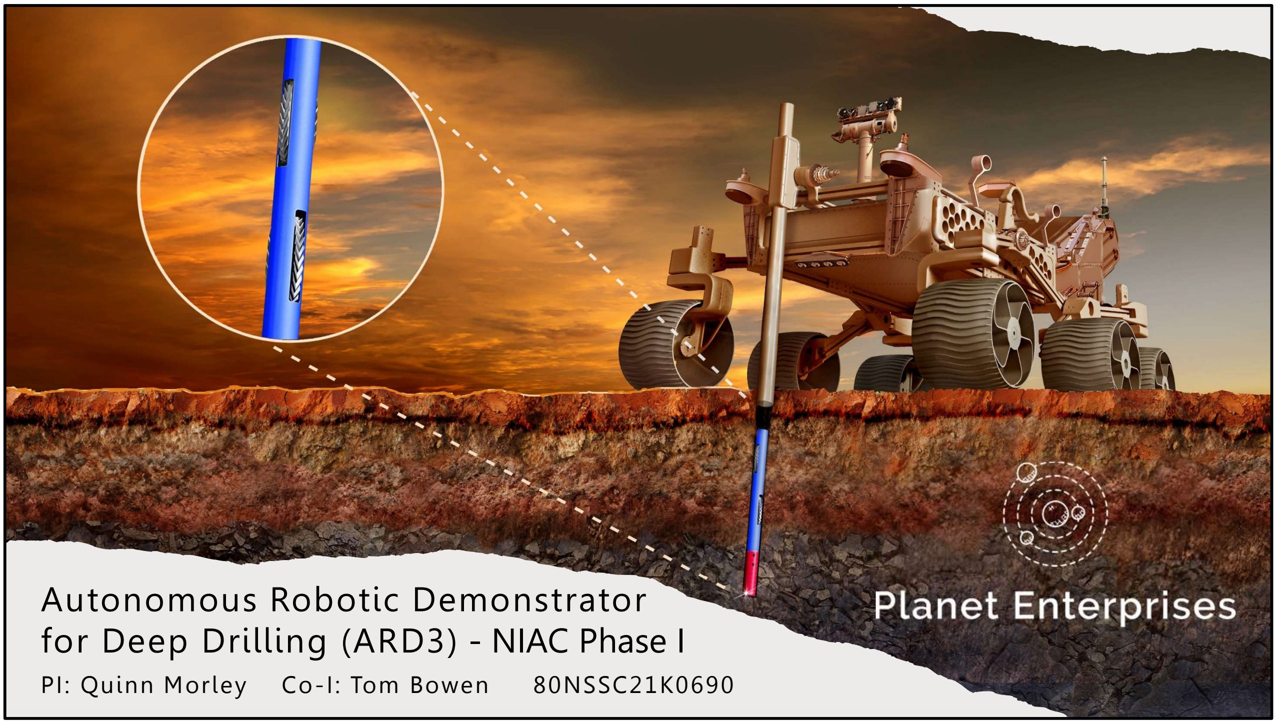


Biographical Sketch – Quinn Morley, Principal Investigator

Quinn is driven to unlock planetary science mission potential through bold and innovative new approaches to space technology challenges. He is the Principal Investigator for the Borebots project, which is officially called the Autonomous Robotic Demonstrator for Deep Drilling, or ARD3. As a graduate of the IAM/Boeing Apprenticeship program and a Mechanical Engineering undergraduate at WSU, Quinn brings a unique perspective to his role as innovator and investigator.

Work History

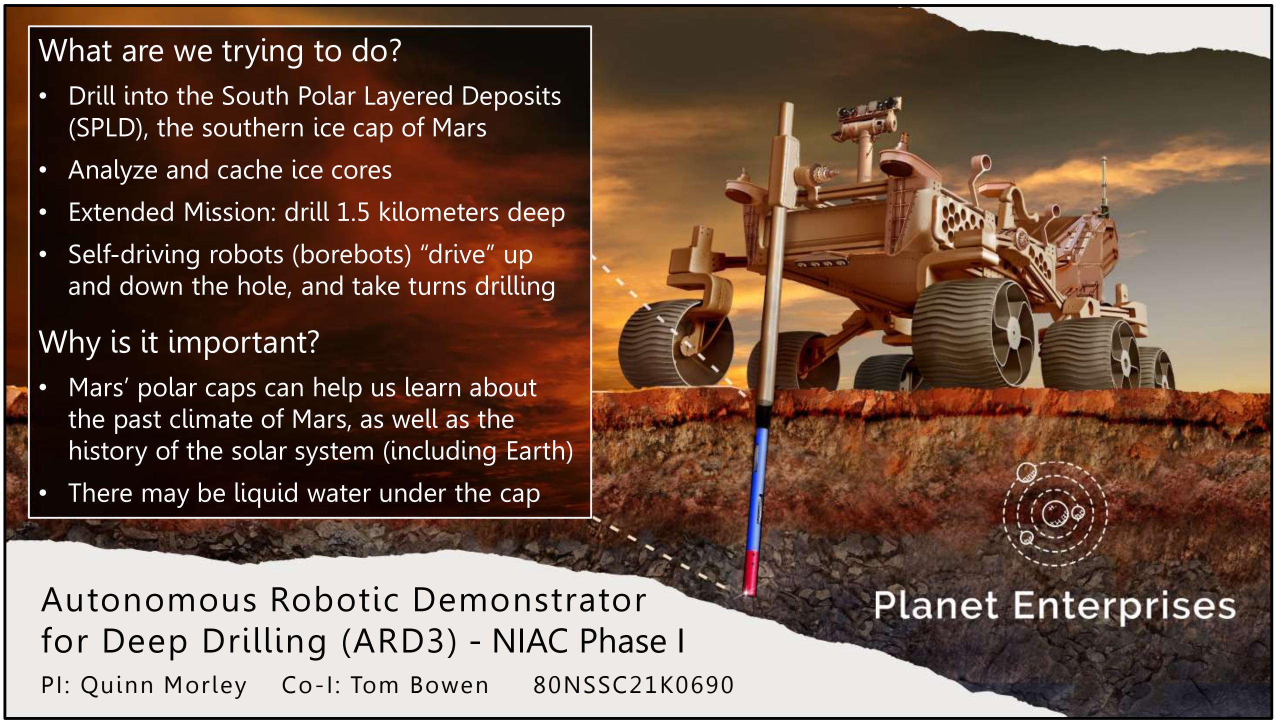
- Principal Investigator / Founder at Planet Enterprises, *June 2020 to present*
- Journeyman Bluestreak Mechanic at Boeing Commercial Airplanes, *Jan. 2017 – June 2020*
- Bluestreak Mechanic Apprentice at Boeing Commercial Airplanes, *Jan. 2013 – Jan. 2017*
- Fabricator / Team Leader at Boeing Commercial Airplanes, *May 2008 – Jan 2013*

Education

- BS, Mechanical Engineering from Washington State University – *Present to May 2023*
- AS, Engineering from Olympic College – *March 2020*
- AA, Mathematics from Olympic College – *June 2017*

Research Interests

- Planetary science technology development
- Space hardware manufacturing cost reductions
- Additive manufacturing applications to space science technology



We are trying to unlock access to the subglacial environment below the SPLD. To do that, this project revolves around self-driving drilling robots called borebots. Most of you are probably familiar with the conclusions of Orosei et al. 2018; mainly, that a subglacial liquid water lake is hypothesized in this location. This is still in dispute, but I would love to point out that drilling through the ice is one *really great* way to find out what the real story is.

SPLD Characterization Summary

- A review of Mars polar science in 2000 concluded that the densification model put forth by Arthern et al. (1999) agrees with orbital observations
  - This conclusion would only apply during periods of positive mass accumulation
  - Clifford, et al., (2000). "The State and Future of Mars Polar…" doi:10.1006/icar.1999.6290
  - Arthern et al., (1999). "Densification of Water Ice…" doi:10.1006/icar.1999.6308
- A thick ice-cemented sublimation lag layer (up to 30 m) is one possible explanation for the "fog" effect that SHARAD experiences in the SPLD
  - This indicates a period of negative mass balance that may still be occurring
  - Whitten & Campbell (2018). "Lateral Continuity of Layering…" doi:10.1029/2018JE005578
  - This layer was well known during Mars Polar Lander era, but the thickness was unknown. Vasavada et al., (2000). "Surface properties of…" doi:10.1029/1999JE001108

The first thing we did on this project was to really dive into the questions about the ice sheet in an engineering context. It turns out there is a lot of uncertainty in regard to the SPLD, and I'll just give an example that the sublimation lag layer is very poorly constrained, and could be anywhere between 5 cm and 50 m. That's three orders of magnitude. So as an inventor trying to make a robot that can drive up and down a hole in this stuff, it was intimidating at first. Whitten and Campbell is cited here under the second point, I'll be mentioning that again on the next slide.

SPLD Characterization Summary

- Zuber et al. claim the SPLD are "clean" water ice with 15% dust. Li et al. showed that this is indeed the case, but that large density variations exist depending on the location (no claim is made as to the density of layers)
  - Zuber, M. et al., (2007). "Density of Mars [SPLD]" doi:10.1126/science.1146995
  - Li, J. et al., (2012). "Density variations within the [SPLD]..." doi:10.1029/2011JE003937
- No CO2 layers are expected in the stratigraphy below the top seasonal layer
  - Phillips, et al. (2011), Supplement to "Massive CO2 Ice..." doi:10.1126/science.1203091
  - Dr. Peter Buhler, Planetary Science Institute, personal communication, June 2021

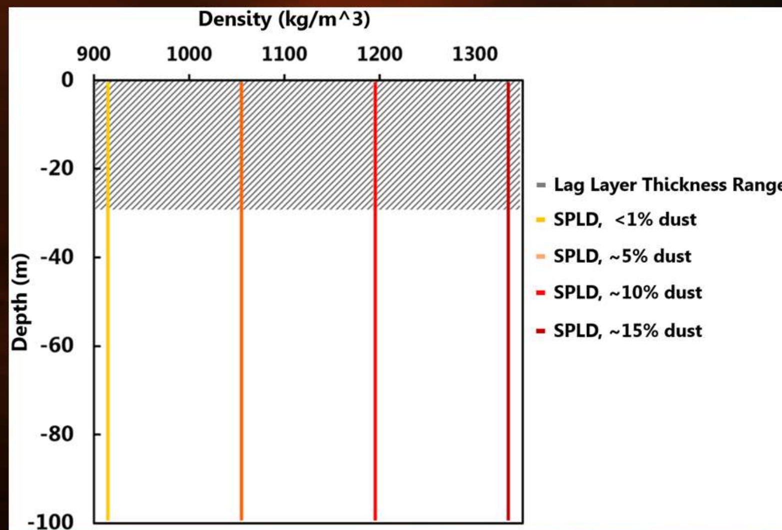
To Summarize: the surface is likely hard, consolidated ice-bound dust/regolith that transitions to a hard and dense water ice with 5-25% dust content, which varies by layer. This result is very favorable in our context.

Luckily after getting into it quite a ways, and talking to planetary scientists about it, I'm pretty confident that we are looking at favorable conditions. Notably, the lag layer seems to be on the thicker side, although I'm guessing that it is less than 45 meters and more than 30 meters thick, based off the explanation in Whitten and Campbell 2018 for the "fog" effect seen by SHARAD – If the lag layer was thicker than 45 or 60 meters the fog effect would be worse, as SHARAD's wavelength is 15 meters.

Two final thoughts here are that ice this cold is very strong, and the admixed dust makes it even stronger. Finally, we do expect a thin layer of loose dust at the very top, just a few centimeters thick.

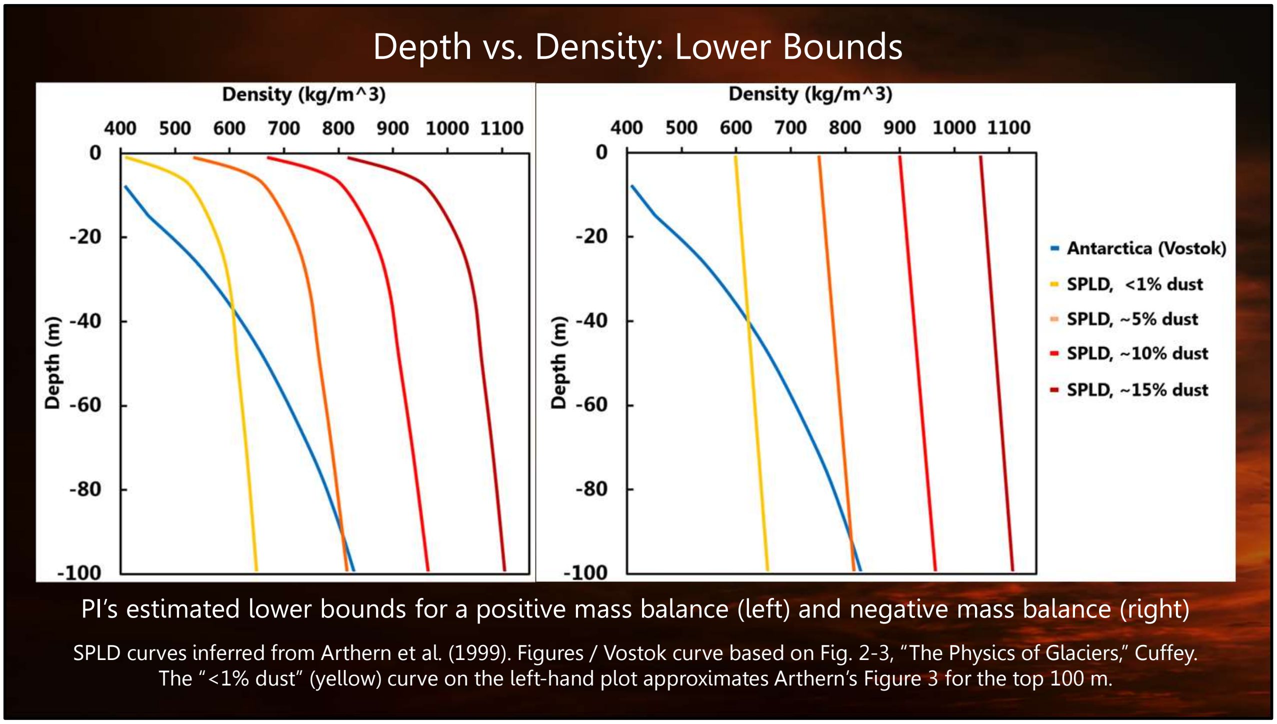
Depth vs. Density: Upper Bounds

- Vertical lines show density of a "perfectly dense" substrate at various dust concentrations (for context)
- Hatched area represents the predicted thickness range of a sublimation lag layer
  - A discontinuous jump in density is likely in areas where a lag layer is present
  - Predictions for the thickness of a sublimation lag layer range from 5 mm to 100 m, although a range of 1 m to 50 m is the most likely



What we are looking at here is an ideal formation – the vertical lines are just the density of solid ice with a various amounts of admixed dust. This is the densest an ice sheet could be, like if you made a 100-meter-thick ice sheet in a giant laboratory.

The top cross-hatch represents the uncertainty of the unconstrained lag layer –- when we go back to the other slide, we are going to neglect the lag layer so I wanted to point it out here.



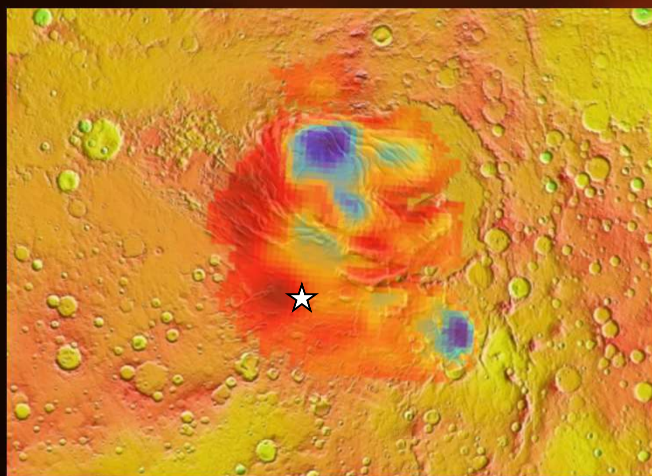
The first thing I want to point out on both of these plots is the blue line. This represents empirical data from the Russian borehole at Lake Vostok, Antarctica, which is the best SPLD analog on Earth. The Earth ice is formed much faster (which means thicker layers of snow), in a higher gravity environment, with less dust.

On the left is a plot showing the density vs. depth when there is some amount of annual snowfall. This would be a situation where **less than** a few mm a year is being laid down (not much!). This is more likely to represent the past history of the ice sheet, during growth periods.

On the right, we are seeing an old ice sheet that is being slowly eroded away by the wind or sublimation, or a combination of the two. Basically, the top layers that were a lower density have been eroded away, leaving a denser, harder ice. We think the current SPLD is better represented by the plot on the right, but the left would be the "worst-case scenario" based on Arthern 1999 for accumulation periods. Overall, we are happy with what we see here.

I want to reiterate here that I'm not a planetary scientist. The Arthern paper is very good, I recommend taking a look at it if you are interested in Mars polar science. I just needed to extract some engineering context from a generally vague understanding of the ice sheet.

Potential Landing Site: -81.00° 193.00°

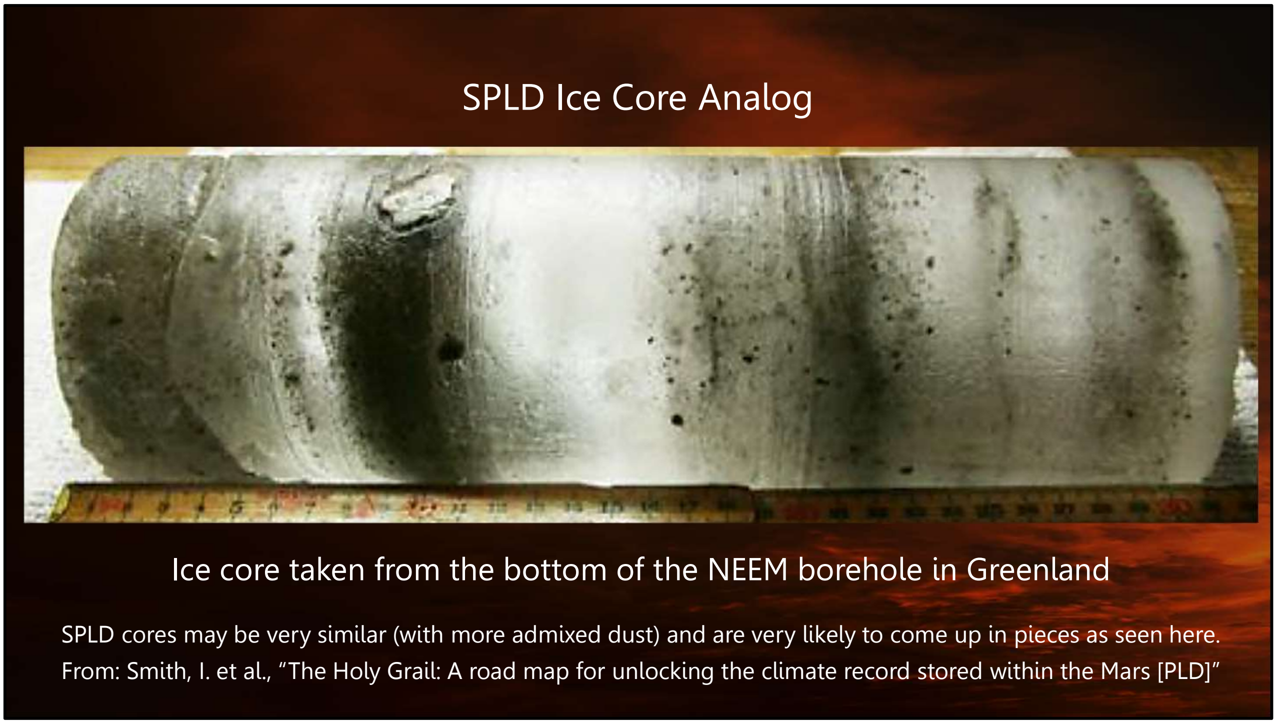


Density at potential landing site: 1200 kg/m^3 $\pm$ 100 kg/m^3
(Density overlay is figure 6-d, Li et al. 2012)

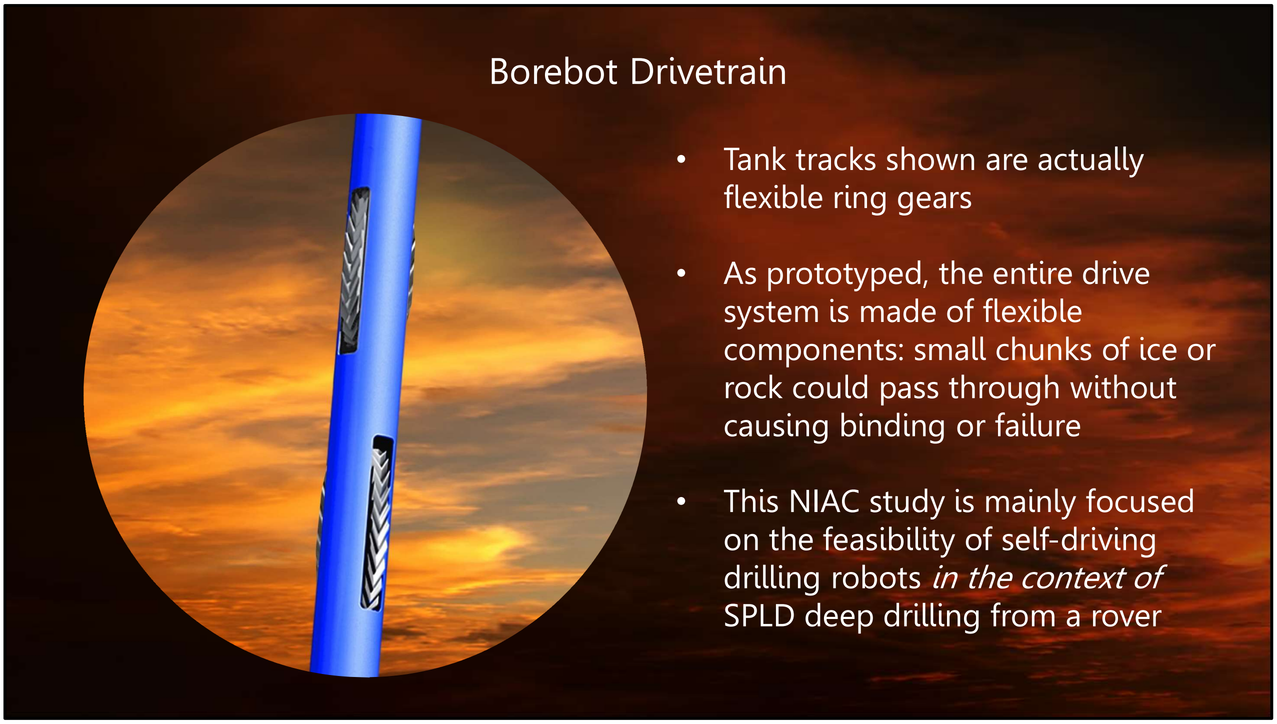
uahirise.org/ESP_066074_0990

Here is a density overlay from Li, et. al, 2012, on top of a map of the south polar region. The location of the “high-reflectance zone” from Orosei et al., 2018 is indicated with a star, and the bulk density there is about 1200 kg per cubic meter. Blue areas are closer to pure water ice (like on Earth) and the dark red areas have a lot of dust mixed in. There is some concern that gravity anomalies are not fully accounted for in the Li et al. model, but since we aren’t in any of the maximum or minimum areas we think this 1200 is a pretty good estimate. Also that puts is in “the greater than 10% dust” region on the plots, which means the ice is stronger because of that.

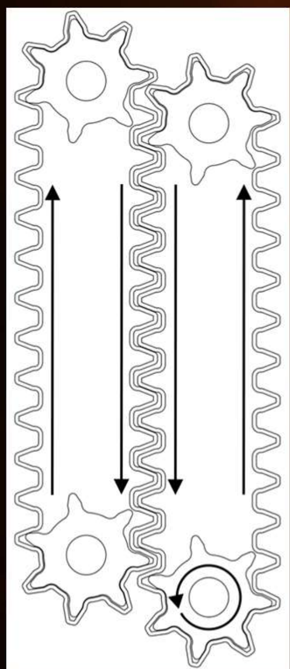
On the right is a Hi-Rise image of a potential landing site at this location, which looks very favorable.



Here is an example of a dirty ice core taken on Earth. This shows the alternating layers of clean ice and dust very well, but actually this is much dirtier than what we expect in the SPLD (once we are clear of the lag layer). We also don't expect many rocks, although we have been planning for them when it comes to technology development. This image is from a very good paper that came out of a workshop on polar deep drilling, I recommend that all of you read it!



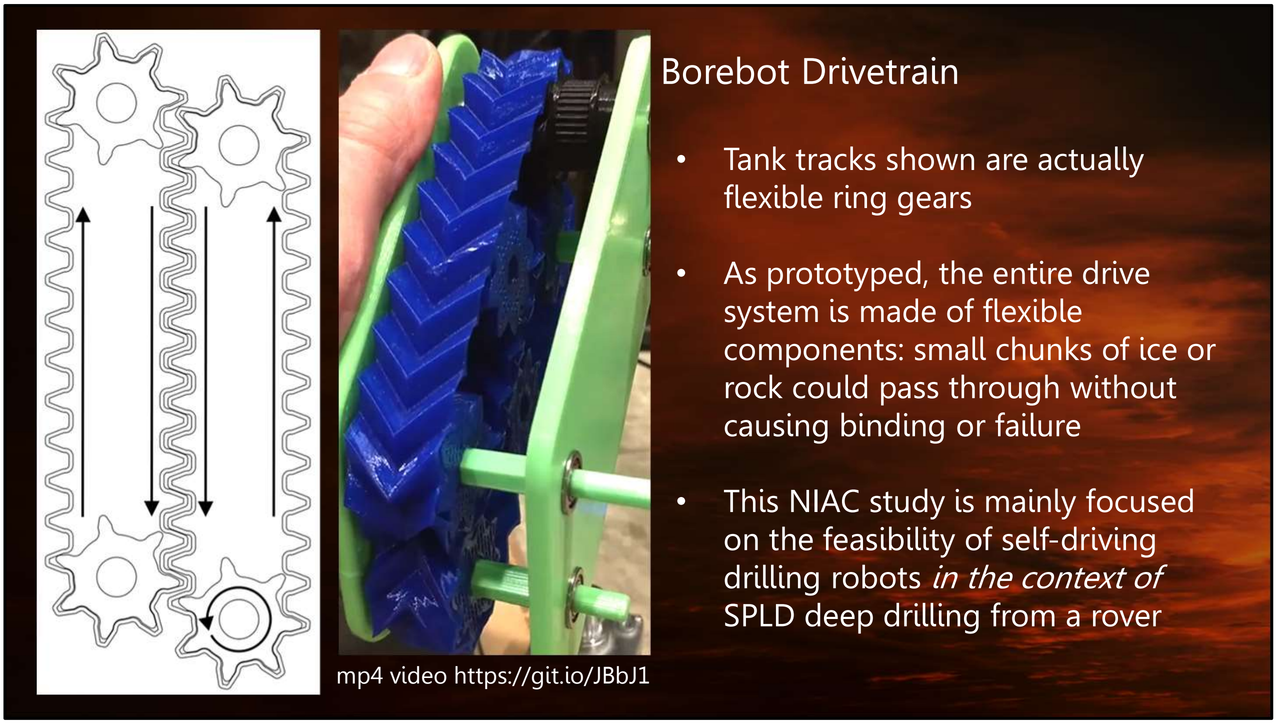
This is a close-up of the borebot showing the drivetrain. I personally like the idea of having two sets of these tank tracks, but we still have some work to do to justify the number of tracks.



Borebot Drivetrain

- Tank tracks shown are actually flexible ring gears
- As prototyped, the entire drive system is made of flexible components: small chunks of ice or rock could pass through without causing binding or failure
- This NIAC study is mainly focused on the feasibility of self-driving drilling robots *in the context of* SPLD deep drilling from a rover

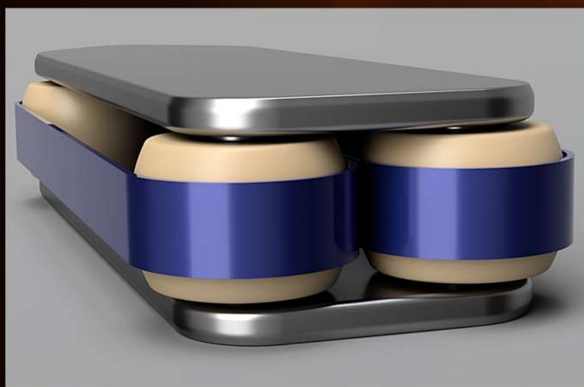
On the left is a diagram of the way the motion works. We can drive one of the gears, or one on each track, and the whole thing works like a geartrain. The belts are really just ring gears, and are printed round. The flexibility is the key to this version of the prototype, and we like how tough and resilient it is.



MP4 video, stored on GitHub: https://git.io/JBbJ1

This is actually a very old prototype, but it is good for showing on video since you could chuck on to one of these axles and turn the thing with a drill motor.

Borebot Drivetrain: Flat Belt Options



- We are also looking at drivetrain layouts that use flat belts, both with and without crowned pulleys
- Generally, the tolerances on a flat belt system have to be tighter, and the interface between the belts is less reliable, meaning independent track control may be a requirement
- The potential to have lower friction / rolling resistance may make it worth the challenges

We are also looking at flat-belt versions of the drivetrain, and so far I think I see three possible ways to do that. The first two work sort of like a belt sander, by using crowned pulleys to keep the drive belts in place. This will take some experimentation, though. It uses a different centering force than the herringbone gears, and we aren't sure if it will be better or worse, and we also aren't sure if the borehole radius removes some of the centering effect from the crowned pulleys. The 2nd version has a greater crown (smaller radius), in case a stronger centering effect is needed. The 3rd would be flat, flanged pulleys with a thick and flexible flat belt.

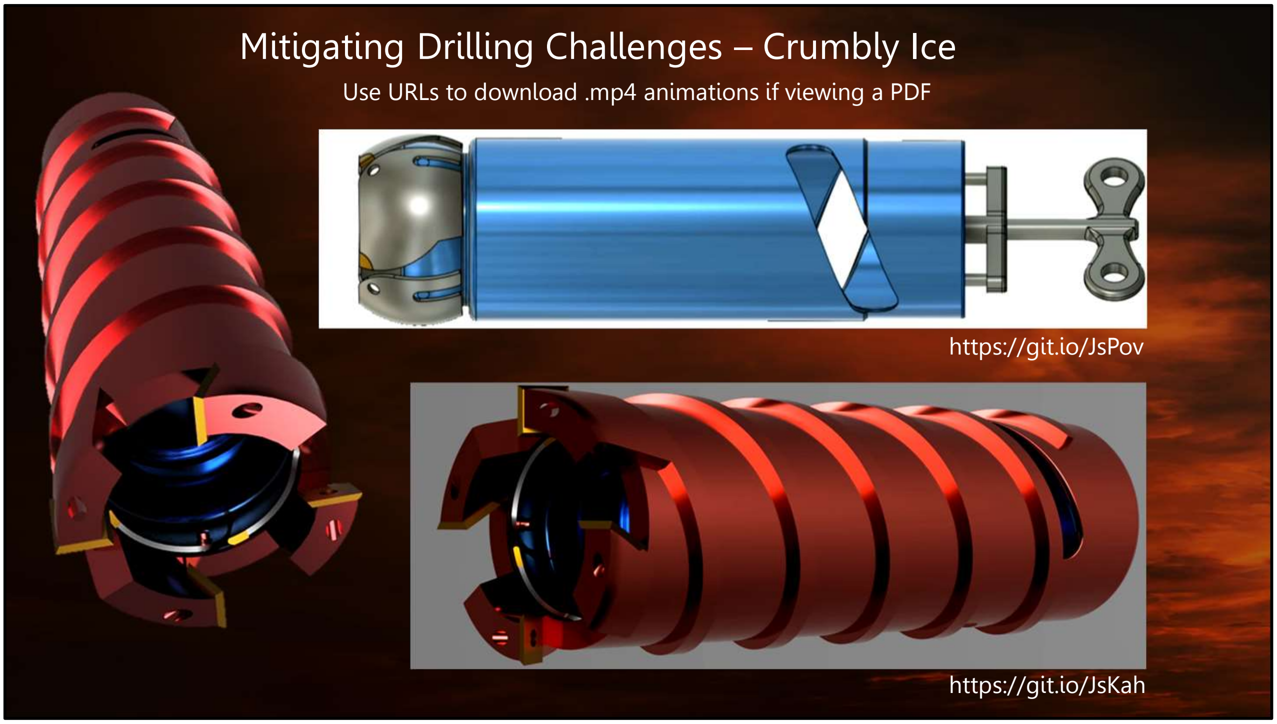
Tom will touch on a more general approach to directional control in a few minutes.

To accomplish true directional drilling with our system, I think the best way to do it is to use two borebots with two pairs of tracks each, connected by an articulated joint. I noticed that this joint would actually need to be a pretty complicated, because you can excavate less material prior to the turn if you have the ability to change the bend radius of the joint while keeping the same bend angle. However, proper excavation of the turn area can allow for easier entry/exit on a frequent basis, so the time investment might be worth it. Note that the tracks we can see facing us are 100% in contact with the bore, it is only the ones laying in the plane of the picture that will lose traction during the turn. And to quickly clarify, this is how you go around a stuck borebot or otherwise blocked borehole without starting over from scratch. It also lets you get a second-shot at taking an ice core at a specific depth.

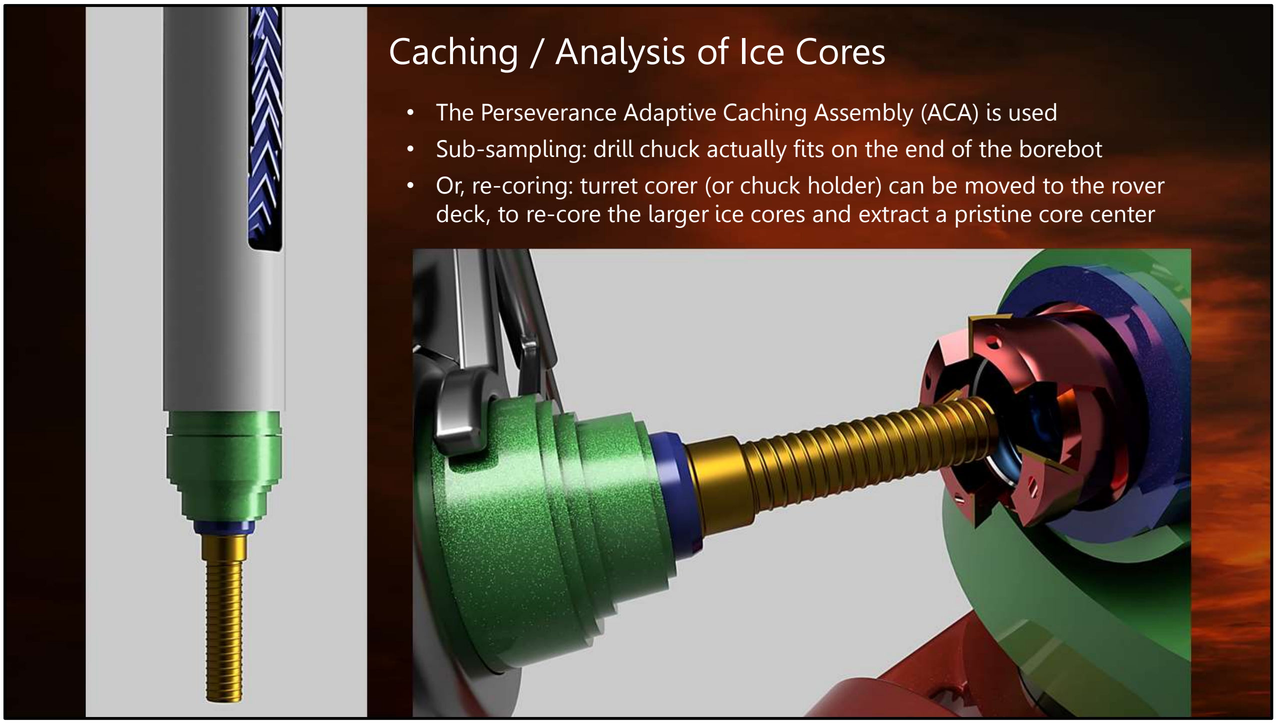
Mitigating Drilling Challenges – Crumbly Ice

- This innovation enables reliable capture of crumbly/non-cohesive ice cores
- Carbide teeth are brazed onto a steel-bladed spherical iris
  - Low annular profile, can take a 40 mm dia. core
  - Larger diameter after throat (room for chips)
- The main drill motor is used to actuate the iris via a clever pin-puller strategy
  - Full drilling torque available to close iris
- A ratchet mechanism could hold the aperture while rotating the drill in order to cut hard/consolidated cores

We are still worried that because of the layering in the SPLD, we may see more fracturing in the ice cores than normal. This is already expected to some extent with ice cores of this size, so we wanted a sure-fire way to retain cores. This may also come in handy when drilling through the lag layer, which has a less certain composition than the deeper ice.



It is difficult to explain how we get this to work in such a small device. Basically, we lock the blue barrel to the frame of the borebot, and turn the red part of the drill. This lets us use the full torque of the drilling motor to actuate the iris. We believe that adding a ratchet mechanism in the top of the drill may allow coring material as hard as rock by cutting the core in increments using this process.

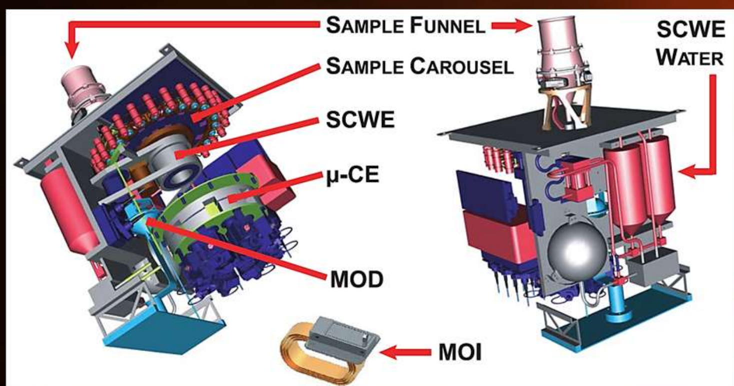


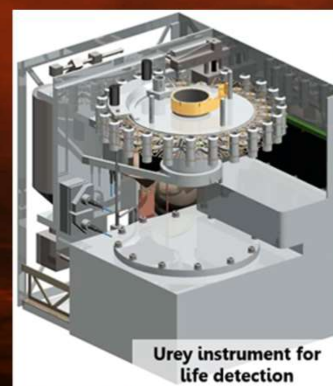
We believe that we can use the Adaptive Caching Assembly from the Perseverance rover by either extracting the heart of our 40 mm ice cores with the Perseverance drill bits, or by attaching the chuck from the turret corer directly to the front of a borebot. To analyze these cores, we can either find a way to route material from the ACA to science instruments, or we could use a pneumatic system to route material dumped on the top of the deck into instruments. A third option may be to stick a hot needle into the center of our large cores, routing the evolved gasses to instruments.

Science Instruments

Rover Instruments

- Urey life detection instrument (in the space used by MOXIE on Perseverance)
- Raman UV Spectrometer (added to ACA vision station, or external [SHERLOC])
- Ice core melting station, with mass spectrometer analysis of released gasses



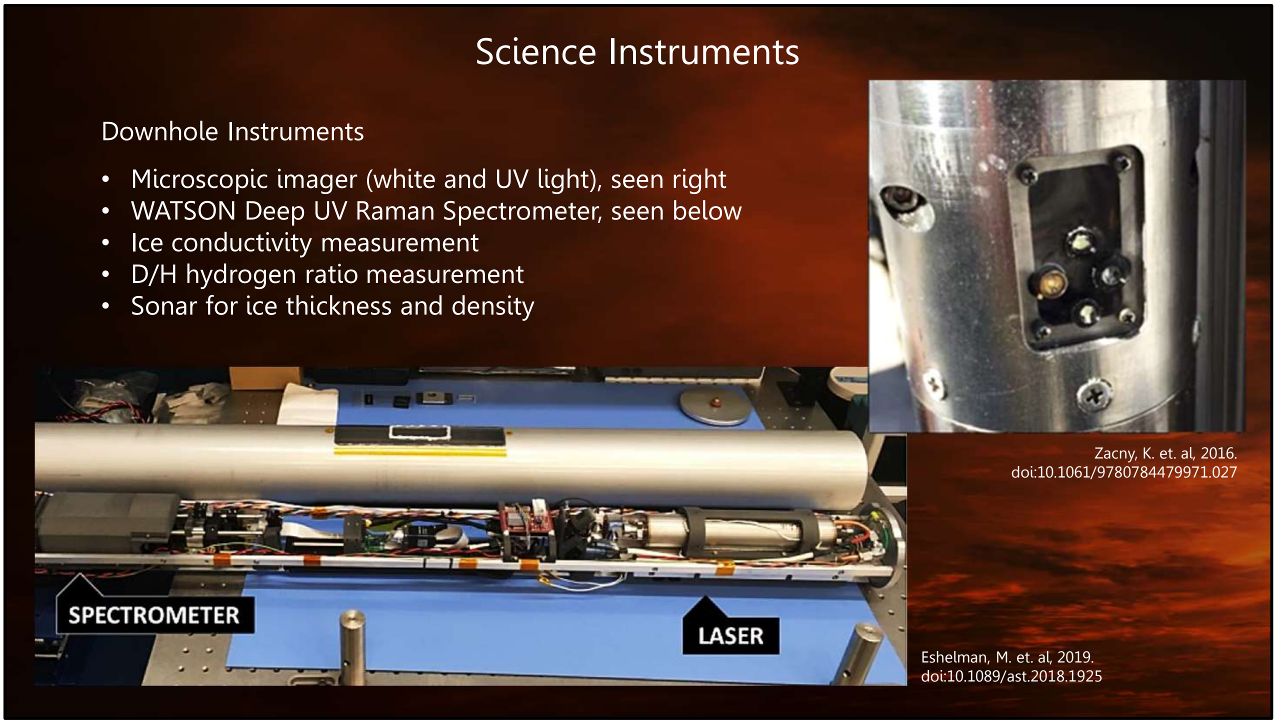


Aubrey, A., et. al. (2008). "The Urey Instrument: An Advanced In Situ Organic and Oxidant Detector for Mars Exploration." doi:10.1089/ast.2007.0169

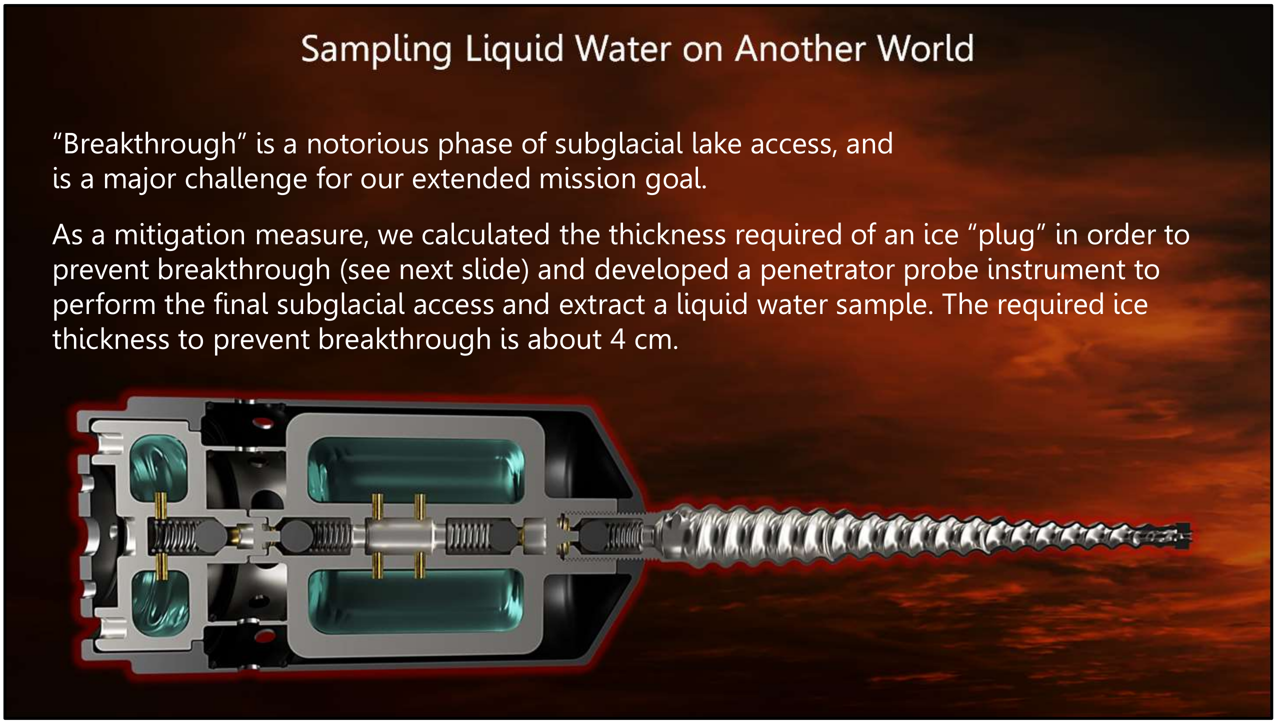
As far as rover-based science instruments, the Urey instrument is smaller and lighter than the MOXIE tech demonstrator on Perseverance. To support more frequent analysis, a rover-mounted Raman UV Spectrometer would be a good option, but it would be great if we could find a way to integrate to the mass spectrometer from SAM on the Curiosity rover into the MOXIE volume with the Urey instrument, and use the evolved gasses from either an ice core melting station or from the heated needle used to probe the ice cores.

The overall idea:

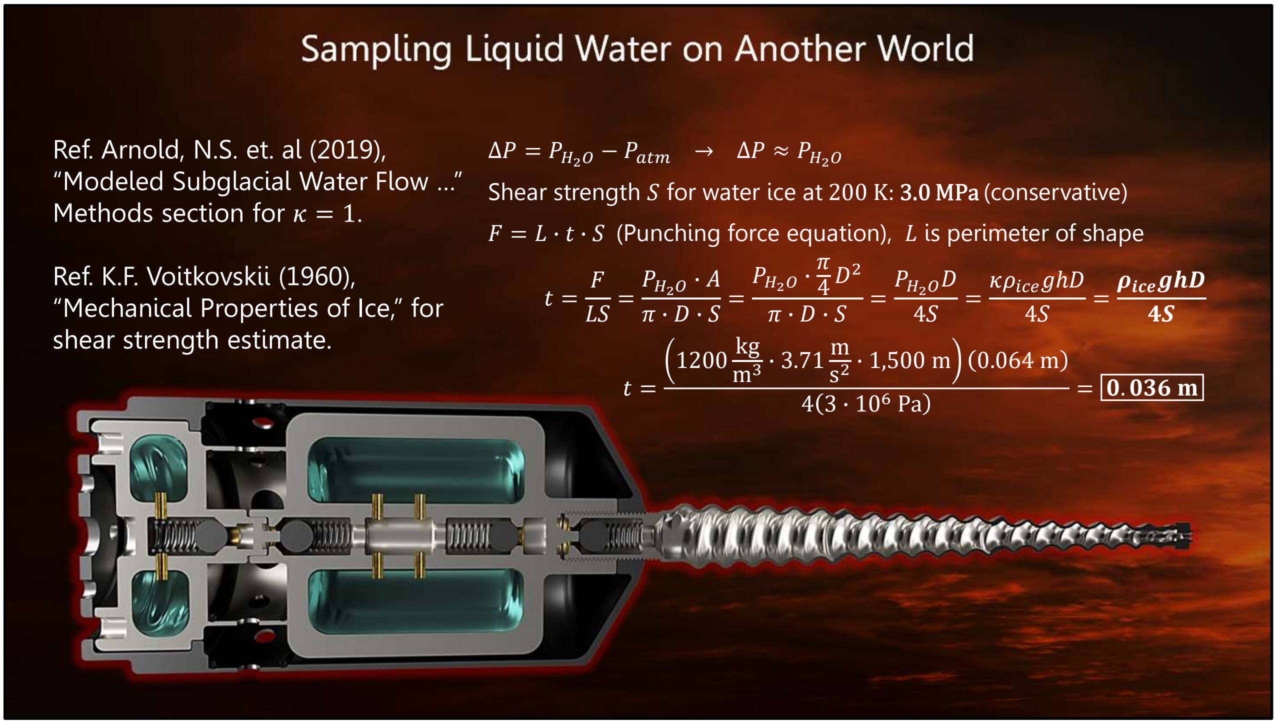
- Urey instrument for life detection / physical analysis
- Sample context with the Raman UV Spectrometer
- Log the climate record with the evolved gases and the Mass Spectrometer



There are lots of good options for attaching a science payload to the front of a borebot, to send down the hole every so often. The most capable one is an instrument called WATSON, which I would suggest everyone read about in Eshelman et al. 2019. We also think we may be able to add microscopy right into the borebot itself.

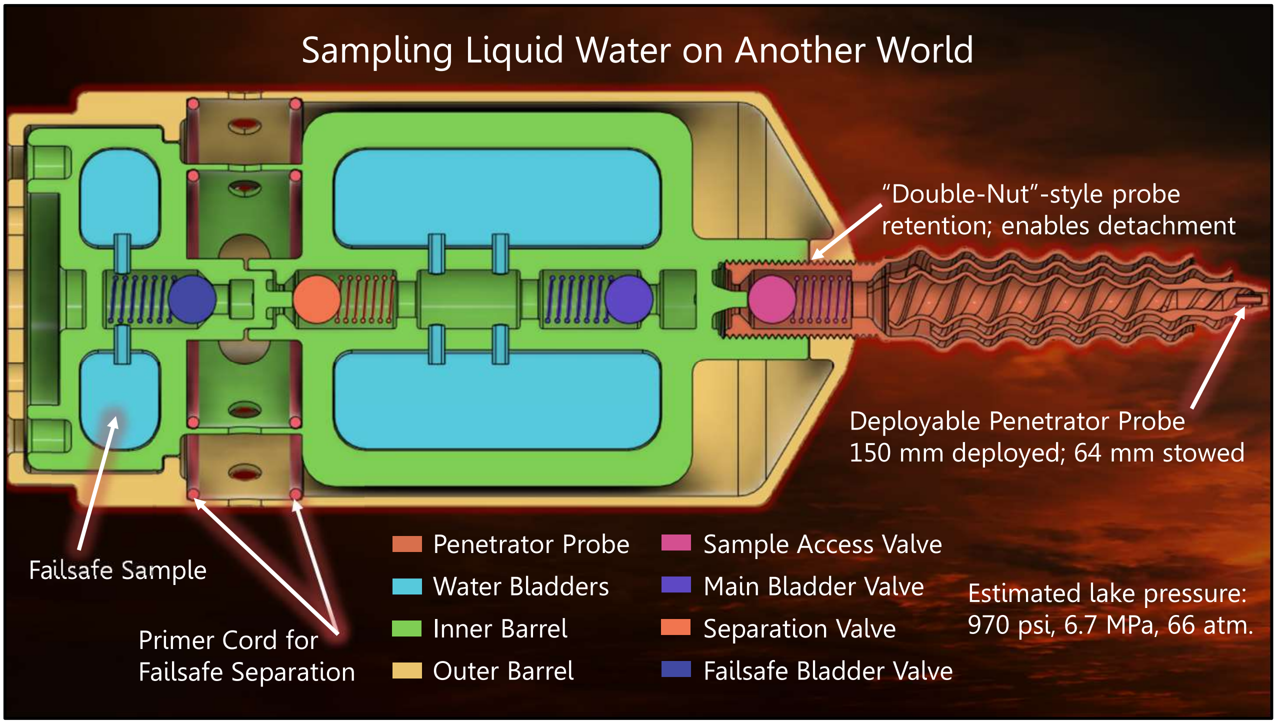


I want to mention quickly that blindly drilling into a subglacial lake with a battery-powered robot is a difficult prospect.



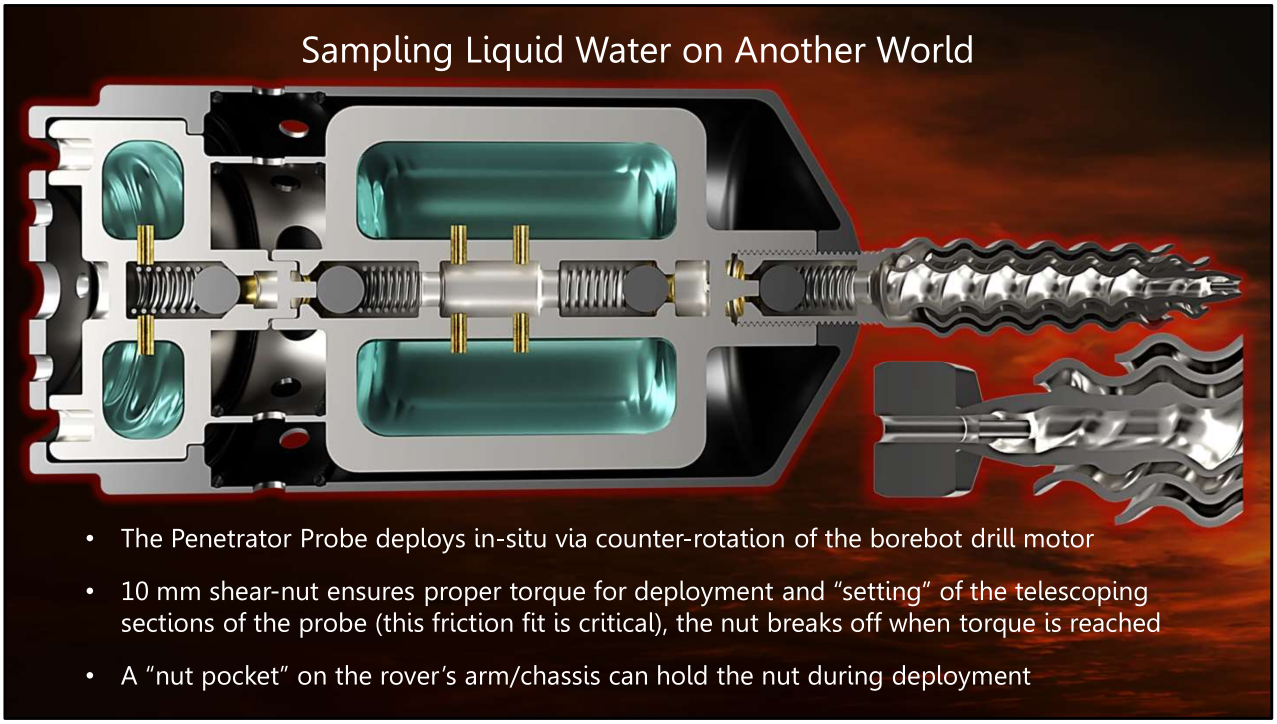
I think the safest and easiest approach is to drill a very small hole with some kind of tapered screw and leave this “straw” and its high-pressure valve plugging the hole.

The math shows that just four cm of ice is enough to keep the lake water pressure at bay.



The probe can be fitted to a water sampling device which can attach and detach from the probe.

The probe doesn't have to be telescoping, but I made the prototype work like that, and it turned out pretty neat. When "breakthrough" happens, the pressure will lock the straw in place in the ice, and the valves will open automatically, letting water into the water sampler. Later, the sampler can unscrew from the probe, leaving the "straw" of the probe in place, and the valve in the probe will close. Another sampler can come down later and screw onto the first probe. Alternatively, after the first water sample is taken, a borebot can drill *around* the probe (which is still plugging the hole) in order to intentionally flood the hole, so the "fresh ice" can be cored or cached later by another borebot.



This concept is basically just a sketch. This is one way that a tapered screw may be able to act as a self-locking straw. We hope to revisit this idea during follow-on work to mitigate risk associated with breakthrough in the event that the wet hypothesis is true. Since there is so much uncertainty around this hypothesis today, our focus on this device is likely to be limited.

The outside surface of the probe would have to be covered in some kind of abrasive, and carbide cutters would have to be installed at the very tip. An algorithm would have to be developed for enlarging the diameter of a threaded / tapered hole while moving the probe deeper via drilling. We also want to make sure that when making further downward progress, we have a significant engagement with the "threads" of the hole.

Biographical Sketch – Tom Bowen, Co-Investigator

From the smallest microcontrollers to the nuclear heart of a submarine, Tom has worked on it all. In the Navy, Tom was a nuclear-certified welder, quality assurance specialist, and mechanical systems expert. His focus has since shifted to mechanical design, electronics, and technology-assisted urban agriculture. As a recent graduate of the WSU Mechanical Engineering program, Tom strives to advance space tech by creating, developing, and testing new concepts.

Work History

- Mechanical Engineer / Co-Investigator at Planet Enterprises, *August 2020 to present*
- Commissioning Engineer at Säzän Environmental Services, *February 2021 to present*
- Electric Circuits Lab Instructor at Olympic College, *January 2020 to August 2021*
- Quality Assurance Specialist at Strategic Weapons Facility Pacific, *2016 – 2017*

Education

- BS, Mechanical Engineering from Washington State University – *May 2021*
- AS, Engineering from Olympic College – *December 2019*
- Defense Acquisition Corps, Production Quality and Manufacturing Level 2 – *Jan. 2018*
- Defense Acquisition Corps, Information Systems Acquisition Level 1 – *July 2017*

Research Interests

- High frequency motors / drives, analog alternatives to digital circuits, mech. system design
- Intensive urban food production through permaculture

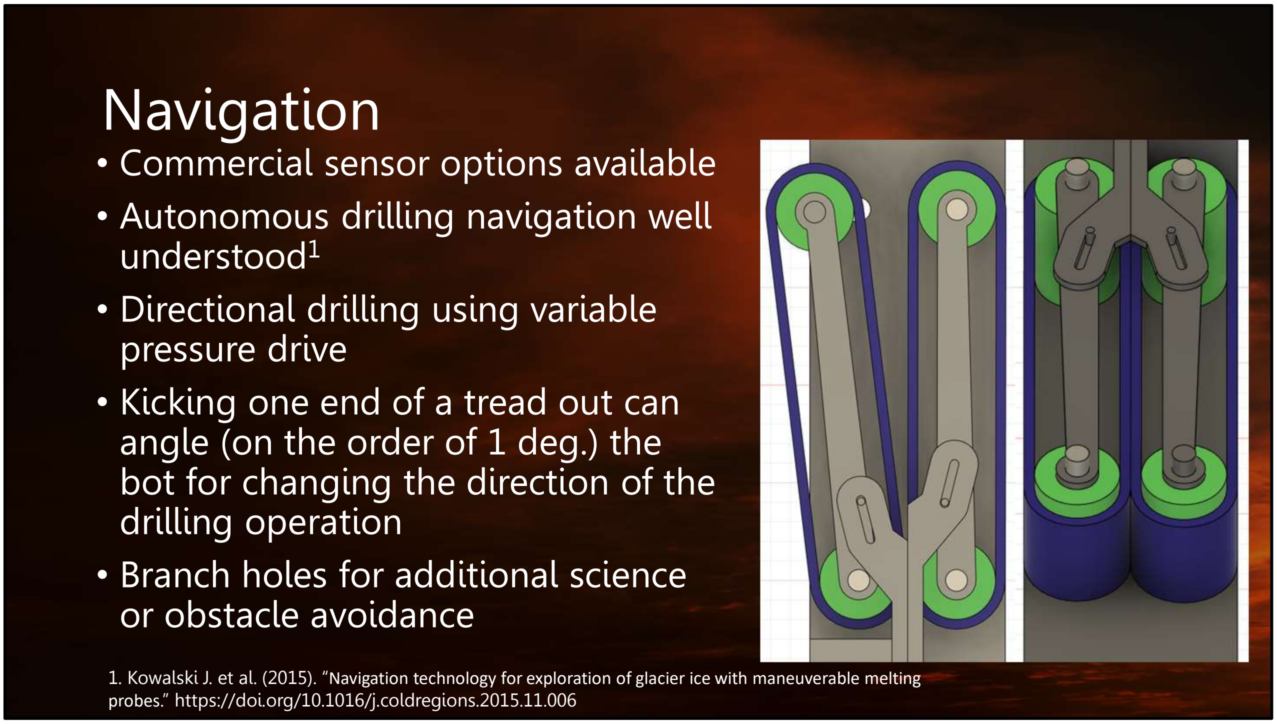
We’re not flying through the air, but we’ll still have plenty of computation to do!

Right now we’re looking at typical microcontrollers for brains, from basic stuff like an Arduino to STM32 or Teensy for the added capabilities and built-in peripherals. These options give us a moderate speed and capacity, are easy to program for, and we can use SD cards for storage (at least for the prototypes). Extra computation for inertial measurement or spectrometry can be farmed out to processers on the instruments themselves.

Higher end System-on-Chip options, with a micro-controller and FPGA. Much higher speed and capacity, but often there is proprietary code for various internal components which we’d want to avoid. These are VERY capable devices though, so if we discover we need a big brain we can shift to that level.

Memory capacity of either option can be supplemented with any number of chips or cards if necessary.

These options would give us more centralized computation and could reduce the need to farm computation out to the instruments, however there is a much higher power requirement. Power is a primary consideration when it comes to our computation options.



There are lots of Micro Electro-Mechanical System (MEMS) sensor suites out there today. Not just in Drones either. Modern Inertial Measurement Units (IMUs) are integrated onto a single chip, with filtering and processing built in. Common communication protocols are used to communicate with the sensor suite.

Some very smart folks have been working on autonomous, steerable drilling algorithms already as well, so there is a good knowledge base in the field. For more on this, see Kowalski J. et al. (2015). Navigation technology for exploration of glacier ice with maneuverable melting probes. doi:10.1016/j.coldregions.2015.11.006.

Directional Drilling – just the process of drilling itself can cause the hole to drift with depth. Using a variable pressure system to control the treads, we can apply a torque in different directions to the Borebot. This gives us about a degree of steering control to keep the hole straight, avoid obstructions, go around stuck borebots, or collect additional samples.

Power Requirements

- Need high density, reliability, cycle life
- Drive efficiency is a big deal – regenerative braking would be great
- Hotel loads offer slow death
- Nominal capacity is reduced to improve cycle life ~40%
- The noble 18650 cell.
- Typical chemistries do not like the cold.
- Lithium Titanate would be great but has a low energy density

Possible battery arrangement with Radioisotope Heater Unit (RHU)

At depth, our round-trip times can be up to 4 hours. That's a long time to be in the cold and dark while working. We are working to narrow the range of travel speeds now, which can help us constrain our power estimates. And we don't even get 100% capacity from the cells because we want to extend our cycle life and increase reliability, so we don't plan on charging them all the way, and we plan to constrain the depth of discharge to a conservative level.

Right now we're modeling with 18650 cells because they're so well studied, cheap, and available. We know how they work, and we know how they fail really well. Unfortunately, the common chemistries and highest performing chemistries don't like the cold at ALL. Lithium titanate are really neat, and seem to have an amazing cycle life, AND tolerate very low temperatures. However, they have a fraction of the energy density of LiFePo for instance which likely rules them out. We are also looking at watt-order Radioisotope Thermal Generators (RTGs) as heat sources to keep the battery packs warm, and are looking at using electrical resistance heaters too.

Battery capability is highly sensitive to drive speed, because of the power draw from the processor and normal the everyday sensors. If we don't drive fast enough then we basically get wasted power because we're having these constant hotel loads that drain continuously. If we drive too fast, efficiency may drop due to losses in the mechanical system.

Thermal Requirements

- Staying above 0C for batteries
- Minimal convection
- Radiation appears to dominate
- Conduction is a risk down hole
- Electric heating, RHU, waste heat from components
- Structure design for warmth
- Phase change materials

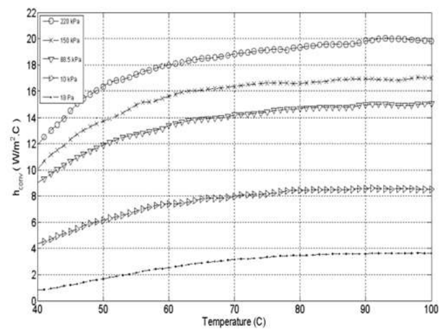


Fig. 4 Convection heat transfer coefficient with temperature at different pressures

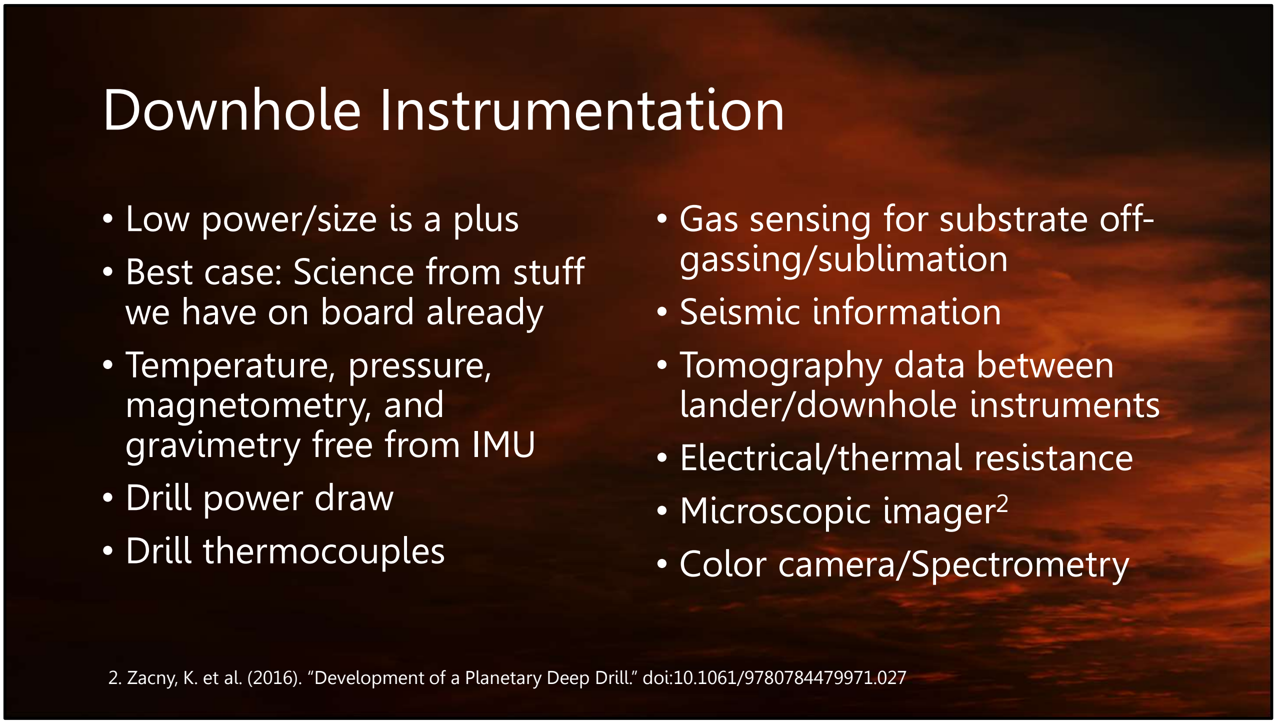
Graph: Saidi, Maysam & Hosseini, R.. (2010). Air Pressure Dependence of Natural-Convection Heat Transfer. Lecture Notes in Engineering and Computer Science. 2.

Speaking of staying warm, military grade electronics are good down to about -40C which is very cold. Unfortunately, the batteries stop working well at about zero Celsius. The substrate temperature is likely to be around -100C based on the current science, so we have to account for a large number of potential losses.

Luckily, the atmosphere is very thin, so convection looks to be very low. Radiation transfer is likely to dominate the losses, but down the hole we have the extra challenge of conduction with the walls of the hole. The core drill will be slightly larger than the bot body just for clearance and ease of travel, so this narrow gap between the walls and the bot body will help us avoid conductive losses.

Electric components generate waste heat during operation, so that will help make up the difference, but we expect to need something more. This could possibly be electric heaters, but we prefer not to because again, power draw; possibly radio radioisotope heating units which take up a lot of space, but they are effective. Right now, our models are showing that the waste heat from the components is about the same order of magnitude as our losses.

Other methods we are looking at are low-emissivity coatings, various kinds of insulation, structure design to maximize thermal resistance, or even using thermal masses and phase change materials like water to help us maintain temperature.



The whole purpose of this concept is to get great science from underground at the south pole of Mars! Which is pretty awesome. So how do we do that? Preferably without using a lot of power because of what I've already mentioned about battery life. If we already have some sensor or device onboard for navigation or drilling or health monitoring, we can get easy science points from those.

The Navigation system will have pressure, temperature, gravitational sensors, magnetometers, that can all provide new and interesting data. Just knowing how hard the drill is working and how hot or cold its getting can tell us a lot about what its cutting into.

Another thing we may be able to use the navigation system for is listening, (just like the Insight probe uses its seismic sensors for) and geologic information from the way sounds travel between the surface and the bot when its down the hole.

Honeybee Robotics has already demonstrated a very capable imager for use on a drill. Various detectors for recording spectrometry data of the hole walls and gasses generated from drilling could also be very valuable.

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To keep up to date with this project, visit https://borebots.fyi

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