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TITLE

USE OF UNDERWATER VEHICLES FOR ARRAY SYSTEM INSTALLATION AND RECOVERY

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Use of Underwater Vehicles for Array System Installation and Recovery

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ABSTRACT

A suite of underwater vehicles has been utilized in the deployment and recovery of acoustic and environmental arrays under the Arctic ice pack. The vehicles performed a variety of tasks including the deployment of 175 km of fibre optic cable, recovery of moorings and equipment under the ice and on the bottom, deployment of working lines for acoustic arrays, and visual inspection. The vehicles range from the autonomous 8,600 kg Theseus vehicle to the tethered 9 kg Seamor vehicle. The capabilities and effectiveness of the commercial off-the-shelf and project designed vehicles will be discussed as well as potential future applications.

1. INTRODUCTION

Commencing in 1988, joint CAN/US ICESHELF experiments were executed in the Lincoln Sea, north of Ellesmere Island, NWT, Canada. These experiments were designed to resolve various aspects of underwater system design and installation in ice-covered waters. This was followed in 1992 by a joint CAN/US undertaking, sponsored by the US Department of Defense and the Canadian Department of National Defence, to install a bottom-mounted research system and associated cable to shore, based on design concepts and lessons learned from the previous work. The permanent ice cover in this area necessitated the use of a range of underwater vehicles to assist in the deployment and repair of various underwater system components. The paper gives a brief description of the underwater system and discusses the capabilities and effectiveness of the vehicles used for system deployment. The vehicles include two custom-built autonomous units, the 8,600-kg Theseus designed for cable laying and the 9-kg Autonomous Line Delivery Vehicle (ALDV) designed for stringing lines under ice, and two commercial off-the-shelf tethered vehicles, a 227-kg Phantom, and a 9-kg Seamor. Because other information is available on the Phantom and Seamor ROVs, this paper will concentrate on the custom-built vehicles.

2. UNDERWATER SYSTEM DESCRIPTION

The underwater system, shown pictorially in Figure 1, consists of a large multi-element bottom-mounted array connected to shore by a small-diameter fibre optic cable. A schematic of the array is shown in Figure 2. It consists of two 20-element vertical line arrays, an 80-element, 2,400 m-long horizontal array line array and a shorter 8-element, 250 m-long cross horizontal array, plus associated underwater nodes and batteries.

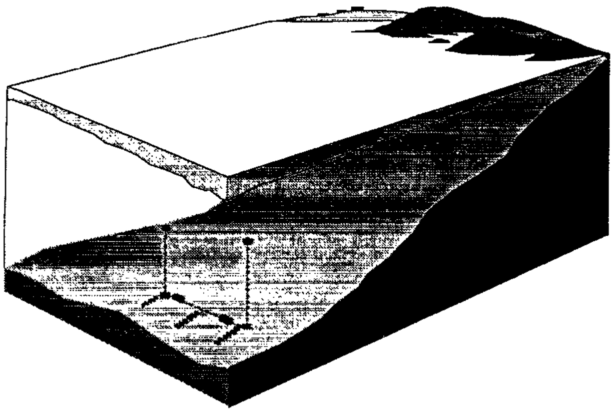


Figure 1. Underwater system

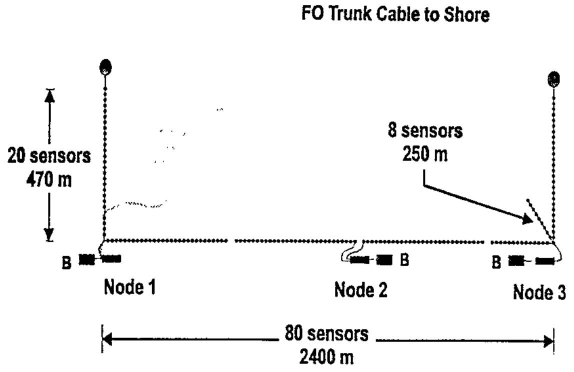


Figure 2. Underwater array schematic.

3. UNDERWATER VEHICLES UTILIZED

3.1. THESEUS

From 1992 to 1996, International Submarine Engineering Research and the Esquimalt Defence Research Detachment of Defence Research Establishment Atlantic worked together to develop a large autonomous underwater vehicle for laying fibre-optic cables in ice-covered waters [1]. The vehicle, named Theseus, was designed to lay up to 220 km of fibre-optic cable. The water depth along the cable route varies from 50 m at the launch site to between 500 and 700 m at the array site.

3.1.1. VEHICLE DESIGN OBJECTIVES

Both the environment and the complexity of the mission imposed severe constraints on the vehicle design. In the operating area the ocean is completely ice covered, mostly by multi-year ice, 3.5 to 10 m thick, with ice keels that can extend to depths of 30 m within 10 km from the launch site, and 50 m further out; water currents vary from 0 cm/sec up to 50 cm/sec near the launch site, and up to approximately 10 cm/sec at the array site; air temperatures vary from -40 to -20° C during the only possible deployment period (late March to early May); and water temperatures vary from -2° C just under the ice to +4° C near the bottom at a depth of 600 m.

To lay the cable, return to the launch site and allow a safety margin required a 450 km endurance and a 220 km cable capacity. The system required a navigational accuracy within 1% of distance travelled, and needed a terminal homing system for the final run-in to the array site. To minimize the amount of cable in the water column, the AUV was required to follow the bottom at an altitude of 20 to 50 m. To facilitate air transport to the launch site, a modular construction was required, with each section weighing under 1400 kg. Since no current AUV could provide the required features, International Submarine Engineering Research Ltd. of Port Coquitlam B.C. was awarded a contract in November 1992 to design and construct an AUV to meet the requirements.

In addition, it was determined that an obstacle-avoidance sonar (OAS) system would be required to ensure that the vehicle would not crash into uncharted bottom features or into ice keels. Acoustic telemetry was also considered essential for occasional enroute communication with the vehicle. The vehicle needed a precise terminal guidance system to facilitate cable recovery A provision was included to allow the vehicle to update its position at acoustic beacons located along the route and also at the cable delivery site. Details on the resulting vehicle are provided in the next section.

3.1.2. THESEUS DESCRIPTION

A cross-section of the Theseus AUV is shown in Figure 3. The principal characteristics of the vehicle are listed in Table 1.

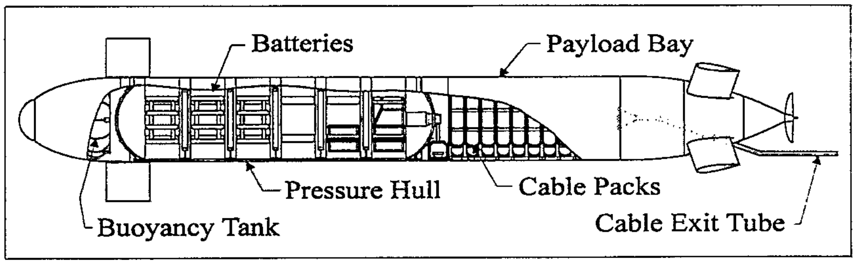


Figure 3. Theseus schematic (foreplanes, exit tube in plan view, remainder in elevation view)

Table 1. Theseus vehicle characteristics.

Length	10.7 m (35 feet)
Diameter	127 cm (50 inches)
Displacement	8600 kg (19,000 lbs)
Speed	2 m/s (4 knots)
Range	700 km (380 nm)
Maximum operating depth	425 m verified, 1000-m (3280-foot) design depth
Cable capacity	220 km
Navigational accuracy	achieved ~0.5% of distance travelled
Propulsion	6 hp brushless dc motor and gearbox / single 61 cm diameter propeller
Power	360kWh Silver Zinc battery pack consisting of 280 individual cells manufactured by Yardney. 450 km mission plus an additional 24 hours of hotel load with a safety factor of two.
Variable ballast	±95 kg (250 lbs) in each of 2 toroidal tanks, 1 fore and 1 aft
Controller	Proprietary real-time kernel running on MC68030 microprocessor
Navigation systems: Transit	Honeywell MAPS Inertial navigation unit EDO 3050 Doppler sonar (bottom tracking)
Terminal Homing	Datasonics ACU-206 acoustic homing system. Ranges up to 10 km in 500m-deep water.
Acoustic Telemetry	Datasonics Model ATM851 using Multiple Frequency Shift Keying (MFSK) plus error encoding operating in the 15 to 20 kHz band.
Fibre Optic Telemetry	Used on outbound leg of mission for vehicle status. Allows operator to assume control
Emergency Beacons	ORE 6702 acoustic transponder located in the tail section. Interrogated with ORE LXT ultrashort-base-line acoustic tracking system operating at 11kHz.
Obstacle Avoidance	Sonatech STA-013-1 forward-looking sonar. 5 by 4 beams.
Pressure hull	5 cm-thick Aluminum (7075), 4.5 m by 127 cm diameter in 5 sections plus end domes. Design depth 1000 m.
Payload Bay	Free-flooding fiberglass shell with syntactic foam lining, top half removable. Inner diam 114 cm, length 228 cm. Payload up to 1960 kg dry, 320 kg in water.
Current Payload	11 packs of 20 km cable, each weighing 60 kg in water. 11 toroidal compensation tanks fill as cable paid out. Tank inner diam 76 cm (30 in).
Transportability	Modular construction in sections under 1400 kg each.

In order to increase the fault tolerance, Theseus manages fault responses using a pre-defined fault table. This table allows the user to divide a mission into any number of phases, where a phase consists of one or more manoeuvres between waypoints. Each phase of a mission script has its own set of responses to each of the vehicle faults: a response is either stop up under the ice, stop down to the sea bed, change to another mission step, or ignore the fault. Therefore, a change of phase occurs when the desired response to some fault changes, such as when approaching a manned camp. At this point a new set of entries in the fault table takes effect. It was decided that 18 phases adequately provided for the changing circumstances during the Arctic mission.

Designing a navigation system to allow an AUV to navigate autonomously under-ice for more than 400 km was a challenge. The presence of a permanent ice cover requires that all sensors used to determine position had to be located below the ice cover but not necessarily on board the vehicle. The chosen solution for navigation was to use an onboard, medium-accuracy positioning system for outbound/inbound transits, and an external, but subsurface, terminal-guidance acoustic positioning system for cable delivery and vehicle recovery.

Theseus monitors its position by dead reckoning. It uses a Honeywell medium-accuracy inertial navigation unit (INU) and a Doppler sonar. The INU provides heading and attitude data, while the Doppler sonar measures forward and lateral ground speeds, as well as altitude above the seafloor. This combination provides positions with an error of approximately 0.5% of the distance travelled, well within the 1% design goal.

The cable is stored on a series of spools which are stacked longitudinally along the vehicle axis. Adjacent spools are spliced together prior to launch. The cable and splices wind off the spools from the inside-out, and exit through a tube in the stern. The tension on the cable (to keep it from free-spooling) is maintained through the use of a special glue applied to the cable during the spooling process. To keep the system simple and reliable, no active tensioning or dispensing devices are used.

As the cable leaves the vehicle, weight is lost. To prevent this from affecting vehicle trim, the loss in cable weight is counteracted by an automatic buoyancy compensation system. Surrounding each cable spool is a toroidal hard ballast tank which is filled with water as the cable is dispensed from its companion spool. This keeps the net buoyancy of each spool/tank assembly near neutral.

3.2. ALDV

The Applied Physics Laboratory (University of Washington) developed and used an autonomous undersea vehicle for gathering environmental information under the ice in the Beaufort Sea [2]. It is launched from one ice hole and runs a preprogrammed course, returning to the original launch hole, or it can be sent to another ice hole with a homing beacon. APL-UW modified the vehicle to deploy a kevlar line enabling it to string a messenger line between a series of ice holes, which would then be used to run stronger lines for utilization in an under-ice deployment of an array.

The vehicle is an untethered, battery powered unit with various sensors for vehicle guidance and control. It is 1.54 m in length and 8.9 cm in diameter. It weighs approximately 8.2 kg in air and is trimmed to an average of 115 g positive buoyancy. Its maximum operating depth is 75 m and its typical speed is 4 knots. ALDV is powered by a 5.4 ampere-hour, lithium/sulfur dioxide battery pack that gives the vehicle a 3 hour endurance at 1.8 m/s. It has been modified to carry a 1,400 m spool of 80 pound break strength kelvar thread, which is secured at one end and deployed by the vehicle's progress through the water. The vehicle records all the sensor and control data during each run. A cross-section of ALDV is shown in Figure 4. Figure 5 shows ALDV in a typical line stringing mission.

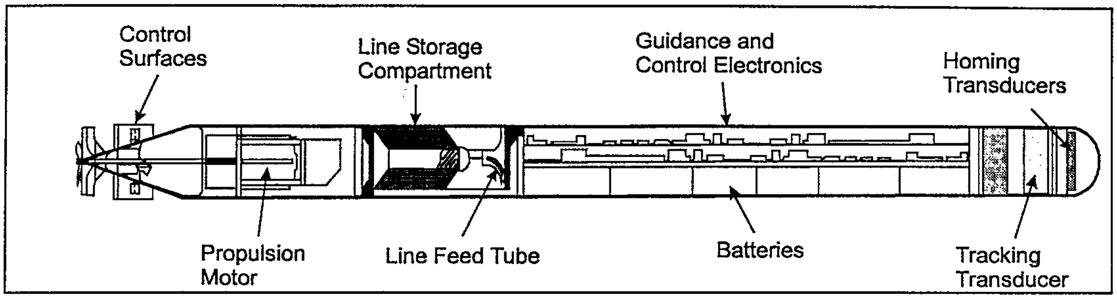


Figure 4. Cross-Section of ALDV

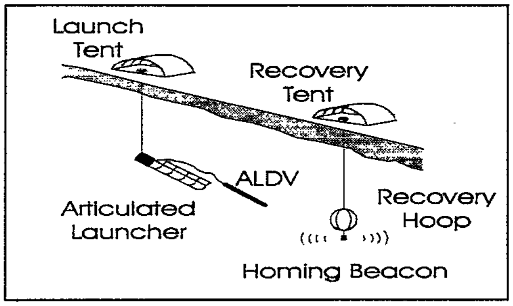


Figure 5. ALDV Stringing Line

ALDV is controlled by an onboard microprocessor that uses a real-time, interrupt-driven operating system for active guidance control. For ICESHELF operations the vehicle operated exclusively in homing mode since the run geometry was always a straight line. The homing system, consisting of electronics, hydrophones and external acoustic beacon, is designed to allow the vehicle to determine range and bearing to the beacon once every 2 seconds. The phase difference between the signals received by two nose-mounted hydrophones is used by the vehicle guidance computer to determine the bearing to the homing beacon. In addition, synchronization of the vehicle and homing beacon via an external precision clock enables the guidance computer to determine the distance to the homing beacon based on the arrival time of the homing pulse.

ALDV is held and lowered through the ice in a device called the articulated vehicle launcher. The vehicle is lowered through a 20 cm-diameter ice hole and is oriented in the proper direction prior to launch. Launch depth is typically 25 m.

The main recovery method is the recovery hoop as depicted in Figure 5. The vehicle homes on a beacon positioned just below a 5-m diameter hoop positioned at the steady-state run depth. As the vehicle passes the beacon, the kevlar line is, ideally, strung through the hoop or can be snagged on hooks on the outside of the hoops if the vehicle does not pass through. The vehicle shuts down automatically and rises to the surface when it senses that the range to the beacon is increasing rather than decreasing. The hoop is then brought up through the ice hole with the captured line. The vehicle can then be pulled back to the hole with the line.

If the vehicle doesn't pass close enough for the hoop to capture the kelvar line, the first backup recovery option is to use the Seamor ROV. The automatic shutdown should leave the vehicle in the vicinity of the recovery ice hole. The Seamor vehicle will then search the area until visual contact is acquired. Seamor attaches itself to ALDV with a grabber device and then both vehicles are pulled back to the recovery hole with Seamor's umbilical.

In the event that the above two options fail, the final option is to pull the vehicle all the way back to the launch hole with the kevlar line. The vehicle is recovered, but the line is not successfully deployed.

3.3. PHANTOM

The primary tethered vehicle used for system deployment and recovery was the Phantom DHD2+2 ROV manufactured by Deep Ocean Engineering of San Leandro, CA. It was used to attach lines to Theseus for recovery, string lines between ice holes, and cut cables and attach lines to cables for system recovery and repair. Phantom was also a backup for ALDV for stringing lines for array deployment, although it wasn't used. The relevant characteristics of Phantom are listed below:

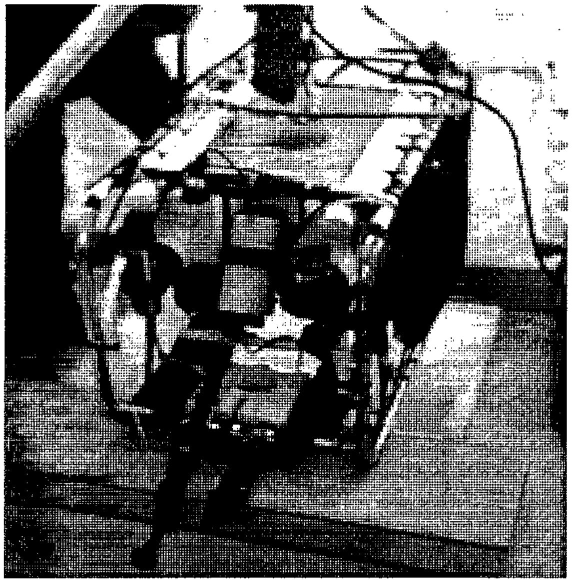


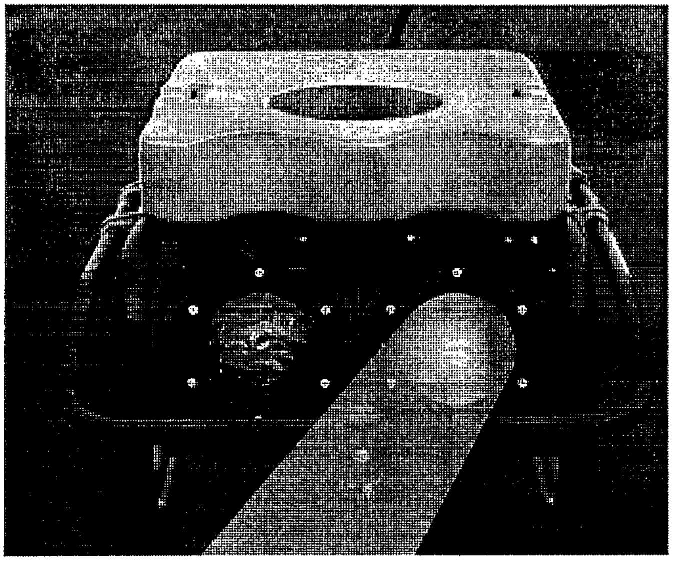
Figure 6. Phantom ROV with DOE cable grabber on right, NRaD grabber on left.

- rated to 610 m operating depth
- 3 knots horizontal speed on a 700 m tether
- 0.5 knot vertical and lateral speed
- dimensions: 143 x 72 x 77 cm
- weight: 227 kg with all accessories mounted
- high resolution NTSC CCD Colour Camera
- 2-250 watt tungsten halogen lamps
- 4 horizontal thrusters of ½ HP each
- vertical and lateral thrusters of ¼ HP each
- precision TCM1 magnetic compass
- Mesotech 971 colour imaging sonar system
- ORE LXT underwater tracking system
- 2nd black and white low lux video camera
- ports for 2 DOE single function manipulators
- DOE cable grabber (attached to manipulator)
- EDRD-designed cable cutter
- NRaD-designed releasable cable grabber

The Phantom, as used in the Arctic is shown in Figure 6. It has proven to be a very useful vehicle for system deployment; it is robust, easy to maintain and operate, and it is capable of operating in currents of up to 1 knot. Vehicle positioning is achieved by using the ORE LXT Short Baseline Tracking system. This system is comprised of a master unit suspended below the launch tent and a transponder unit mounted on Phantom. Reliable range and bearing information was obtained for all situations up to the maximum range of the tether.

3.4. SEAMOR

The fourth underwater vehicle used for system deployment was the SEAMOR tethered vehicle manufactured by RSI Research of Victoria, B.C., Canada. SEAMOR, shown in Figure 7, is a very small, light-weight ROV, which is easy to deploy and operate. Its main function in the system installation was to aid in recovering ALDV and to carry out underwater inspections of system components prior to lowering to the bottom. It was also instrumental in the recovery of current meter moorings which were acoustically released and floated to the surface. Its relevant characteristics are listed below:



- rated to 50 m operating depth
- up to 1.5 knots horizontal speed
- 70 m tether
- dimensions: 35 x 26.6 x 22.5 cm
- weight: 9 kg in air
- 100 watt quartz variable intensity lamp
- 2 horizontal thrusters
- 1 vertical thruster
- maximum power - 500 watts
- CCD Colour Camera
- Imagenex 855 subminiture imaging sonar system
- Sony HI-8 video recorder

Figure 7. SEAMOR ROV

4. SYSTEM INSTALLATION

The underwater system installation was carried out in two separate phases: the array installation in which the array was deployed from the ice surface and lowered to the bottom, and the cable installation. The array was installed from Ice Camp Knossos. The cable was deployed from Jolliffe Bay to Knossos, a distance of 175 km to the north. A map of the general area is shown in Figure 8 and a more detailed map of the area close to shore is shown in Figure 9

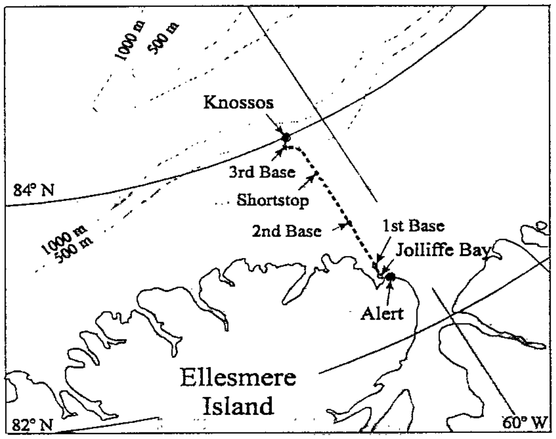


Figure 8. Cable route and beacon locations.

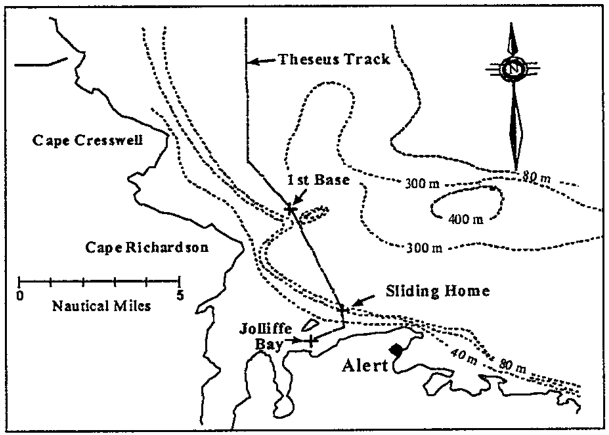


Figure 9. Near-shore locations

4.1. *ARRAY INSTALLATION*

The array was deployed from Ice Camp Knossos, located on the only large ice floe in the target area. The camp, which was established on 5 April, consisted of 14 shelters spread over a distance of 3.75 km. A schematic of the camp layout is shown in Figure 10. Also shown in the figure are the ALDV run distances.

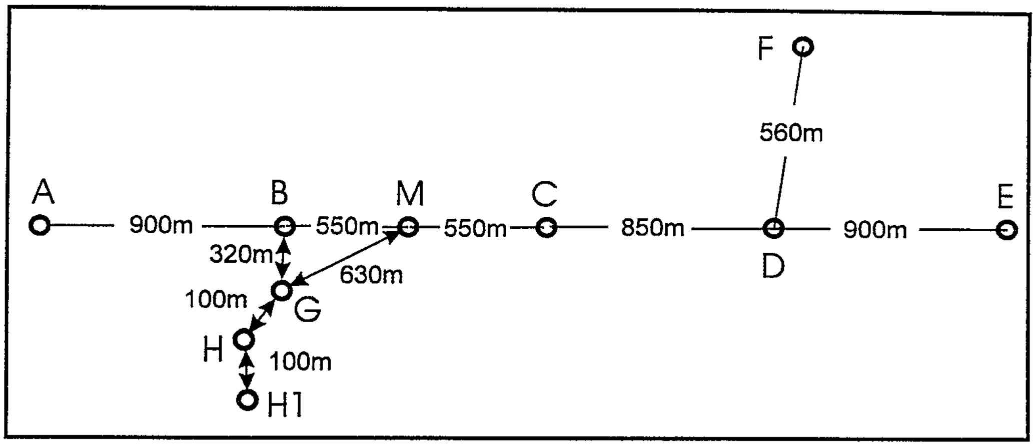


Figure 10. Ice Camp Knossos Layout showing ALDV run distances.

After the initial camp setup, the first part of the deployment was the stringing of lines between the various locations shown in Figure 10. A summary of the ALDV runs, executed between 8 and 14 April is given in Table 2.

Table 2. ALDV run summary.

RUN	FROM - TO	DISTANCE (m)	COMMENTS
1	H to G	100	Seamor recovery
2	B to G	320	Hoop recovery
3a, b, c	B to A	900	Missed
3d	B to A	900	Hoop recovery
4	B to M	550	Hoop recovery
5	C to M	550	Hoop recovery
6	D to C	850	Hoop recovery
7	D to E	900	Hoop recovery
8	D to F	560	Hoop recovery
9	G to M	630	Seamor recovery
10	H to H1	100	Hoop recovery

The misses on runs 3a and 3b were attributed to a faulty pitch sensor that had been inadvertently cold soaked on the trip to the Arctic. The miss on run 3b was caused by a timing synchronization error resulting in early vehicle shut down.

Following each run, the kevlar thread was used to pull a medium line (227 kg break strength), which was used in turn to pull the final working line (1,800 kg break strength).

The array was deployment commenced on 14 April. It was first deployed just below the ice surface for system checkout. When Theseus was about 12 hours from arrival at Knossos, the array was lowered to the bottom. The last lowering line was released on 17 April. At this point, the water column was clear of all working lines except the fibre to the array, which was left on the surface to be spliced onto the trunk cable after Theseus' arrival.

4.2. CABLE DEPLOYMENT

The 175 km fibre-optic cable was deployed under the Arctic ice pack, between the shore camp at Jolliffe and the array camp at Knossos by the AUV Theseus. The launch and recovery procedures and the technique of catching the fibre-optic cable at the ice camp are sufficiently new that they are discussed separately.

Theseus was launched through a large (1.5 m x 12.8 m) ice hole made by cutting 0.9 m x 1.5 m x 1.7-m-thick ice blocks with a hot water slot cutter. The ice hole was located at Jolliffe Bay (Figure 9) in a large (11 m x 20 m) heated tent which housed the vehicle and served as a maintenance shop. Two travelling gantries with 5450 kg hoists were erected inside the tent to handle Theseus (8600 kg) and to hoist the ice blocks (2000 kg) out of the water.

When Theseus returned after a mission it parked itself either on the bottom or up under the ice within ROV range of the large hole. The Phantom ROV was sent out to attach a recovery line to Theseus which was then pulled back to the launch hole.

When Theseus arrived at Knossos it delivered the fibre-optic cable by flying through a loop suspended from the ice surface. This catchment loop was in the shape of an equilateral triangle, 200 m on the side, and it consisted basically of two ropes and a saddle-shaped weight. After the vehicle passed through the triangle, the cable sank slowly into the saddle at the bottom of the triangle. (The saddle kept the fibre-optic cable from kinking over the small-diameter rope.) The saddle was then pulled to the surface, and the cable was recovered. However, before the cable could be cut and spliced to the array cable, it was necessary to allow for possible ice motion during the splicing period (estimated at 2 hours). To compensate for cable that might be pulled away by ice motion, one extra kilometre of fibre was pulled up onto the ice.

The Knossos mission consisted of navigating from Jolliffe Bay to the array site via 35 waypoints. Acoustic beacons were located at six locations as shown in Figures 8 and 9: Sliding Home, First Base, Second Base, Shortstop, Third Base and Knossos. First Base and Second Base were manned in order to make acoustic telemetry contact in case the vehicle encountered problems.

The mission began at 00:22 on 17 April. Theseus passed First Base at 02:20 and Second Base at 11:12 with successful homing and acoustic telemetry contact at both. Shortstop was passed at 19:00 without successful homing but continued on to Third Base as programmed. (Later investigation revealed that the Shortstop beacon was not functioning). At 01:18, 18 April, Theseus arrived at Third Base, homed to the transponder there and continued on through the catchment loop. The cable settled down into the saddle at the bottom of the catchment loop and was recovered.

Theseus was given a final position update through the the deployed cable which provided a communication link with the shore station, and, after the ballast was adjusted, the cable was cut, and Theseus was sent home. Theseus returned to Jolliffe via homing beacons at Shortstop (a new beacon was now in place), Second Base, First Base and Sliding Home. At First Base, the homing step failed to complete, possibly due to poor acoustic conditions. In this situation, the Fault Manager had been programmed to have Theseus stop and park under the ice to await further instructions. Acoustic telemetry and surface tracking were established, and the vehicle's health was checked. The vehicle's ballast was adjusted, and it was sent on its way. At 11:40 (19 April) Theseus came to a stop under the ice at the launch hole. Lines were attached by the Phantom ROV, and Theseus was recovered safely.

As Theseus passed by the accurately-positioned acoustic beacons at Second Base and Third Base, it made corrections to its own position. From these corrections it is possible to determine Theseus' navigational accuracy. When Theseus arrived at Third Base its overall cross-track error was 0.5% of the distance travelled, and its along-track error was 0.4%.

A new heading-error correction was calculated for the return trip in order to reduce the cross-track error. Nothing was done for the along-track error since it was not deemed to be as important. (In this mission Theseus did a position update at each acoustic beacon. Therefore, it was important that the heading be accurate enough to bring Theseus close to the beacon; the distance-travelled accuracy was not as important). With the new heading-error correction, the cross-track error on the return was 0.04% of the distance travelled, a substantial improvement. The along-track error measurements were contaminated, but over a short range of good data (from Short Stop to Second Base) the along-track error was 0.6%, essentially the same as before.

The energy used on this mission was 149 kWh, less than half of the estimated battery capacity.

5. SYSTEM RECOVERY AND REPAIR

Data was received from the underwater system for 2 months. However, on 19 June 96, the optical signal from the array was lost due to a break in the fibre optic trunk cable 10 km south of the array. In April 1997, a preliminary optical inspection identified a second break in the trunk cable 14 km from shore. A physical separation in the trunk cable was located at 14.4 km and recovered using Phantom. The cable was successfully repaired on the ice surface and redeployed to the ocean bottom. Phantom was also used to recover the primary electro-optic node of the bottom-moored array system in 570 m of water. A new node and battery pack for the array were also deployed successfully. Unfortunately, ice conditions at the original cable break precluded a repair attempt at that time. Efforts are underway to complete the cable repair in 1998.

6. POTENTIAL FUTURE APPLICATIONS

The underwater vehicles described in this report were critical components in the deployment of an underwater system in the Arctic. However, they could also be used for other underwater system installations. Theseus is currently configured solely for cable laying; however, its modularity and design features make it suitable for other missions. The fiberglass payload bay can be modified or even replaced economically to accommodate other payloads. These factors combined with Theseus' qualities of covertness, endurance and navigational precision make possible such tasks as remote route surveys, remote mine hunting, the rapid deployment of surveillance systems (acoustic and non-acoustic), and even the towing of mobile sensor arrays. Longer missions could be accommodated by replacing the current silver-zinc batteries with fuel cells or other AIP (Air Independent Propulsion) power plants.

Phantom proved itself to be an extremely rugged and versatile vehicle. It also can be adapted for many different roles by adding special purpose manipulators and sensor systems.

Seamor, while lacking the speed and manipulator capabilities of Phantom, is a small, light-weight, low-power vehicle that can be rapidly deployed for quick recovery operations and inspections of underwater activities.

The present configuration of ALDV makes it particularly effective in under-ice operations. However, it can be adapted to many other roles [2] requiring a light-weight autonomous vehicle.

7. CONCLUSIONS

A major underwater system was deployed successfully in the hostile environment of the Arctic through the use of the four underwater vehicles described in this report. The largest and most complex vehicle, Theseus, was used to deploy 175 km of fibre-optic cable from a shore site on northern Ellesmere Island in the Canadian Arctic to an array site under the permanent ice cover of the Arctic Ocean. The ALDV, a small autonomous vehicle was used successfully to string lines for distances of up to 900 m between ice holes to assist in the deployment of the underwater array system. The two tethered vehicles, Phantom and Seamor, were used as the workhorses for many underwater tasks. Phantom was critical in the recovery of Theseus after each under-ice mission, and it was essential for cutting cables and attaching lines to system components required for in-situ repair operations. Seamor, the least capable of the vehicles, was very useful for rapid underwater inspections, mooring recovery operations and as a backup for recovering ALDV.

8. ACKNOWLEDGEMENTS

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