth works as a system and how it is changing” and JPL Quest 7: “Use our unique expertise to benefit the nation and planet Earth”

Publications and References

Publications:

Clark, E. B., Schachter, J., Limonadi, D., & Castano, R. (2019, August 20). *IceNode: A Buoyant Sensor Pod for Persistent In-situ Measurement Beneath Ice Shelves*. International Glaciological Society. Sea Ice Symposium, Winnipeg, CA.

JPL NTR 50734. This NTR predates our FY20 R&TD award and introduces an initial concept for IceNode, but the concept has changed significantly since then. The NTR will be updated.

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[2] Stanton, T. P., Shaw, W. J., Truffer, M., Corr, H. F. J., Peters, L. E., Riverman, K. L., … Anandakrishnan, S. (2013). *Channelized ice melting in the ocean boundary layer beneath Pine Island Glacier, Antarctica*. Science, 341(6151), 1236–1239.

[3] Girton, J. B., Christianson, K., Dunlap, J., Dutrieux, P., Gobat, J., Lee, C., & Rainville, L. (2019). *Buoyancy-adjusting Profiling Floats for Exploration of Heat Transport, Melt Rates, and Mixing in the Ocean Cavities Under Floating Ice Shelves.* OCEANS 2019 MTS/IEEE SEATTLE, 1–6.

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[5] Thompson, A. F., Willis, J., & Payne, A. (2015). *The Sleeping Giant: Measuring Ocean-Ice Interactions in Antarctica*. Keck Institute for Space Studies.

[6] National Academies of Sciences, Engineering & Medicine. (2018). *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space.* The National Academies Press.