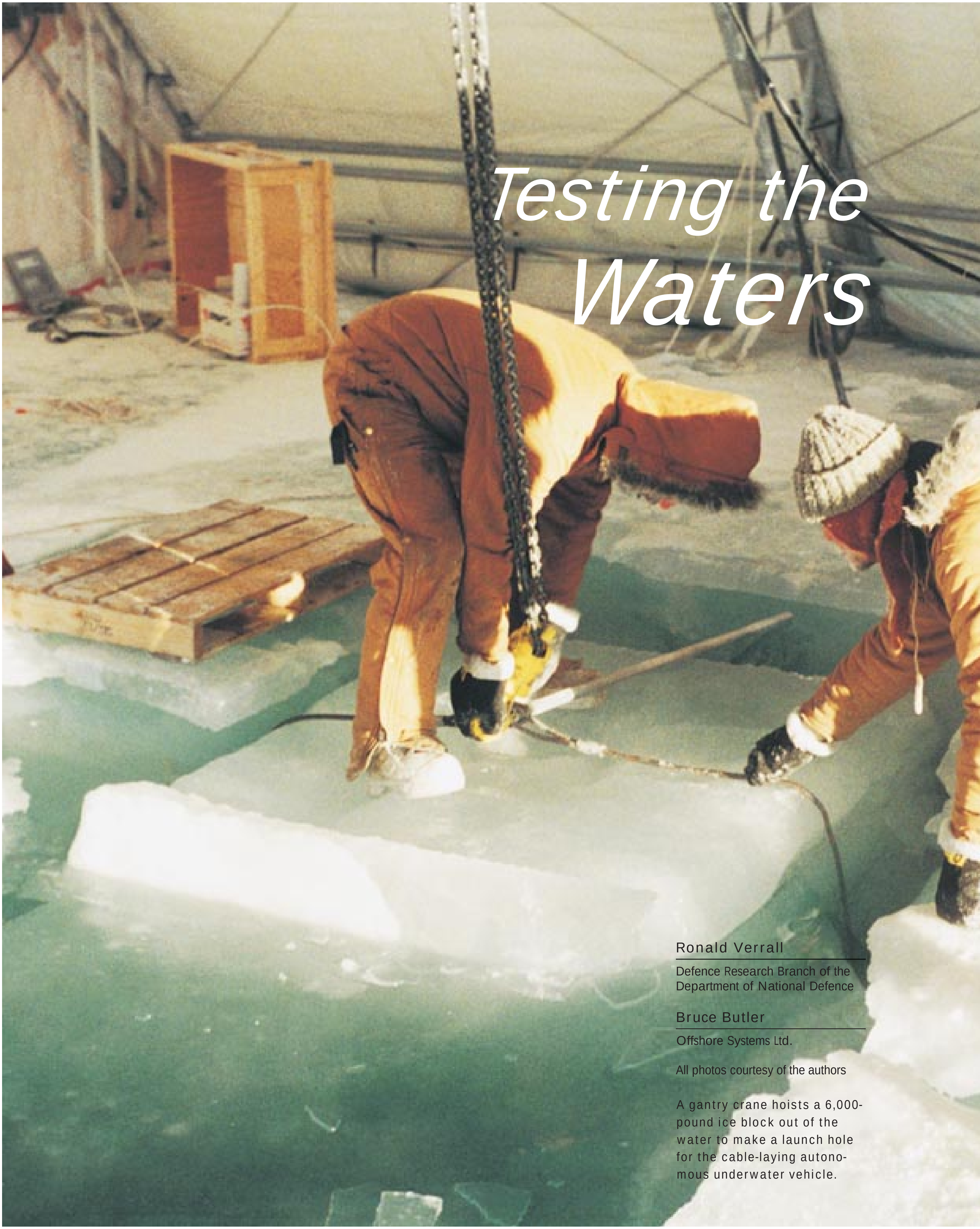
Testing the Waters



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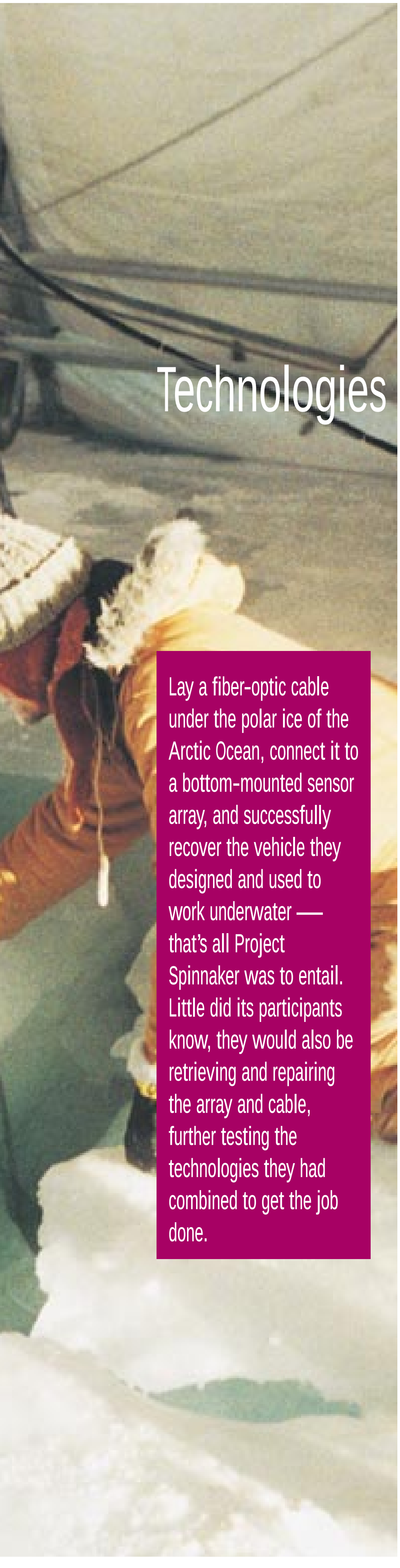
All photos courtesy of the authors

A gantry crane hoists a 6,000-pound ice block out of the water to make a launch hole for the cable-laying autonomous underwater vehicle.



Technologies Converge to Lay Arctic Cable

About thirteen of us (some American, some Canadian, and some military "augmentees") arrived from Victoria yesterday on a C-130 Hercules aircraft with about 20,000 pounds of freight. We joined the other team members who had arrived at Alert over the last 10 days. A small army of people unloaded, sorted, and put away all the freight that had arrived on the Herc. The experienced people were kept busy finding and explaining jobs for the newbees. It looked a bit like a kicked-over ant hill.

The weather is gorgeous; it's only about –23 °C; there is no wind, and there is not a cloud in the sky. This is great for people, but we are worried that the ice may not be sufficiently thick to keep it motionless. Generally, moving ice is not too much of a concern for us, but when we are trying to recover something off the bottom, we can't afford to drift away from the X that marks the spot. — *Ron's Newsletter #1, Iceshelf 98, March 30 (an almost-daily status update e-mailed to interested followers during Project Spinnaker's final Arctic mission)*

Lay a fiber-optic cable under the polar ice of the Arctic Ocean, connect it to a bottom-mounted sensor array, and successfully recover the vehicle they designed and used to work underwater — that's all Project Spinnaker was to entail. Little did its participants know, they would also be retrieving and repairing the array and cable, further testing the technologies they had combined to get the job done.

Project Spinnaker, which precipitated three Arctic Iceshelf expeditions, first took shape in Victoria, British Columbia, Canada, at a brew pub from which it derived its name.

Back then, in 1992, scientists from the Defence Research Establishment (DRE) Pacific in Victoria and their American counterparts with the Naval Research and Development Center in San Diego, California, dreamed of placing a sensor array under the polar ice of the Arctic Ocean and connecting it to land-based monitors using a fiber-optic cable. Four years later, we did. We also returned the following two years to retrieve and repair the cable and array — unplanned but fruitful endeavors in their own right.

Ron Verrall, a scientist at DRE, has long been interested in underwater acoustics in the high Arctic. Bruce Butler, on the other hand, is more interested in autonomous underwater vehicle (AUV) designs that enable an AUV to safely travel long distances. Both of us are fascinated by the technical challenge of working in the high Arctic. Project Spinnaker incorporated all these interests, combining science with vehicle technology and innovative Arctic logistics.

Although nothing so ambitious had been attempted in the past, it was evident that no real technical barriers stood in our way. Nothing major had to be invented. Still, success would require a lot of technical ingenuity and a generous share of luck.

ON THE EDGE — ALERT

The acoustic array would be mounted on the bottom of the Arctic Ocean, 180 kilometers north of the Canadian Forces Station Alert — the northernmost permanently established community in the world. Located on the north coast of Ellesmere Island, the most northerly island of Canada's Arctic Archipelago, Alert is a military station served by about 70 people who reside there during their six-month postings. Most of the scientists who take advantage of this small refuge in the far north live there during the summer months when the sun is up. Nothing but ice and water lies between Alert and the North Pole, with the nearest neighbor 670 kilometers to the south in Thule, Greenland.

Dividing the Duties. Nearly all of Project Spinnaker's participants, both Canadian and American, had extensive experience in the Arctic. Each team, though, brought slightly different skills to the task, making the division of labor quite natural. The Americans would develop and deploy the Spinnaker Array together with the necessary micropower electronics and the laser that would drive the cable. The array — a series of hydrophone sensors — would gather data for shorebound researchers wishing to study under-ice noise and sound propagation.

We, the Canadians, would tackle the technical challenge of

Theseus (Figure 1) was designed to carry 11 spools of fiber-optic cable (above), laying the more than 220 kilometers of cable on the ocean bottom and enabling connection to land-based monitors. The craft had to be assembled at Jolliffe Bay in a 36 × 65–foot tent (right).

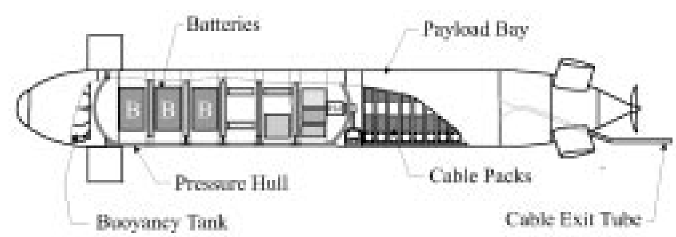


Figure 1

developing an AUV that could navigate to the array and back to shore, laying more than 180 kilometers of 2-millimeter-diameter fiber-optic cable under the polar ice of the Arctic Ocean.

We employed a bevy of technologies throughout the project — everything from acoustic beacons, Doppler sonar, and inertial navigation units (INUs) to a special glue designed to hold the cable gently in its spool. GPS also played an important — albeit transparent — role in our efforts. We positioned the acoustic beacons, relocated the cable, and monitored moving ice using either standard C/A-code receivers or a P-code unit.

Had we experienced significant problems with the GPS devices, they might have been a more memorable part of our fieldwork. The receivers worked very well, though, with their only weakness being a dislike of the cold.

Warm Start. To keep our handheld units working at –20 ºC and colder, we had to keep them in an inside parka pocket and bring them out only for quick readings. Fortunately, because the GPS satellite orbits have a 55-degree inclination and a 22,000-kilometer altitude, GPS signal availability and coverage in the Arctic has always been good.

AN ARCTIC AUV

From 1992 to 1996, we conducted Arctic field trips every year to measure bathymetry and water currents and thereby determine the best location for the array and cable. We spent the rest of the year developing the necessary tools and equipment to lay the cable. For us, the most important task was designing and building the AUV, which we accomplished by contract with International Submarine Engineering Research, a Vancouver-based company.

We named our craft *Theseus*, after the Greek hero who laid a string behind him on his way into the Minoan labyrinth to kill the Minotaur. Although our *Theseus* had no such deadly intent, it did lay a “string” behind it, and this, of course, suggested the name.

The Arctic Maze. Both the complexity of the mission and the harsh environment imposed severe constraints on *Theseus*’s design. The Arctic sea ice tends to be particularly thick north of the Canadian Arctic islands because it converges there and forms more ridges than are normal. (Ridges form when two sheets of heavy ice push into each other and crush the ice along their contact line. Some of the ice chunks are pushed upward; most are pushed downward, the deep underwater formations being called *keels*.)

In our area of interest, the ice almost completely covers the ocean to a depth of 3.5–10 meters, with the keels dipping to much deeper — sometimes to 30 meters. Water currents have been measured at 25 centimeters per second (0.5 knot) near *Theseus*’s launch site and slightly higher near headlands. Both the ice and the water current affect the maneuvering and safety of the vessel.

Arctic air temperatures are quite often near –40 °C during March and early April — the period when we start our fieldwork. This extreme cold is often hard on both people and equipment. Fortunately, we were able to design portions of the AUV to withstand such temperatures; other parts must be kept relatively warm. Water temperatures, on the other hand, vary from about –1 °C near the surface to about 4 °C at depth. Once the equipment is in the water, therefore, it is no longer in any danger from the cold.

Cable-Carrying Capacity. To lay the cable, return to the launch site, and allow a reasonable safety margin given the 180 (straight-line) kilometers to the array, *Theseus* needed to be able to carry 220 kilometers of spooled cable and have enough stored energy to travel 450 kilometers. Its navigational accuracy had to be better than 1 percent of the distance traveled. Also, to minimize the amount of cable falling through the water, the vehicle had to be able to “fly” fairly close to the bottom without, of course, running into it.

The final main design constraint for *Theseus* stemmed from the need to carry the vehicle to the launch site by small aircraft (either a Twin Otter airplane or a helicopter). This necessitated a modular design, with each section weighing less than 1,400 kilograms (3,000 pounds).

In the end, we created a small (19,000-pound), seven-section yellow submarine that is pushed by a single 24-inch-diameter propeller. Its typical mission speed is 2 meters per second (4 knots), and it can reach a maximum speed of 2.5 meters per second (5 knots). A bank of rechargeable silver-zinc batteries provides 360 kilowatt hours of energy, about twice as much as one mission should require.

The forward section of the submarine’s hull contains a pressure vessel to keep the sea water away from the batteries and all electronics (see Figure 1). The payload bay contains 11 spools, each with 20 kilometers of fiber-optic cable. The cable weighs more than 1,300 pounds in water, so as it winds off the spools from the inside out, *Theseus* gets lighter. To compensate for the lost weight, toroidal ballast tanks surrounding each spool fill with water to maintain the vehicle’s net buoyancy.

Craft Control. The onboard computer managing vehicle operations employs an AUV control system that allows us to use scripts, which are small, self-contained subroutines within the program that are written in a

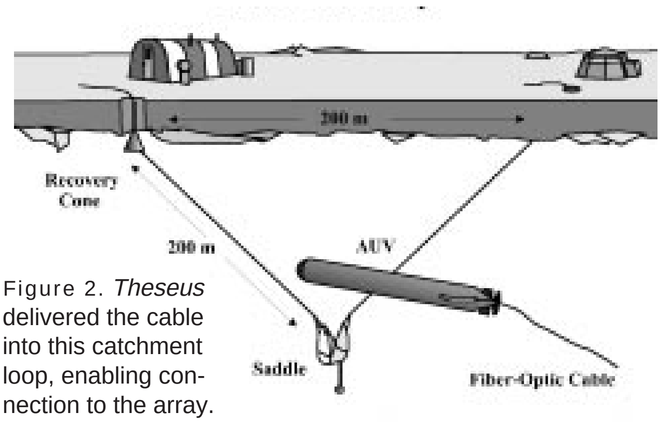


Figure 2. *Theseus* delivered the cable into this catchment loop, enabling connection to the array.

very English-like programming language. The highest-level script, or operation rule, is the mission plan, which delineates the waypoints leading to the array and the speed and depth at which the vehicle will travel.

Theseus also incorporates a fault manager to monitor both external and internal parameters. If any of these fall outside a preset range, the operating system triggers the appropriate response based on preprogrammed scenarios. If, for example, *Theseus* gets too close to the bottom, the fault manager signals an altitude fault; moving too close to the ice generates a depth fault. The AUV's response to the signal will vary depending on the fault's nature and mission circumstances. It may ignore the fault, change to another mission step, or stop just beneath the ice or down on the seabed.

SUBMARINE NAVIGATION

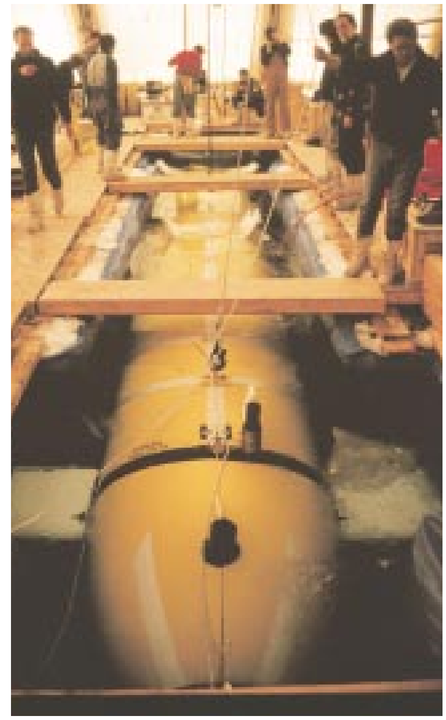
Theseus computes its position en route by dead reckoning. A medium-accuracy INU employs a combination of ring-laser gyros and accelerometers to provide vehicle heading. A bottom-tracking Doppler sonar measures speed over ground. This combination enables vehicle positioning to better than 1 percent of the distance traveled.

This accuracy, however, is not good enough to complete the mission. After all, a 1-percent error over the length of a 200-kilometer track represents a miss of 2 kilometers. And to deliver the fiber-optic cable, *Theseus* must fly through "the eye of the needle." This *eye*, which is a triangular-shaped, rope catchment loop measuring 200 meters on the side (see Figure 2), is suspended from the ice over the bottom-mounted array (at the site known as Camp Knossos).

To increase navigational accuracy, we programmed *Theseus* to head toward intermediate waypoints equipped with acoustic beacons, which we lowered through the ice at strategic locations along the course. Because the craft was making a round trip, touching at a number of sites, we named the beacon locations with a baseball theme: Third Base and Catcher on either side of the loop to help guide *Theseus* through it; Sliding Home near the shore to facilitate navigation through some shallow water; and three more beacons — First Base, Second Base, and Shortstop — at roughly equal intervals along the track.

During the mission, we place the beacons as indicated, determine their latitude and longitude using a P-code GPS receiver, and download these data into *Theseus*'s memory. The craft's programming tells it to automatically start an acoustic interrogation when its dead-reckoning calculations indicate it is close to a beacon. When it gets a response, *Theseus* homes in on the beacon's signal and determines the associated range and bearing. Once it is close enough (100 meters or so), the AUV updates its own position and turns toward the next waypoint.

Telltale Tests. We held our first Arctic trials in April 1995 in Jolliffe Bay, a small bay just 6 kilometers west of Alert. We tested *Theseus*'s navigational accuracy and the range of its acoustic telemetry. This system, which is quite distinct from the acoustic navigation beacons, allows us to communicate with and control the craft by way of acoustic transponders as far as several kilometers away. This ability can prove useful when *Theseus* has problems and stops midocean.



As *Theseus* was assembled, another team cut a 5 × 40–foot hole through 6-foot-thick ice to enable launch into the ocean (left). But what does one then do with the 65,000 pounds of ice? Why "icehenge" of course. The team's creation (bottom) looked quite impressive and provided some enjoyable diversion after much hard work.

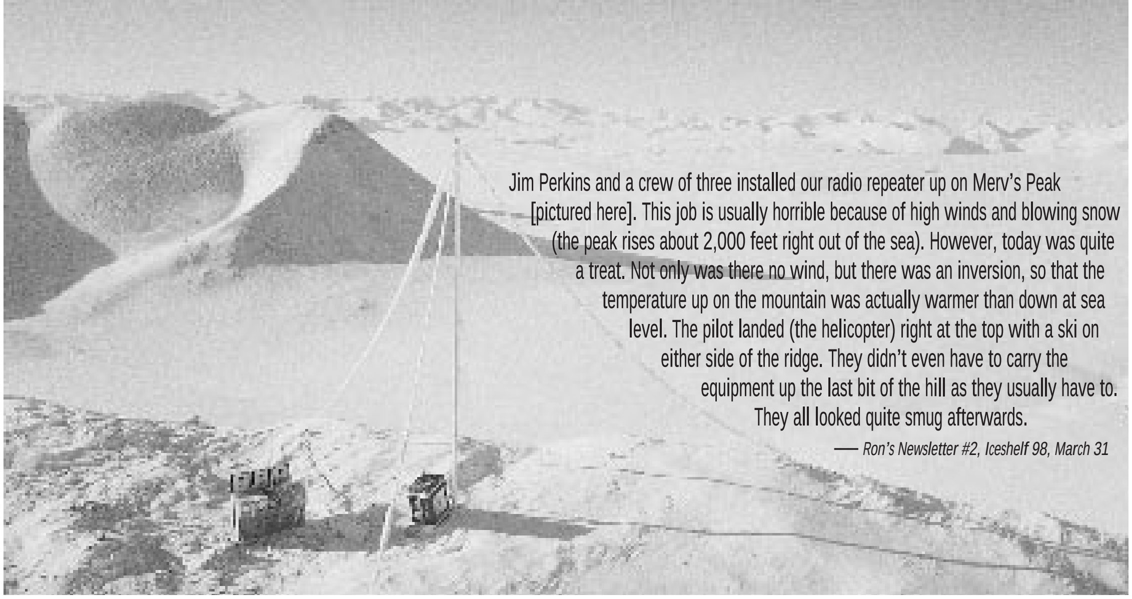
Full-length Trials. In January 1996, we conducted extensive navigation trials at the Canadian Forces Maritime Experimental and Test Range at the Nanoose Range on Vancouver Island. We completed a full-length Arctic simulation to evaluate vehicle endurance and reliability. After some initial adjustments, we reduced *Theseus*'s navigational cross-track error to only 0.05 percent of the distance traveled.

In addition, *Theseus* successfully homed in on beacons and used their location to update its own position. The acoustic telemetry system also performed well, although 40 hours into the run we unexpectedly lost all communications with the vehicle because of an unrecoverable synchronization error in the onboard communications software. We were happy to discover, though, that *Theseus* completed its mission autonomously according to plan. Our AUV was ready for the planned March cable deployment.

THE ARCTIC ADVENTURE

With *Theseus* ready, it was time to head into the Arctic once again and put our craft to the test. Alert would become our home away from home for just over a month.

Staying on the edge of civilization isn't actually so bad, as the accommodations in Alert are reasonably comfortable. When inside the heated sleeping quarters, mess hall, or bar, you



Jim Perkins and a crew of three installed our radio repeater up on Merv's Peak [pictured here]. This job is usually horrible because of high winds and blowing snow (the peak rises about 2,000 feet right out of the sea). However, today was quite a treat. Not only was there no wind, but there was an inversion, so that the temperature up on the mountain was actually warmer than down at sea level. The pilot landed (the helicopter) right at the top with a ski on either side of the ridge. They didn't even have to carry the equipment up the last bit of the hill as they usually have to. They all looked quite smug afterwards.

— *Ron's Newsletter #2, Iceshelf 98, March 31*

can even forget that the temperature outside is probably somewhere between –15 and –40 °C. In fact, we often complain that the buildings are too hot. Out on the ice, we live and work in heated, insulated tents, which some of us find more comfortable because we can adjust the temperature to our liking.

Our missions typically begin right around the spring equinox, when the sun is up for only 12 hours. Just three weeks later, though, we have a full 24 hours of daylight. This actually facilitates our efforts, as one group can work through the so-called night, and another can take over in the morning.

The Arctic's meager snowfall also makes our job somewhat easier, although we must still cut through the ice (to place the beacons, launch *Theseus*, and, during later missions, to repair the cable). The ice can be anywhere from a few inches to 80 feet thick. It pays to be able to judge that thickness when trying to land an airplane or cut a hole in the ice. Landing strips must be on smooth ice that is at least 2 feet thick, although ice this thin has a good chance of being crushed before the field season is over.

When it comes to making holes for our underwater equipment, we like the ice to be as thin as possible if the hole is just temporary, but we want it to be 4 feet or more if we are to be camped at that spot for some time and if there is any possibility of the ice crushing.

Iceshelf 96. Our work out of Alert over the past few years has been given the name "Iceshelf," and the cable-laying mission was known as Iceshelf 96. For that expedition, the Canadian team flew in on five separate CF-130 Hercules flights between March 5 and 28. Two brought people and general freight, one carried a disassembled helicopter, and two others delivered *Theseus*.

As the American team set up their camp on the offshore ice and prepared to install their array, the Canadian team set up a camp at Jolliffe Bay. We erected 11 tents on the reasonably smooth ice, including a very large tent for *Theseus*'s assembly and launch. This shelter, known locally as the Circus Tent, measures 36 × 65 feet. It took 10 people two days to set it up.

After that, we cut a 5 × 40–foot hole through the 6-foot-thick ice with a hot-water drill, hauling away 65,000 pounds of ice. Two traveling gantry cranes were set up inside the tent, and a helicopter air-lifted *Theseus* out to the site. We rushed the pieces inside the tent to keep them from cooling off. On a track inside the tent, the AUV then began to take on its proper shape.

While *Theseus* was being assembled, other team members scouted beacon sites using the Twin Otter aircraft and helicopter. We knew roughly where we wanted the beacons, but their exact placement would be determined by such factors as ice thickness and the availability of a 1,000-foot-long, smooth landing strip.

We used an onboard C/A-code GPS unit to navigate to our desired beacon locations, found a suitable landing strip, and then cut a hole in the ice. As the hole was drilled, we obtained its GPS position with a P-code receiver. We recorded the latitude and longitude and later entered the data into *Theseus*'s mission plan. We periodically checked these positions during the mission to make sure the ice hadn't moved.

CAN YOU REPEAT THAT?

To facilitate VHF communications between the camp at Jolliffe Bay and the remote sites, we install a temporary radio repeater on top of Merv's Peak.

Located 40 kilometers north-northeast of Alert, the peak doesn't actually have an official name — it's too far away from civilization. Geological features that we use regularly, though, tend to get named after someone in our party. In this case, Merv Black had suggested using the peak as a VHF repeater site and had calculated its radio range. Thus, it seemed quite natural to call it Merv's Peak.

The peak is 2,200 feet above sea level, which is high enough to be able to communicate with Camp Knossos, 150 kilometers farther out to sea. The repeater is a standard commercial system. Its electronics fit into a couple of suitcase-size boxes, and its power comes from solar cells with several car batteries as backups. Although we guy the antenna to withstand the area's high winds, it has been known to blow down.

INTO THE LABYRINTH

Out at the array site, 180 kilometers from shore, the Americans were progressing very nicely, although they were having to contend with some ice motion. On April 8, the ice moved 2.8 kilometers, and there was serious concern that they might have to move their camp and do their work all over again. Fortunately, the ice stopped and seemed to stabilize.

The array preparations were finished before *Theseus* was ready, so the Americans had to mark time for a couple of days (a pretty nervous time, we're told). Then, once *Theseus* and all its navigational aids were assembled and programmed, all we had to do was check the weather, take a deep breath, and launch.

Though there were still many unknowns that could affect the mission's outcome, we all felt certain we could successfully lay the cable and recover our yellow submarine. In fact, several of *Theseus*'s designers decided to prove their confidence in the craft's abilities by placing items of sentimental value into the AUV's hull. Engineering iron rings, driver's licenses, pictures of wives, a set of house keys, and a return plane ticket were all placed in the vehicle with much outward bravado (and plenty of internal qualms).

With fingers crossed, we launched *Theseus* from Jolliffe Bay at 0022 on April 17. On the outward-bound track, we could communicate with the vehicle through the fiber-optic cable that it was laying and could therefore monitor its health and position. *Theseus* passed First Base at 0220 and Second Base at 1112, successfully homing in on the beacons and updating its position at both locations.

At Shortstop, we encountered our first problem. *Theseus* could not home in on the beacon because, as we later discovered, the transponder was not functioning. That position update was not strictly necessary, however, and the craft continued

The ice camp at Jolliffe Bay (above) included *Theseus*'s large launch tent in the middle and 10 other smaller tents for sleeping, storage, meals, and other work. The AUV had to be airlifted to the site in pieces (left), with garbage bags placed on the ice to indicate the helicopter's landing site.

to Third Base as programmed. There, it ascended from 420 meters to 30 meters in preparation for flying through the catchment triangle. It completed a successful homing at 0118, April 18.

Theseus then traveled, in a line perpendicular to the catchment triangle, toward Catcher and the Knossos array site, about 1.6 kilometers away. Initially, the AUV received good homing signals from Catcher, but as it approached the loop, the homing capability deteriorated. This forced those monitoring the mission's progress back at Alert to take control by way of the fiber-optic cable. They issued a couple of minor course corrections to pilot *Theseus* through the loop and park it up against the ice some 600 meters beyond. To do this, they used position information obtained from a surface-based acoustic tracking system at Knossos and relayed to Alert by way of radio.

After we retrieved the cable from the catchment loop and pulled 1 kilometer of excess cable up onto the ice, mission controllers back at Alert adjusted the AUV's ballast for the trip home and commanded it to return to the launch site, again using the fiber-optic link. We then cut the cable, which permanently isolated *Theseus* from any help or control. Its voyage home would be truly autonomous.

The craft returned by way of Shortstop (where we had installed a new transponder), then on to Second and First Base. At First Base the vehicle failed to complete the homing, causing *Theseus*'s fault manager to activate. It instructed the AUV to stop, park beneath the ice, and await further instructions by way of acoustic telemetry. A field team took a telemetry unit to First Base, where a controller contacted the craft and sent it back on its way. At 1140, April 19, *Theseus* parked itself at the launch hole in Jolliffe Bay. Success!

With the array hooked up and running and *Theseus* back on the surface (with everyone's personal effects), we all breathed a sigh of relief. We had proved that existing technologies can be combined to create an AUV that will lay fiber-optic cable under the polar ice to connect a submerged array with its land-based monitors.

Little did we know, this Arctic adventure was not over.

AN ARCTIC ADDENDUM

Although the Spinnaker Array was designed to operate for three to five years, its data flow suddenly stopped on June 20, 1996, about two months after the installation. Something had cut off the optical signal carrying the sensor readings.

To assess the problem, one of our team members went to Alert with an optical time-delay reflectometer (OTDR) to look down the cable. The OTDR sends out a burst of laser light and receives the reflections produced by such things as splices, kinks, or — the ultimate reflector — a break. From the light's round-trip time, the device computes the distance to the discontinuity. We found that the cable was good out to at least 160 kilometers, the OTDR's maximum range. We were uncertain, therefore, whether the fault was caused by the electronics at the array site or by a break in the cable beyond the 160-kilometer limit.

Iceshelf 97 — here we come.

Recon, Repair, Restore. The 1997 repair mission had several goals: to determine the cause of the telemetry loss, to repair the array node and/or the fiber-optic cable, and, if possible, to restore the entire setup to working order. (We call the pressure vessel holding the underwater electronics and laser a *node*.) Through extensive cooperation, the U.S. and Canadian project participants (most of whom were involved in Iceshelf 96) developed a detailed plan for the node/cable inspection and repair.

A Sticky Situation. As both teams considered the possible causes for the malfunction, we (particularly the Canadians) initially thought the problem probably lay with the array itself. We figured that once the cable was safe on the bottom of the ocean, it would be all right. Although the cable is only 2 millimeters in diameter, its breaking strength is more than 200 pounds. Some of us, however, did suspect that all was not well.

During deployment, the weak glue that held the cable in its spool should have produced a pull tension of 1–2 pounds. The company that wound the cable had found it difficult to maintain the desired weak bond, though, causing the tension to be too high as *Theseus* moved through the water and released the cable.

It is possible that the strong glue weakened the cable in places, perhaps by kinking it slightly as it pulled away from the spool. Then, after strong currents had worried it for several months, the cable broke at one of these weak points. We wouldn't know for certain, however, until we could return to Alert and use a more powerful OTDR to check the cable. We therefore came prepared to both replace the array node and splice the cable.

From AUV to ROV. The most important piece of equipment for any underwater repair is a remotely operated vehicle (ROV). In ocean-bottom work, such a craft is both the eyes and hands of the operators up top.

Fortunately we already had a very effective ROV — a *Phantom*, made by Deep Ocean Engineering. We had used the *Phantom* as a tender for *Theseus* during the cable installation in 1996. For example, the ROV attached the lines to *Theseus* that allowed us to pull the AUV up to the ice hole.

Unlike an AUV, *Phantom* is powered and controlled from the surface. The electrical power for the thrusters, the video signal from the underwater cameras, and the control signals for these two components are all passed through a cable known as the umbilical. It is fairly large (about three-quarters of an inch in diameter) so that it can carry all the necessary wires.

For the 1997 repair job, we acquired some attachments so that *Phantom* could grab our cable on the bottom and cut it. The ROV required no other significant changes, though, and

Outfitted with an underwater camera and an attachment to grab and cut the cable, the ROV *Phantom* (above) was lowered many times through ice holes and into the Arctic Ocean, enabling an initial cable connection and multiple cable repairs.

we were fortunate to already have several skilled operators who could participate in the repair efforts.

ICESHELF 97

Our 1997 mission officially began on March 24, when the first team members landed back in Alert and began onsite preparations for the repairs. A large contingent arrived the next day, and one of the first things we did was recheck the fiber-optic cable. We employed a more powerful OTDR in hopes that we could see out to the exact source of the problem. What we found, however, was a break only 14 kilometers from Alert — a break that had not been there the previous June.

This break was in shore-fast ice — ice that would not move with the wind or current. The array location, on the other hand, was associated with ice that would quite easily set sail in a good wind. We consequently decided to work at the outer location first, as it was going to be harder, and we could do the 14-kilometer site at any time.

After losing a few days because of a malfunctioning hydraulic motor in the Twin Otter, we finally made it out to the array site and established a small camp (Knossos). By April 1, both the helicopter and the airplane were busy hauling equipment to the site. From the beginning, we kept a very close watch on the camp's position, monitoring its location with a P-code GPS receiver.

On April 3, just as the hole drilling was about to begin, the ice started to move. It moved 340 meters that day and then 250 meters overnight. We decided to put this site on hold and work at Camp 14 until the motion had stabilized. (For easy identification, we simply named each camp after its distance from the shore. Camp Knossos, of course is the exception.)

We stationed two people at Knossos to look after the camp and provide P-code GPS positions and weather reports. The rest of the team concentrated on the break at 14 kilometers. Using the OTDR distance measurement together with *Theseus*'s navigation data from the previous year, we determined the coordinates of the break. We took the helicopter out to the site, walked the area until we found reasonably thin ice (only 6 feet thick), and set to work cutting a hole for *Phantom*.

We also cut two splice holes 400 meters to either side of the ROV hole. *Phantom* later strung a tag line between the two holes, which we used to pull a piece of fiber-optic cable from one hole to the other. We would eventually splice the north and south ends of the underwater cable to the new section and drop it back to the bottom. Of course, we first had to find the broken cable. The first day's search located the seaward end of the cable, with the shoreward end showing up the next day.

Immobile Ice. On April 10, our attention once again shifted to the Knossos site, as the ice there had been stable for several days. Because the American team (our array electronics experts) was scheduled to leave a week later, the array took priority. So, we packed up all but one tent and moved to Knossos.

We put a 12 × 20 tent over the ROV hole, a 10 × 10 tent over the ROV's diesel power generator, and slung the so-called tent-on-a-sled over the splice hole. *Phantom* began work at the Knossos site on April 11, easily locating the pile of fiber-optic cable on the sea floor near the array. (This was the extra kilometer of cable spooled off after *Theseus* delivered the link.)

Unfortunately, a kink developed in *Phantom*'s umbilical cable about 50 feet behind the vehicle. As *Phantom* looked for the cable end, the kinked umbilical swept up loops of fiber-optic cable such that, by the time the problem had been discovered, the tangle was too severe to undo underwater.

As the ROV pulled the whole mess to the surface, the fiber-optic link broke, leaving operators with only the shoreward-going cable in hand. To add insult to injury, a quick OTDR reading on that end revealed another break 10.065 kilometers away, probably the original break that necessitated the repair expedition in the first place.

Unfortunately, luck continued to elude us, as *Phantom* was not able to retrieve the cable leading to the array. Had we been able to, we would have discovered right then that the array nodes were in fact working perfectly. Because this was not possible, we sent *Phantom* down again to retrieve the array.

Even more challenges confronted us during this process, but we ultimately brought up the array's node. The Americans installed a new one, which they connected to the shoreward-going cable. We then placed the entire package back on the sea floor. Not long after wrapping up this work, the ice started to move again. But by this time it no longer mattered; the 12 of us were already in a small tent enjoying a well-earned party.

Back at Camp 14. After the brief celebration, we returned to our camp at the 14-kilometer break. We hoped we would be able to return and fix the newly discovered break 10 kilometers from the array, but at that time, the ice in its neighborhood was much too rough. The obvious thing to do was work at Camp 14.

The weather and various complications with *Phantom*'s equipment — such as the clamp falling off as it tried to grab and bring up the cable — occasionally interrupted our efforts, but we eventually completed the repair. Unfortunately, when we looked down the cable toward the array, the OTDR encountered another break 14.4 kilometers away. So long Camp 14; hello Camp 28.

We attempted to locate both ends of the cable at Camp 28 but encountered several setbacks. We mapped the cable position as best we could, but our time had run out. We were forced to pack up and return to Alert.

Plans for Iceshelf 98 were already in the works.

BACK ON ICE

Our third year out on the ice for Project Spinnaker began on March 30, 1998. We knew of two breaks in the cable, at 28 and 160 kilometers from Alert, the latter one being the one we found 10 kilometers from the array. We also knew of a kink (an attenuation in the light transmission of about 10 decibels) at about 15 kilometers from shore. We budgeted one week for each repair. Our previous experiences certainly helped prepare us for this expedition, but of course the Arctic is an unfriendly place for machines, and it is always unpredictable.

Camp 160. On April 1, we flew to the approximate break site at Camp 160 and started to monitor the ice motion. Two days later, we determined that the ice had moved 2.6 kilometers. That is a lot of motion, so all we could do for the time being was cross our fingers and hope it settled down.

Fortunately, this year we wouldn't need to return to the site every day to check its location. Jim Perkins, one of our indispensable technicians, had devised a remote location monitor. This device, which became known as Perkins's Box, employed a single-board, eight-channel GPS receiver to determine its position and an older-model computer to act as the on-ice controller. The entire package ran off a couple of car batteries. Jim says that the whole thing cost very little, and he put it together in a day or so.

Every minute the controller grabbed a new position; and every three hours it took an average of these positions, turned on the VHF transmitter, and sent out the averaged readings for the past nine hours. Thus, every reading was sent three times, which allowed for possible bad reception on our end. For simplicity, Jim set the 300-baud modems to simplex (no handshaking).

Although this monitoring method didn't give P-code accuracy, it did save us from having to leave two valuable team members at that camp.

SEARCH AND REPAIR

Our repair efforts during Iceshelf 98 proceeded much like the previous year. *Phantom* started off by blowing power transistors and refusing to cooperate, but once fixed, it gave flawless service.

After much initial ado at Camp 28, we located the cable ends only to find two more breaks nearby. We were able to pull the cable onto the ice and past those two spots, only to discover yet another break 4 kilometers away (toward the array).

After successfully fixing the sections at 28 kilometers, we debated about how to proceed. Perkins's Box told us that Camp 160 was continuing its headlong rush toward Greenland, so we decided to set up Camp 32 and begin repairs there.

Phantom found the cable at the 32-kilometer site relatively easily, but it couldn't locate a break. We decided to cut the cable, pull it onto the ice, and use the OTDR to pinpoint the problem. We managed to grab the cable and cut it, but a few snags turned the rest of the process into an exercise in frustration.

Caught in the Loop. As we pulled the cut cable toward the hole in the ice (with a tag line), it became looped around the rocks on the sea floor and stopped dead. We sent *Phantom* down to help clear the snag, but the cable caught almost immediately another rock. To make a long story short, we used the ROV to lift the cable over many dozens of rocks before we finally pulled it onto the ice.

We experienced similar difficulties with the other end of the cable but eventually managed to splice the two parts together. Then, for once, good news: We could see all the way to the 160-kilometer break and to the 15-kilometer attenuation. This meant we only had those two problems left to address. The complete repair of the cable was still possible.

Camp 15. After moving all necessary equipment to Camp 15, we lowered *Phantom* through its hole and went down after the cable. We found the cable fairly quickly, cut it, and brought the north-going end to the surface. An OTDR check revealed a continuous line out to the 160-kilometer break. We pulled the south-going end up,

Jim Perkins stands with his GPS box, which enabled remote ice movement monitoring during Iceshelf 98. Two bamboo poles lashed together support the antenna, with the electronics in an aluminum box, car batteries in wooden ones, and solar cells leaning against them.

used the OTDR to locate the fault 153 meters away, and continued to pull the cable to the surface for the repair.

The cable unfortunately snagged about 20 meters from the section needing repair and broke. We therefore needed to drill a new splice hole to access and fix the break. Once that task was complete, the rest of the repair proceeded without hindrance. Three down, one to go! The date was April 14.

Perkins's Box showed that the ice at Camp 160 was still moving. In spite of this, we moved all necessary equipment to that area, hoping the ice would stabilize. It was wait and watch time.

On April 17, the ice had been stationary long enough to attempt the repair. We searched for the cable for days, frustration mounting as the cable continued to elude us.

Mystery Movement. Although we eventually found the south-going cable — 600 meters away from where it had been laid — we couldn't figure out what had caused the motion. Now that we have had a chance to investigate the mystery, the most plausible conjecture is that a data buoy (perhaps Russian) drifted into these shallow waters. The buoy's weight, dragging on the bottom, may have snagged the cable and pulled it until it broke.

The search for the other end of the cable continued for another six days, another six camps, and another six *Phantom* holes cut through the polar ice. People were working very hard, putting in long hours, and getting very frustrated. Finally, at 1157, April 26, the radio came to life with John Newton's voice: "Houston, Houston, we've found the cable!"

After looking for its end for almost two hours, we decided to cut the cable and bring it up to be spliced to the shoreward link. As luck would have it, the ice had started to move once again, so expediency became critical.

Disappointing Development. At 1703, the people on the ice called in to say that they had looked toward the north with the OTDR. They had found yet another break at a range of 3.5 kilometers. Unlike a dime novel, this story may not have a happy ending.

Shocked and unable to even discuss our options, we completed the splice and dropped the cable away. The ice was still moving and the Americans, who formed much of the crew, had to leave Alert on April 30. After much discussion and several schedule changes, those who could stay decided to try a fifth repair. We placed Perkins's Box out near the break and waited. We would monitor the ice until it either stopped moving or we ran out of time.

It didn't stop, and sometime on May 2, we passed the "drop dead" hour. All possibility of fixing the last break had vanished. We shifted our attention to bringing back the equipment and packing up for the journey home.

We are, of course, quite disappointed that we never got the cable completely fixed. We have to keep reminding ourselves that we did do far more than we had planned. Six months ago, we were looking at doing two repairs. We budgeted time and resources for three, just in case. And many people (including me) thought we would be hard pressed to finish three. We ended up doing four repairs, and, with a little timetable juggling, we had time enough to do a fifth. In the end, the ice motion and weather were the factors that put a halt to the work. I am sure that we set a number of records for the repair of fiber-optic cable under the ice of the Arctic Ocean. (We had a good time, too.) I am pleased to have been a member of this very proficient and knowledgeable team. — *Ron's Newsletter #33, Iceshelf 98, May 2*

DEAD IN THE WATER

By now, the array's sensor batteries have run out and its preamplifiers are dead, as they were only designed to work for three years. We currently have neither funds nor plans to test the technologies further. With defense budgets being cut and the Arctic having a relatively low priority, the future doesn't hold much promise for projects of this magnitude.

None of us, however, feel our efforts were wasted. We proved out the technology of installing a large array and cabling it to shore. We learned a lot, and if we had to do it again, we would have a running head start.

Technical Thanks. Through the years, we have come to appreciate the technologies that support our efforts in the Arctic. Some, of course, we consider tried-and-true: airplanes, helicopters, hot-water drills, VHF communications, and so forth. But others still have the aura of newness about them: underwater vehicles such as *Theseus* and *Phantom*, autonomous and remote navigation, fiber-optic telemetry, and the marvelous accuracy of GPS. We would be hard-pressed to do what we did without every one of them.

In fact, every now and again we can't help but be a bit wonderstruck. Just think, we traveled to the middle of the Arctic Ocean, drilled a hole in the ice, sent down an ROV to look for a cable, and there it was! And nobody was even surprised, let alone amazed, that we had found the tiny X that marked the spot. ■

MANUFACTURERS

For positioning and navigation in the field, Project Spinnaker participants used **Magellan** (San Dimas, California) 5000DX receivers and **Garmin** (Olathe, Kansas) 45 GPS units, as well as a **Rockwell** (Cedar Rapids, Iowa) P-code receiver. They also used two Magellan 5000 Pro receivers (one roving, one fixed) and postprocessing software to conduct ground truthing for the inertial navigation unit. The support helicopter employed a MX9112 GPS receiver and a MX50R beacon receiver from **Magnavox** (El Segundo, California). Perkins's Box combined a **Motorola** (Northbrook, Illinois) Oncore GPS receiver with a **Tandy** model 100 computer.

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Bruce Butler, *P.Eng., obtained his B.Sc. in computer science and physics at the University of British Columbia in 1983. Employed by ISE Research from 1985–1997, he was the systems engineer for the* Theseus *project and responsible for the vehicle's inertial/acoustic navigation system. Butler is currently with Offshore Systems Ltd. (North Vancouver), where he is responsible for the engineering of several differential GPS networks. He always travels with his GPS receiver.*