S1 - The British Antarctic Survey Rapid Access Isotope Drill - Experiences in the Field

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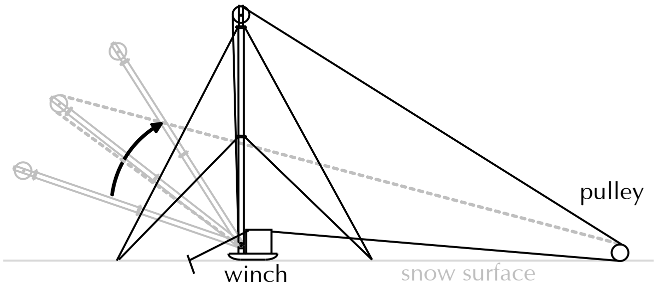

Fig. S1. Method for raising the mast using the winch. The mast is initially assembled on the ground. The winch cable is then run out and fed around the pulley, back over the sheave wheel at the top of the mast and back to the winch. As the winch cable is paid in the mast is pulled upright.

INTRODUCTION

This document outlines the experiences of the British Antarctic Survey (BAS) Rapid Access Isotope Drill (RAID) during the four seasons where it was used in Antarctica. The first two seasons were test seasons carried out near BAS's summer logistics hub at the blue ice runway at the Sky Blu. The last two seasons were science seasons as part of the Beyond Epica Oldest Ice project, in the Little Dome C area about 40 km from Concordia research station.

SKY BLU - 2014-15

Aims

1. Develop a method for raising the nearly 10m mast with two people
2. Initial test of the drill especially the unconventional outer rotating barrel

Experiences

Four days of testing was carried out, with three personnel, at the end of a shallow drilling campaign just south of Sky Blu (S 74°51'52.34", W 71°35'58.52").

A simple way to raise the mast was developed which utilised the winch itself to lift the mast from close to horizontal in a controlled manner. This method required a large pulley to be used (the BAS shallow drill sheave wheel was used in this season), and still requires one person to help lift the mast initially. The method is shown diagrammatically in Fig. S1.

Drill testing initially started very well with the drill easily penetrating the snow and the outer rotating barrel set-up looked extremely good. Drill testing was however brought to a premature end by damage to the plastic drill spirals on the long drill barrel and the spare. It was found that when the ice was warm it was sintering in the barrel and was damaging the spirals when unloading. Both our long barrel and the spare were damaged. By this time a 30 m borehole had been drilled with ≈1.4 m drops taking place with the long barrel. Although this is a good depth considering it was the first attempt there was still some uncertainty about whether the outer rotating set-up was optimal. A number of times the CAN Bus communications had to be reset and this initially was thought to be noise on electrical supply caused by the generator however switching generators did not fix this.

Conclusions and Modifications

1. A simple method to safely raise the mast with two people was devised. A dedicated pulley was added to the equipment for this purpose in the future.
2. Plastic drill spirals are not strong enough especially if working in warm conditions where sintering can occur. A local company was found that specialises in spiral manufacture. On their recommendation new spirals were made out of grade 304 stainless steel with a pitch of 35mm.
3. Drilling worked well and the unconventional outer rotating barrel was found to work. However, it was decided that the conventional centre rotating configurations should also be tested. As two motor sections were manufactured originally, one was reconfigured for conventional inner rotation by removing the epicyclic module. This was then tested and compared to the outer rotating set-up.
4. Further programming of the drill controller and the motor controller was carried out to try to improve the CAN Bus communications.

SKY BLU - 2015-16

Aims

1. Compare the inner rotating spiral configuration to the outer rotating barrel set-up.
2. Test modifications from previous year.
3. Test different cutters with and without central spike.
4. Test drill performance.

Experiences

12 days of testing was carried out with two personnel, once again at Sky Blu, although ≈ 4 of those days were lost to bad weather where the wind speed was above 15 ms^{-1}.

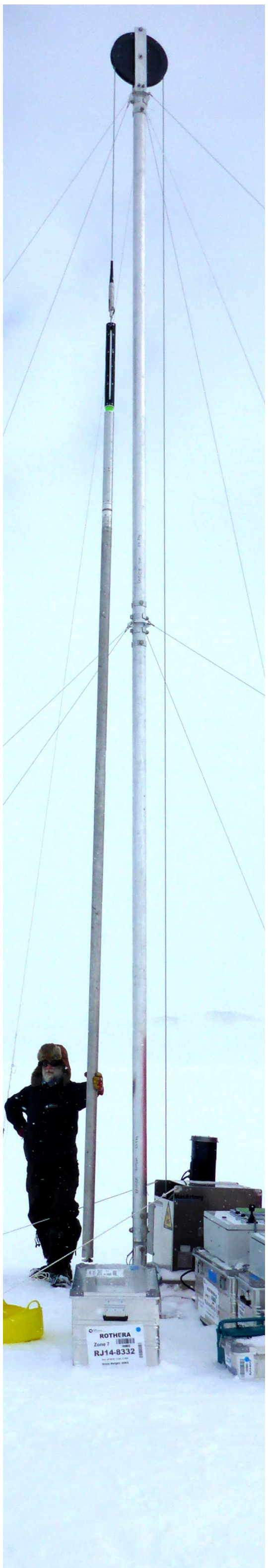

Fig. S2. BAS RAID drill during testing at Sky Blu 2014-15, with driller for scale

Two holes were drilled close to the Sky Blu main station (S 74°51'49.38", W 71°35'19.8") with the first hole, drilled mainly with the outer rotating set-up, reaching 9.98 m and the second, drilled mainly with the inner rotating set-up, reaching 5.68 m. Penetration rate on both holes significantly reduced when reaching about 5.2 m. It was discovered at this depth that drilling was into a tongue of blue ice extending from the nearby blue ice runway.

The drill test site was then re-sited back to the previous year's test site about 500 m south of the main station (S 74°51'52.34", W 71°35'58.52"). Two more holes were drilled reaching depths of 3.57 m with the inner rotating set-up and 16.9 m with the outer rotating configuration. In both cases it was found that the pitch of the auger was too small and that packing occurred very close to the bottom of the spirals. Both inner rotation and outer rotation did drill well, however clearing of chips from the hole seemed to work better with the outer rotating configuration. More aggressive cutters were found to work better than the standard ones. Drilling performance was worse with a central spike fitted.

CAN Bus communications were still temperamental when using the winch cable but this was solved in the field by resetting the power to the drill sonde. Care had to be taken when doing this as cycling the power too quickly could damage the DC to DC converters.

The plain bearings originally used in the motor section to save space were found to be wearing significantly.

Conclusions and Modifications

1. New stainless steel spirals are strong enough.
2. Both inner and outer rotating configurations drilled however clearing of the borehole was better with the outer rotating set-up.
3. The rotating inner barrel/ fixed outer barrel design penetrated the ice significantly slower than the rotating outer barrel design, and we concluded that the rotation of the outer barrel caused less static friction on the borehole and created a true vertical borehole.
4. More aggressive flared cutters performed better in all cases, however a central spike was detrimental to drilling performance.
5. The pitch of the auger was clearly incorrect. The poor chipping transportation this season motivated us to do simple auger tests in the laboratory in order to choose the right auger pitch. Brown sugar was used as the transported medium with approximately the same grain size, but not the same shape, as chippings collected in the field. Four augers marked as SP1 to SP4 made of nylon were 3D printed using selective laser sintering, with pitches varying from 35 mm to 140 mm in steps of 35 mm. A simple test stand equipped the 70 mm OD auger and 72 mm ID transparent outer barrel was built using the same drill motor as the BAS RAID (250 W at the time) to power the auger to rotate (inner rotation set-up) from 50 rpm to 200 rpm in steps of 50 rpm. Sugar was poured in the bucket. The surface of the sugar was flattened before each test. The test spiral was then put in the bucket directly from the sugar surface at its bottom to make sure that the total transported mass is the same for each test. Motor was run and stopped at 30 s, 60 s and 120 s to record the transport height, respectively. A photo was taken at 120 s (for example see Fig. S3) after which the sugar was removed from the auger by reversing the motor.
   We assume the initial transport mass is the same for each test, results from these experiments are outlined below:

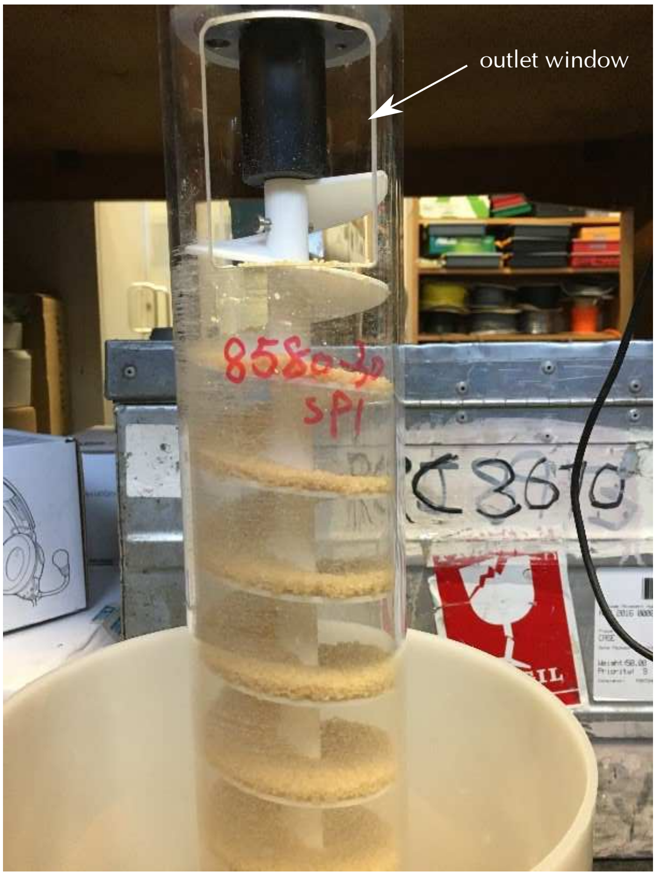

Fig. S3. Spiral Test set-up showing SP1 and the transparent outer barrel with outlet window.

(a) With spirals SP1, SP2 and SP3 sugar was able to reach the outlet window at 200 rpm but SP4 failed due to the angle is too steep.

(b) With spirals SP2, SP3 and SP4 the sugar dropping back into the bucket became worse with increasing auger angle.

(c) With spirals SP3 and SP4 sugar was predominantly towards the outer edge, whilst with spirals SP1 and SP2 the sugar was more evenly distributed. This means spiral angle will affects the mass flow rate.

(d) Sugar constantly dropped in the clearance gap between spiral and outer barrel.

Fig. S4 shows transport height vs rotation speed at various auger angle using the data at 60 s.
The above results suggest that SP2 spiral with a 70 mm pitch is the best choice for this design for its high transported height (especially at our operating point of 110 rpm) and low volumetric efficiency at the same time among all tested spirals.
It was decided that the design would stick with only the outer rotating configuration and new left handed stainless steel spiral was made with a 70 mm pitch.

6. To improve CAN Bus communications cycling of the power was automated in order to speed up the drilling process.

7. A redesign of the bearings, this time using angular contact bearings, in the motor section was carried out. A temporary support cradle was also made to be attached around the bearings when moving the drill from the horizontal to the vertical, and vice versa, as the drill is unsupported at this time.

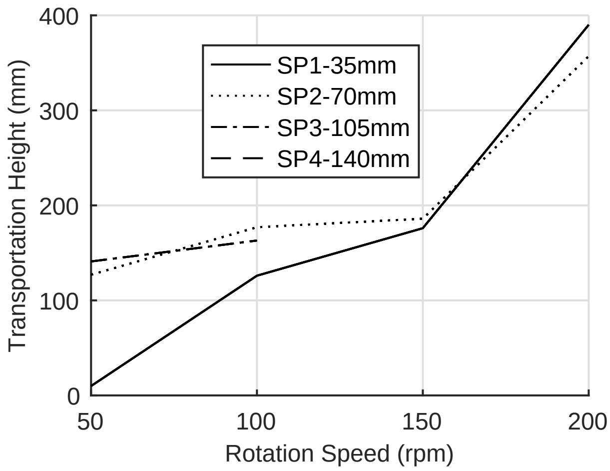

Fig. S4. Transportation height vs rotation speed for various auger pitches after 60 s, note that results where the sugar dropped back into the bucket have been removed.

Little Dome C RAID1 - 2016-17

Aims

1. Test new drill spiral performance.
2. Drill to 600 m, collecting isotope samples.
3. Provide an access hole for the temperature measurement system.

Experiences

This drill site was the Little Dome C RAID1 site (S 75°18'39.54", E 122°17'37.86"). Drilling started on the 21th of December 2016 and finished on the 7th of January 2017 with a depth of 105.2 m reached, however of the 17 days in this period only 6 (roughly 8 hour days) where more than 3 hours were spent drilling. A number of issues occurred right away with the automatic cycling of the power which resulted in damage to the high voltage power supply. This necessitated bypassing of the relay that controlled this. Communication issues when using the winch were also a problem. CAN Bus issues were finally traced to the connector on the winch cable that connected to the drill sonde. Lack of drilling time was also due to the lone driller being responsible for the radar equipment which was also temperamental.

When drilling went smoothly, it was found that the motor didn't seem to be quite strong enough to fully fill the long barrel and once the motor stalled it was very hard to empty the chippings when on the surface, which slowed down the overall drilling rate. Because of this the depth drilled per drop was very conservative at only 75 cm when running well. It was also found that the cutters became blunt very quickly. In the end despite the drilling running smoothly it was realised that the target depth would not be reached by a long distance in the time left in the season, it was decided to stop at $\approx$ 105 m as that was the amount of cable available to install a 'coffee can' (Hamilton and others, 1998). The extended, consistent data collected during this season was however invaluable in working out the power requirements for the drill for the following season. The temperature sensing system was tested in the hole.

Conclusions and Modifications

1. A new drill spiral was manufactured with a Xylan coating to reduce the friction between it and the ice this should improve transportation and reduce the power required for this.
2. The 250 W motor was replace with a 400 W to ensure that there was sufficient power to fill and empty the entire long barrel.
3. Data collected from this season showed that heat from the motor and electronics meant that during normal running the internal temperature of the sonde was usually above -20 °C allowing lower (industrial rather than military) specified components to be used.
4. The new motor incorporated a thermistor in the windings which allows the motor to be overdriven, at higher currents than usually allowed, at low temperatures. As a new motor controller PCB was required for this temperature measurement it was decided that a different off-the-shelf motor controller be used rather than the special low temperature one previously used. This resulted in much more stable CAN Bus communications.
5. The cutters material was upgraded to A2 tool steel hardened to 58 on the Rockwell C scale and a method of sharpening with buffing wheels developed.

LITTLE DOME C RAID2 - 2017-18

Aims

1. Test new drill spiral performance.
2. Test new drill motor and motor controller performance.
3. Drill to 600 m, collecting isotope samples.
4. Provide an access hole for the temperature measurement system.

Experiences

This drill site was the Little Dome C RAID2 site (S 75°21'54.40", E 122°24'55.38"), approximately 5km from the RAID1 site from the previous season.

Drilling started on the 27th of November with the short barrel. This was swapped to the long barrel after reaching a depth of 11.44 m. The drill operated extremely efficiently with the new coated spiral, more powerful motor and hardened cutters producing a very easy drill to use. For the first six and half days of drilling the drill worked very consistently reaching a depth of 284.61 m at which point a DC-DC converter in the drill failed. This failure in turn damaged the surface high voltage power supply. Unfortunately there were no spares available, the previous spare having been damaged the season before and 2 weeks were spent waiting for a spare to be flown in. The only other minor issue that happened up to this point occurred at 206.83 m when a very high load was recorded on the winch (≈200 kg). Snow was found to have sintered within the anti-torque section preventing the skates from retracting properly. After this incident the anti-torque section was thoroughly cleaned at the end of each working day.

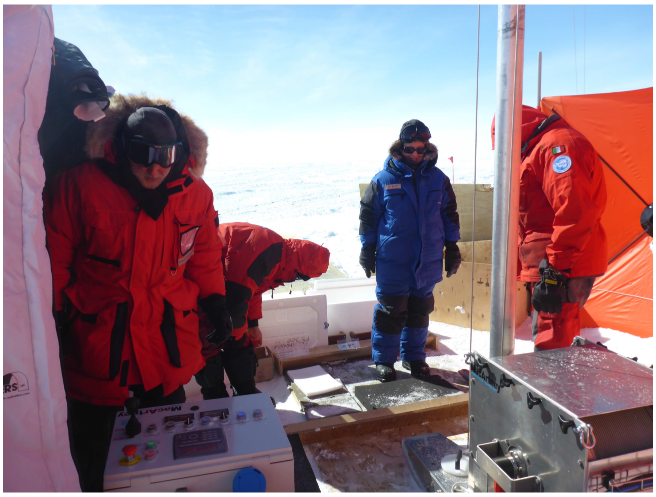

Fig. S5. BAS RAID drill at LDC RAID2 site 2017-18, Winch controller and controls is shown to the left of the winch.

Once the new power supply was connected drilling continued. A minor modification at the lower end of the barrel was to remove 15 mm of the leading part of the scoops to make the openings larger. This modification made emptying the drill quicker without losing chippings during tripping up the borehole. Drilling continued and with virtually no problems until the final day when another DC-DC converter failure necessitated more repairs. The DC-DC converter was replaced and the anti-torque blades sharpened and adjusted. The next run drilled well but during the 2nd run after the repair the drill sonde stopped penetrating, with load coming off the winch. At this point the drill was stopped and found to be stuck in the hole at a depth of 461.58 m. The motor was still able to rotate freely in both directions. After an hour of trying to free it with the winch, and as this is a dry hole, about 2 litres of warmed neat ethylene glycol was dropped down the hole in bags made from layflat and zip locked bags. The ethylene glycol was left for 3 hours with no effect. The crane on a piston bully with a 2 tonne pull was then used to put more force on the cable in the hope of freeing the drill sonde or breaking the fork termination however the link to the crane snapped at high load and the winch was damaged. It was left for a day and the cable was still found to be stuck, it was then decided to cut the cable so that it could be pulled to one side. It was hoped that by pulling the cable to the side the borehole instrumentation could still be lowered unimpeded.

Reasons to why the drill got stuck have been discussed and three hypothesises have been postulated. The first is that some mechanical failure occurred, most likely in the anti-torque section as this was recently adjusted and had also previously been the cause of high load on the winch. The second idea is, as this is a dry hole that the borehole closed and trapped the drill. This second hypothesis is not as readily understood for a number of reasons: The widest part of the drill (apart from the cutters) was still able to spin easily. The drill got stuck whilst drilling and according to Talalay and others (2015) the borehole is most likely to close higher up. The third idea is that the cutters clogged up, the scoops did not clear the bottom of the hole and ball of ice formed at the base of the drill. This last hypothesis has been discounted as the drill was able to easily rotate in both directions.

The temperature measurement system was successfully deployed to the depth of 450 m. Measurements were carried

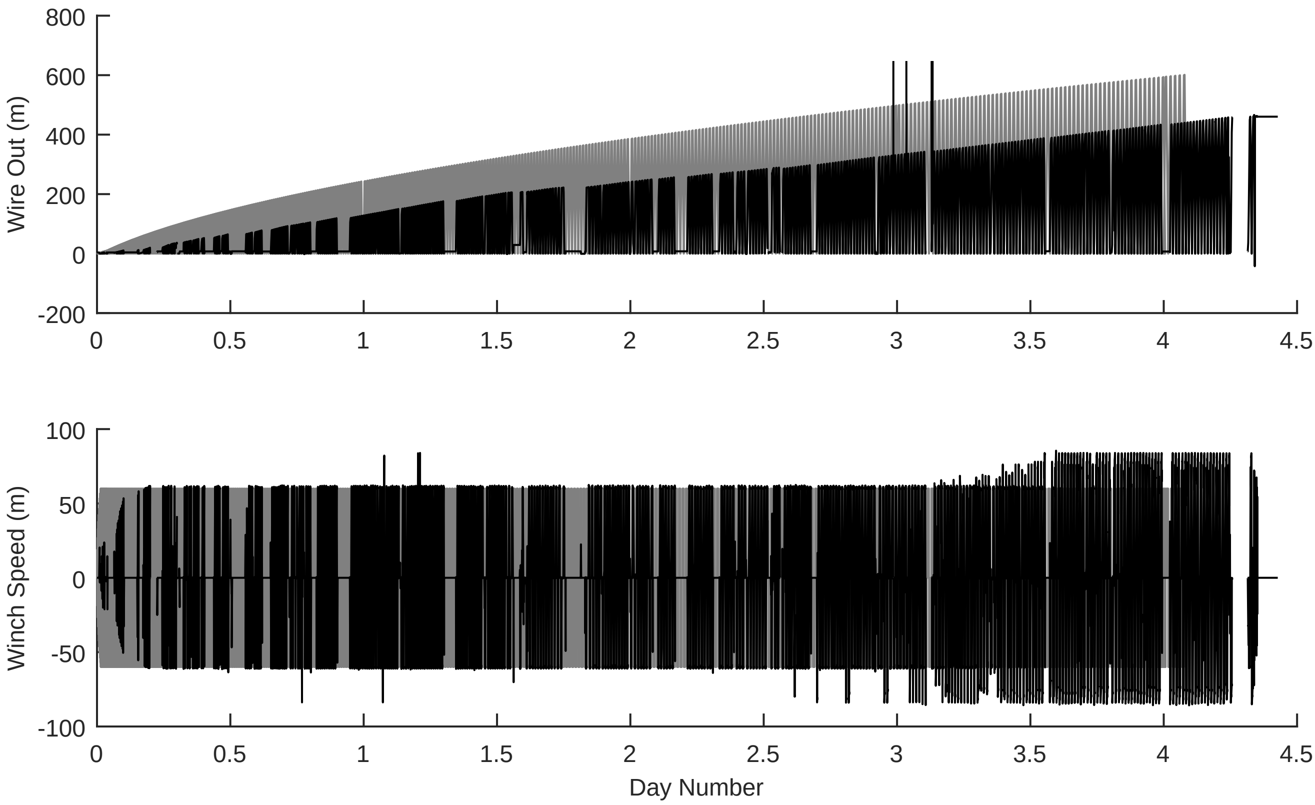

Fig. S6. Figure showing winch wire out and speed for theoretical (grey) and measured data (black). This only shows the data collected during working hours with all other time removed.

out for 4 days and repeat measurements will take place in January 2019.

Conclusions and Modifications

1. The BAS RAID drill works extremely well and the low friction coating on the spiral, the more powerful motor and hardened cutters have transformed the productivity.
2. The anti-torque section may have been the cause of the stuck drill and modifications have been carried out to make larger openings in the casing and sloped surfaces to encourage snow egress.
3. Borehole closure may have been the cause and slightly larger cutters will be made. Calculations will also be carried out so that next time the drill is deployed 24 hour drilling may have to occur to minimise borehole closure.
4. The repair of the winch and new cable has allowed a smaller 4.75 mm diameter cable to be used. This saves a further ≈50 kg and allows a simpler connector to be used.

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