Theseus AUV—Two Record Breaking Missions

Designed to Lay Fiber-Optic Cable from a Site Near the Shore of Ellesmere Island to a Scientific Acoustic Array in the Arctic Ocean

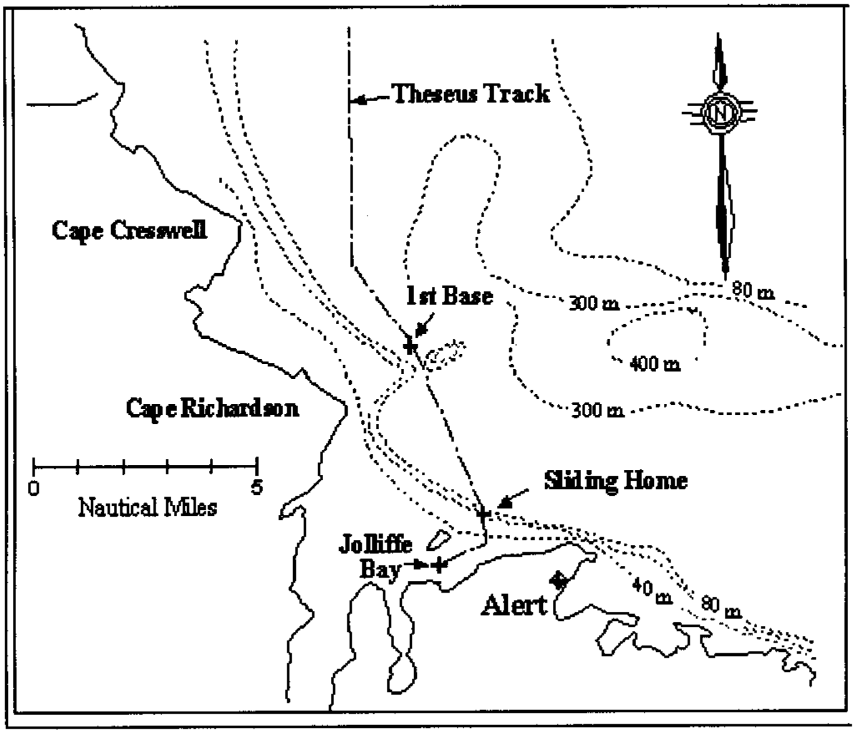
By James Ferguson
Vice President

Allan Pope
Program Manager
International Submarine Engineering Ltd.
Port Coquitlam, British Columbia, Canada

Bruce Butler
System Engineering Consultant
Offshore Systems Ltd.
Vancouver, British Columbia, Canada

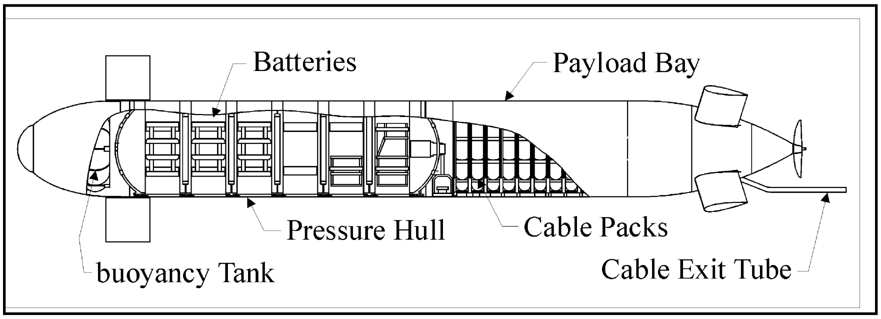
and

Dr. Ronald I. Verrall
Defence Scientist
Defence Research Establishment Atlantic
Halifax, Nova Scotia, Canada



Since 1992, International Submarine Engineering (ISE) and the Defence Research Establishment Atlantic (DREA) of the Canadian Department of National Defence have worked together to develop a large AUV for laying fiber-optic cables in ice covered waters. The vehicle, named Theseus, was designed to lay up to 220 kilometers of fiber-optic cable from a site near the shore of Ellesmere Island in the Canadian Arctic islands to a scientific acoustic array in the Arctic Ocean about 200 kilometers from shore. The water depth along the cable route varies from 50 meters at the launch site to about 600 meters at the array site. The development and a complete description of the mechanical systems in the vehicle was described in *Sea Technology* (April 1995). Following this, Arctic trials and two record breaking missions were conducted under ice from Ellesmere Island.

At left is Theseus AUV Layout. Above map shows track of the Theseus AUV under the Arctic icecap at the end of a mission.



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 meters thick, with ice keels that can extend to depths of 30 meters within 10 kilometers from the launch site, and 50 meters further out; water currents vary from 0 to 25 cm/sec near the launch site and 0 to 10 cm/sec at the array site; air temperatures vary from -40º to -20ºC; and water temperatures vary from -1ºC in the shallow waters near the launch site to +4ºC near the bottom at a depth of 600 meters.

An endurance of 450 kilometers was required to lay the cable, return to the launch site and allow a reasonable margin for contingencies. A navigational accuracy of 1 percent of distance traveled combined with an acoustic terminal homing system was needed to bring the vehicle through a 200 meters wide cable recovery loop at the cable delivery 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 meters.

The vehicle is 10.8 meters in length and has a diameter of 1.28 meters. It's large size is driven entirely by the volume and buoyancy requirements of 16 fiber-optic cable payload. With the full payload of 220 kilometers of cable, the weight of the vehicle is 8,600 kilograms. At a speed of 3.7 knots (design survey speed) it's range is 920 kilometers. As a prelude to the description of the Theseus mission, major components of the vehicle's guidance and control system are outlined below.

Computer Control System

Overall vehicle operation is managed by an MC68030 computer running a real time executive kernel that was developed by ISE research for AUV control. The executive is implemented in C++ in an object-oriented fashion with a layered architecture.

One of the fundamental characteristics of the executive is the ability to reconfigure the control system without modifying source code. The concept of "scripts," which are collections of tasks (sequencing components) organized into one or more steps, was developed. Each step in a script may contain any number of "threads" of tasks. Scripts are English-like statements that can be organized by nonprogrammers to reconfigure the system for a desired sequence of events.

Scripts can be developed to run in parallel at different priority levels, and have many useful operators. The highest level script is the mission plan, a series of mission steps that instruct the vehicle to go from one waypoint to the next—specifying en route conditions such as depth/altitude, speed, and fault response.

In order to increase the tolerance to system faults, the control system manages fault responses using a predefined fault table. This table allows the user to divide a mission into any number of phases, where a phase consists of one or more maneuvers between waypoints. Each phase of a mission script has its own series 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 or phase occurs when the desired response to some fault changes, such as when approaching a manned camp. At this point a new series of entries in the fault table takes effect. Eighteen phases were used to adjust to the changing circumstances during the 1996 Arctic missions.

Navigation System

Designing a navigation system to allow an AUV to navigate autonomously under ice for more than 450 kilometers is a challenge. The presence of a permanent ice cover requires that all sensors used to determine position must 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 transits, and an external terminal-guidance acoustic positioning system for cable delivery and vehicle recovery.

Theseus monitors its position by dead reckoning. It uses a Honeywell 726 ring-laser-gyro INU and an EDO 3050 Doppler sonar. The INU provides heading and attitude data, while the Doppler sonar measures forward and lateral ground speeds, as well as altitude. This combination was selected to provide positions with an error of less than 1% of the distance traveled.

The vehicle is fitted with a Sonatech model STA-013-1 forward-looking obstacle avoidance sonar system. This sonar operates at 200 and 230 kHz and projects 20 beams in a 4 x 5 array that covers the region ±9 vertical and ±25 horizontal out to a range of 180 meters. A control system allows the vehicle to autonomously steer over, under or around obstacles.

The cable is stored on a series of spools that are stacked longitudinally along the vehicle. The ends of each spool are spliced to adjacent spool ends prior to launch. The cable winds off the spools from the inside out, and exits through a tube in the stern. A deployment peel tension of 2 kilograms is maintained through the use of a special adhesive applied to the cable jacket during the spool winding process. To keep the system simple, no active tensioning or dispensing devices are used.

As cable leaves the vehicle, weight is lost. To prevent this from affecting trim, loss in weight is counteracted by an automatic buoyancy compensation system. Surrounding each cable spool is a toroidal hard ballast tank that is filled with water as the cable is dispensed from its spool. This keeps the buoyancy of each spool assembly near neutral. Metallic tabs at the end of each cable spool signal the vehicle control computer as each pack is emptied.

Arctic Trials

Arctic trials were carried out in April 1995, in shallow ice-covered water near Ellesmere Island. The objectives were to verify launch and recovery procedures, test vehicle systems in an under-ice environment, and refine techniques for delivering the fiber-optic cable to the ice surface.

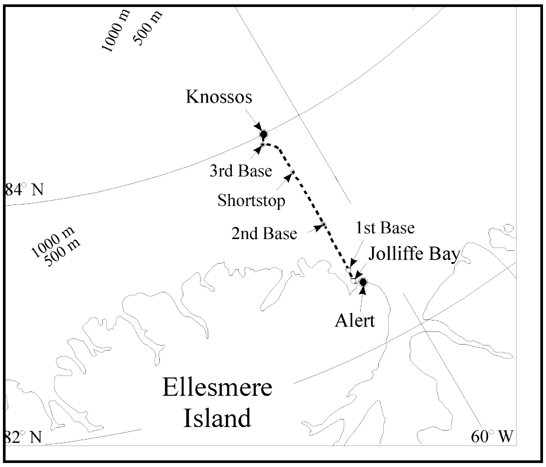
Four dives were carried out with the longest being 5 kilometers. The cable deployment system worked well, just as it had in the south, and the on-ice cable recovery system was successfully tested. A 9-kilometers length of fiber-optic cable was left on the ocean bottom until April 1996 to provide some information on long-term survivability.

Following this first Arctic trial, the vehicle controller software was completed between June 1995 and January 1996 and the Ag-Zn battery banks were commissioned. The next trials were carried out at the Canadian Forces Maritime Experimental Test Range in Georgia Strait during January 1996. Here, a full mission-length trial was carried out to verify the endurance of the vehicle, to test the power budget, and the navigational accuracy.

Theseus ran a total distance of 360 kilometers over 51 hours without stopping. An extra 18 kilometers on previous trials brought the total distance that was traveled on the battery to 378 kilometers that used a total of 145 kWh. Since approximately 360 kWh was available from one charge, the energy margin was more than adequate.

Theseus' navigation was checked by comparing its position, as determined by the range, with its calculated position. On the first leg the vehicle's cross-track error was 0.45% of the distance traveled (bearing error of 0.26°) and its along-track error was about 0.5%. This was much better than had been expected. At the start of the next leg, a heading error correction was sent to the vehicle over the acoustic telemetry link. This correction had the effect of rotating (in software) the heading of the Doppler sonar relative to the INU. After this correction was applied, the navigational accuracy was exceptional; the average cross-track error was of the order 0.05% of the distance traveled (bearing error of 0.03°).

The vehicle's ability to home to a beacon and do an automatic position update were tested on the final five round trips. The homing system worked very well to a range of 5 kilometers, and the position update procedure worked flawlessly.



Theseus launch and recovery site—Ellesmere Island.

Cable Laying Missions

In April 1996, a fiber-optic cable was laid from Jolliffe Bay (just west of CFS Alert) to ice camp Knossos, a one way distance of 175 kilometers. At this time of year, the Arctic Ocean is completely ice-covered. Theseus was deployed through ice that was 1.7 meters thick and the fiber-optic cable was delivered to an ice camp where the ice was 2.7 meters thick. The launch and recovery procedures and the technique of catching the cable at the ice camp are sufficiently different to be discussed separately.

Theseus was launched through a large (2.0 x 13 meters) ice hole made by cutting 0.9 x 1.5 x 1.7 meters thick ice blocks with a hot water slot cutter.

The ice hole was located at Jolliffe Bay in a large (11 x 20 meters) heated tent that housed the vehicle and served as a maintenance shop. Two traveling gantries with 5,450 kilograms rated hoists were erected inside the tent to handle Theseus and to hoist the ice blocks (2,000 kilograms) out of the water.

When Theseus returned after a mission, it parked itself on the bottom or up under the ice within tethered vehicle range of the large hole. A Phantom DHD2+2 ROV was used to attach a recovery line to Theseus that was then pulled to the recovery hole.

When Theseus arrived at Knossos it delivered the cable by flying through a loop suspended from the ice surface. This loop was in the shape of an equilateral triangle, 200 meters 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 to the saddle at the bottom of the triangle. The saddle was then pulled to the surface and the cable recovered. However, before it could be cut and spliced to the array cable, it was necessary to allow for ice motion during the splicing period of about two hours. To compensate for cable that might be pulled away by ice motion, one extra kilometer was pulled up onto the ice.

Cable-Laying Run

The mission consisted of navigating from Jolliffe Bay to the array site via 35 waypoints. Acoustic beacons were located at six locations—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 April 17. 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, April 18, Theseus arrived at third base, homed to the transponder there and continued on to catcher, located about 1.6 kilometers away. Homing was good at first, but deteriorated as Theseus approached the catchment loop. As a result, the decision was made to fly Theseus through the loop under shore-based pilot control through the cable telemetry system.

A surface-based tracking system at Knossos provided position information via voice radio to the pilot who was located in the Theseus control room at Alert. Under human pilotage, Theseus successfully flew through the loop and parked under the ice some 600 meters away. The cable settled to the saddle at the bottom of the catchment loop and was recovered.

Theseus was given a final position update through the cable, and the cable was cut. Theseus returned to Jolliffe via homing beacons at shortstop (a new beacon was not 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 and it was sent on its way. At 11:40 (April 19) Theseus came to a stop under the ice at the launch hole, lines were attached, and it was recovered.

As Theseus passed by the acoustic beacons at second base and third base, it made corrections to its own position. From these corrections it is possible to determine navigational accuracy. When Theseus arrived at third base, its overall cross-track error was 0.5% of the distance traveled, 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 important.

With the new correction, the cross-track error on the return was 0.04% of the distance traveled. The along-track error was 0.5% (essentially the same as before). During this mission the energy used was 149 kWh (less than half of the estimated battery capacity).

Following this success, it was decided to lay a backup cable to a second site; slightly closer in, the run distance was 160 kilometers each way. Some risk was associated with this; the adhesive in some of the cable packs was known to have settled to the bottom during the drying process and there was a concern that it might have hardened to the point where it would cause a cable break.

This concern proved justified at 117 kilometers, when the cable did in fact break. Theseus carried on, however, passing through the saddle and back to the recovery site. While a cable was not successfully laid, the vehicle did what it was programmed to do and it completed a 320 kilometer under ice transit. In terms of AUV operations, this indeed was a success.

Other Uses

Other Arctic cable laying missions are being considered for the future. The vehicle is currently configured solely for cable laying; however, its modularity makes it suitable for other missions. The fiberglass payload bay can be modified or replaced to accommodate other payloads. These factors combined with Theseus' qualities of covertness, endurance, and navigational precision make possible such tasks as long range route surveys, remote minehunting, the rapid deployment of surveillance systems (acoustic and non-acoustic), and the towing of mobile sensor arrays. Missions of over 1,000 kilometers can be accommodated by replacing the current silver-zinc batteries with fuel cells or other air independent propulsion (AIP) power plants. /st/