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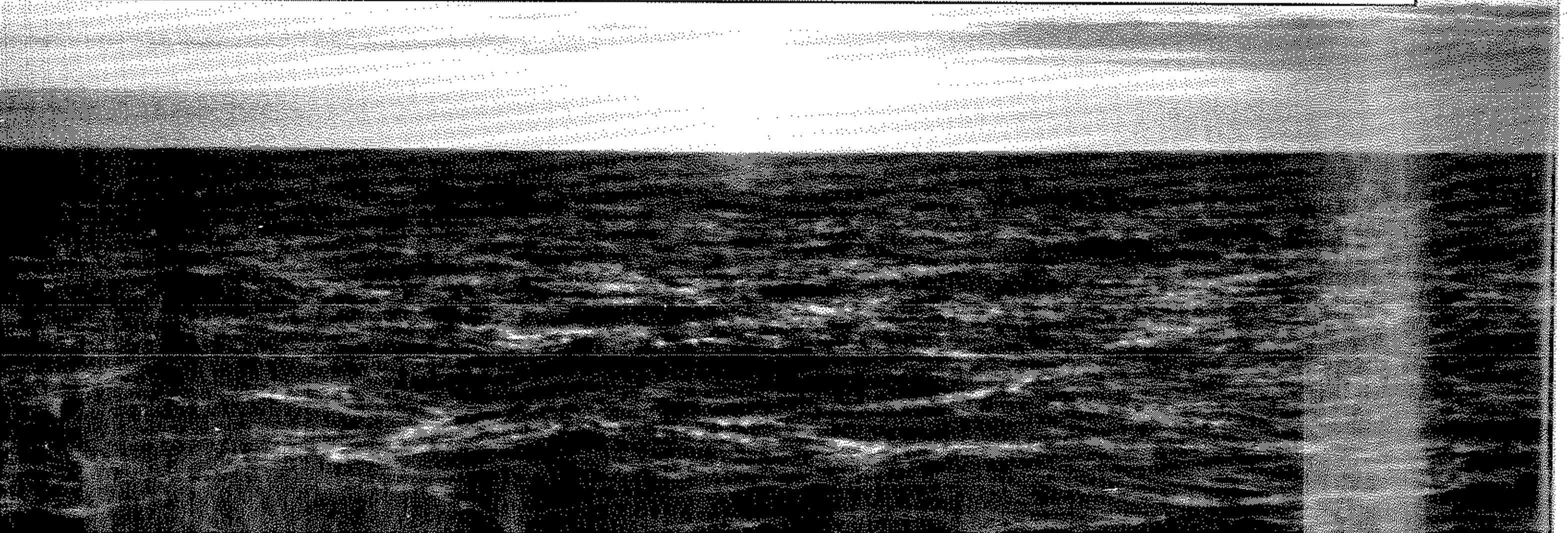

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Small, Inexpensive AUVs Perform Arctic Ocean CTD Profiling, Under-Ice Line-Deployment Missions

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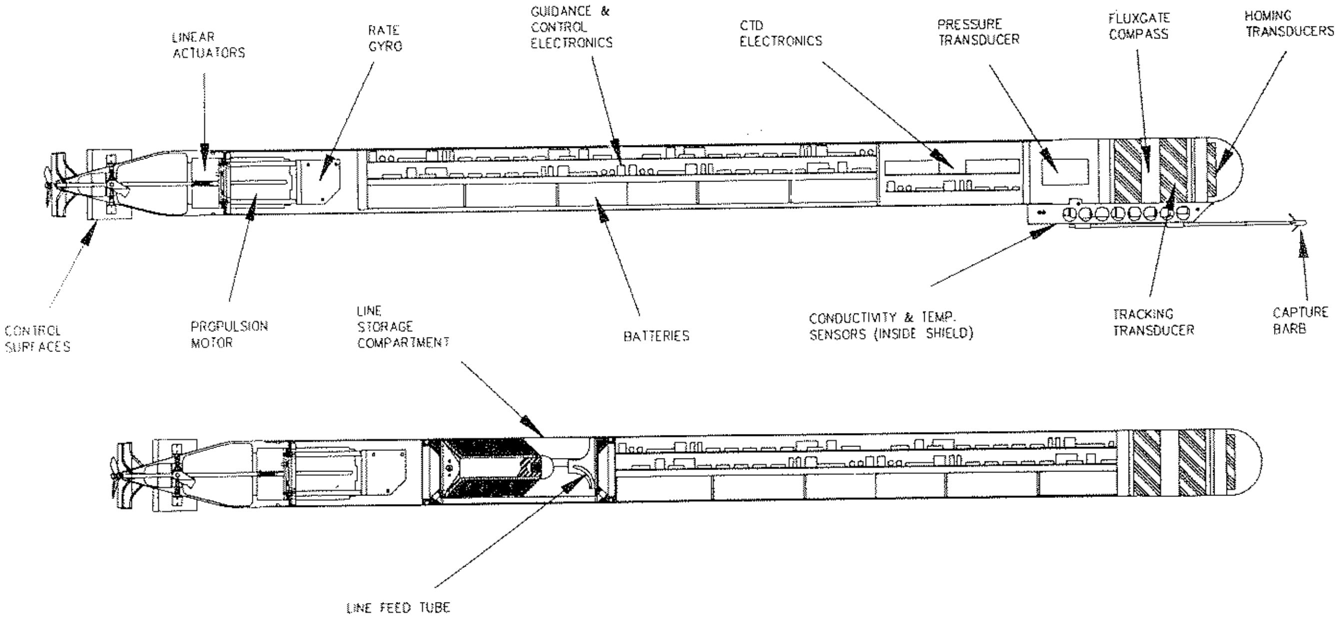
The Applied Physics Laboratory at the University of Washington (APL-UW), under contract with the Naval Sea Systems Command, developed an inexpensive, expendable, mobile underwater target for training destroyer sonar operators during the 1970s. The device, originally called the "miniature mobile target (MMT)" and later designated the Mk 38, is a small, torpedo-shaped, self-propelled, untethered vehicle equipped with an acoustic transponder. It is 132 centimeters long and 8.9 centimeters in diameter, and weighs less than 9 kilograms in air. The vehicle swims within a preset depth window by using a pendulum-actuated elevator for pitch control and cycling the motor "on" and "off" with a dual pressure switch.

In the late 1980s, APL-UW, with Office of Naval Research funding, augmented the Mk 38 with an active guidance system, an active homing system, and a payload-carrying capability. The goal was to provide the scientific community with an inexpensive AUV capable of carrying small instrumentation packages on preprogrammed paths and returning to an acoustic homing beacon. Design goals were a maximum operating depth of 250 meters and a mission duration of two hours at a maximum speed of 2 meters/second. In-water testing of this device, named the SeaShuttle, was performed in 1988.

SeaShuttle Configurations

The vehicle uses an on-board microprocessor for active guidance control. Feedback from a fluxgate compass, pressure transducer, pitch/roll sensor, and yaw-rate gyro are used to control the vehicle during dead-reckoning operation. A sequence of user-defined run segments consisting of a heading, depth, and duration is used to determine the desired track. An acoustic homing system is employed at the end of the dead reckoning to steer the vehicle to a recovery location.

Run configuration, diagnostics, and post-run data extraction are performed using a standard DOS-based computer via an RS-232 serial interface port. All vehicle interfacing utilizes a custom, user-friendly program which runs on the computer. Synchronized with a precision external



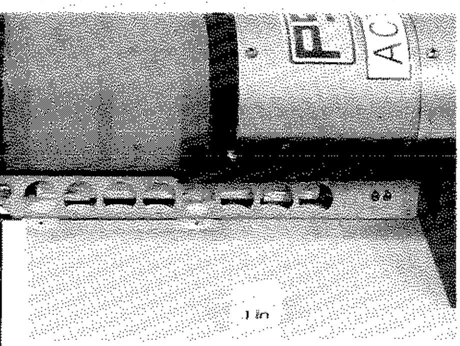
The autonomous conductivity temperature vehicle (top) displaces 9,500 cubic centimeters and carries CTD sensors and monitors. The ALDV displaces 8,700 cubic centimeters pulls a light line between the holes so that a heavier line can deploy instrumentation.

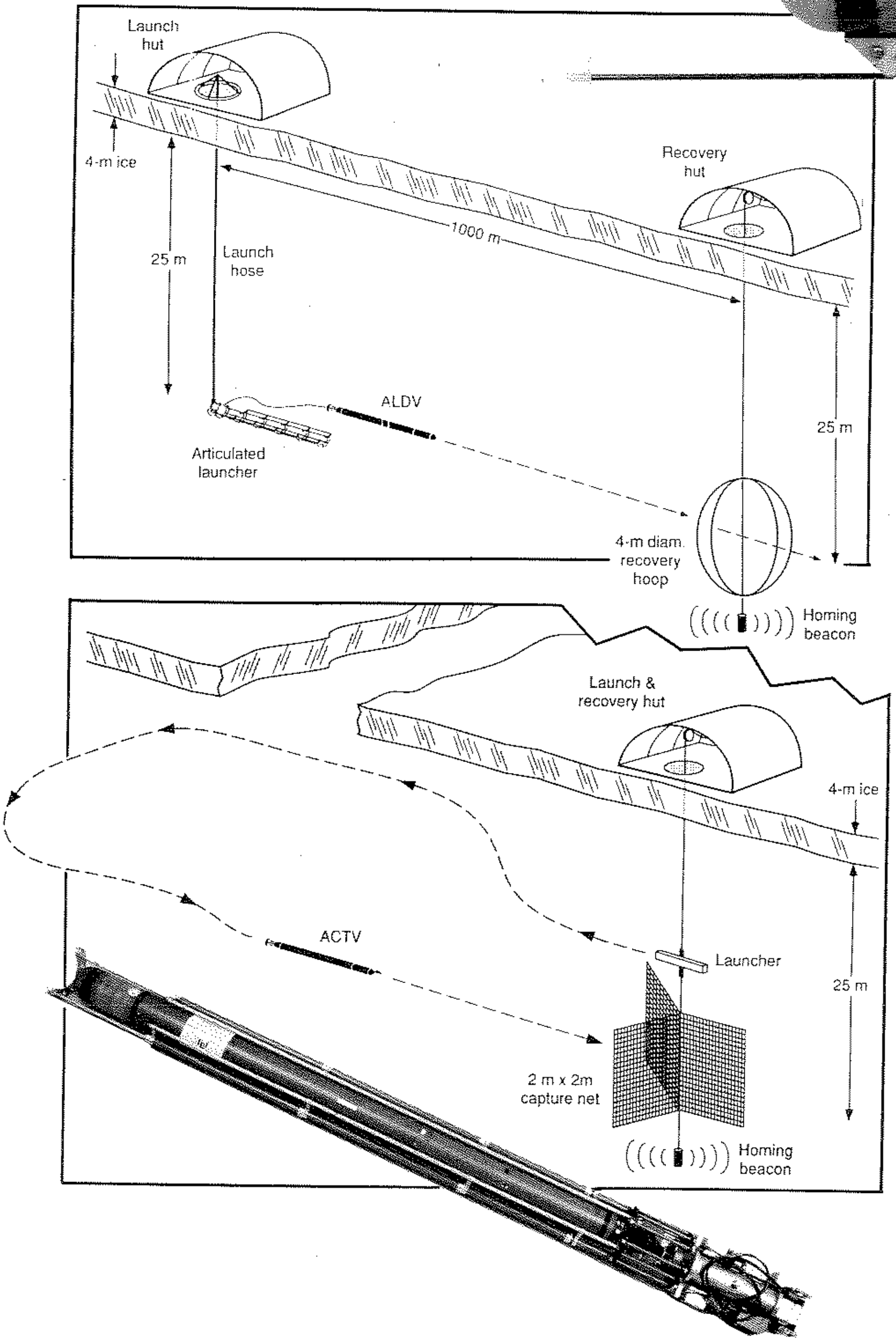
clock prior to deployment, SeaShuttle maintains an accurate clock which is used to transmit an acoustic pulse to an APL-UW designed synchronous tracking range and end-of-run location equipment. The synchronized clock is also used with the acoustic homing system to determine the range to a synchronized acoustic beacon.

In the vehicle nose there are two hydrophones and phase-detection electronics for determining the bearing angle to the acoustic homing beacon.

In 1989 two SeaShuttles, fitted with CTD sensors and renamed "autonomous conductivity temperature vehicles (ACTVs)," made more than 50 successful runs under the arctic ice pack in 1989, 1991, and 1992. Run times varied from several minutes to as much as 50 minutes at depths from 5 to 120 meters. SeaShuttle has also been used for experiments in local coastal waters.

With a barb mounted on its nose the ACTV is recovered with a net consisting of three 2- by 2-meter panels arranged in a paddle wheel configuration suspended by a cable. The homing beacon is suspended directly below the net. During homing, the vehicle runs into the net and is caught by the barb. The assembly is raised to the surface and is pulled through the ice hole with the net collapsing like an umbrella. The vehicle, trimmed and ballasted for slight positive buoyancy (nominally 113 grams), also can be retrieved directly from the sea surface.





Forward hull section of ACTV above shows recovery barb and conductivity cell. Its typical arctic run sequence is shown in lower diagram. The ALDV (photo below with unit in its launcher) run sequence is shown in upper diagram.

In the early 1990s under contract to the Space and Naval Warfare Systems Command, APL-UW began adapting the SeaShuttle to deploy a light messenger line between two ice holes about 1,000 meters apart. The light line is used to pull a heavier line between the holes that can then be used to deploy instrumentation. This vehicle was named the "autonomous line deployment vehicle (ALDV)." Two vehicles were constructed.

The payload section was modified by adding two watertight bulkheads, one aft of the electronics section and the other forward of the propulsion motor/tail section to create a flooded amidships section containing a line spool. The line is a commercial sewing thread of Kevlar® 29 fiber, with a nominal diameter of 1.07 millimeters and a breaking strength of 80 pounds. Approximately 1,300 meters of line can be wound on an industrial sewing bobbin (diameter 7.6 and length 15, all in centimeters) and paid out with a minimal decrease in vehicle speed—a more efficient method than pulling a line from a source at the launch point.

Since line deployment capability changes the center of gravity (and therefor pitch and trim) and buoyancy from the start to the end of a run, the flooded section is located as close to the center of gravity as possible. Oversized elevators and rudders compensate for the remaining pitch, trim, and total net buoyancy change.

The ALDV was field tested under the arctic ice pack in April 1993. Fifteen runs were performed in varying ice conditions, deploying 900 to 1,050 meters of line on each run.

Mechanical Design

The SeaShuttle is based on the concepts of the Mk 38, now phased out of the Navy. Technology advances have enabled the vehicle to be low cost, robust, and retrievable.

Many of the Mk 38 parts and features have been incorporated into the SeaShuttle, including the molded, glass-filled ABS tail section, internal supports, aluminum hull, and dual ceramic-ring transducer forming the forward hull section. The tail section has been modified to accommodate movable, tandem rudder and elevator surfaces. Two linear actuator motors and a pitch/roll sensor (the motors drive push rods attached to yoke assemblies for moving the rudder and elevator surfaces) have been installed inside the tail. These surfaces have adjustable yoke-attachment points so that identical pitch angles can be set in each pair of surfaces. Lip seals are used on the shafts to the control surfaces. Cruciform tail fins and a ring shroud provide dynamic and static control.

A 1/4-horsepower DC permanent-magnet motor drives a single, three-bladed propeller through a needle bearing and dual-lip shaft seals. The motor and a yaw-rate sensor attach to the tail section, forming a single assembly.

A removable vent plug in the tail allows drawing a vacuum on the vehicle prior to operation to check seal integrity. An external four-pin glass feed-through connector in the tail provides an opto-isolated serial interface to the external computer.

The main hull has been elongated to accommodate new electronics and to create an uncommitted payload section.

The electronics section consists of two stacked printed circuit boards mounted together as a single assembly which can be rotated to achieve the vertical center of gravity necessary to offset the propeller torque. They are mounted above a lithium battery pack.

The forward hull section, a modified Mk 38 section with a dual ceramic-ring transducer, is used as an acoustic beacon so that the vehicle can be tracked. This now can hold a pressure transducer and a fluxgate compass. A new hemispherical nose section houses two homing hydrophones spaced 4.32 centimeters apart (3/8 the wavelength of the 13.5-kHz homing beacon). A homing receiver determines the bearing to an acoustic beacon by measuring the phase difference between the received signals.

An assortment of Mk 38 cast ABS parts are used for supporting the electronics. Standard O-rings are used throughout except for the control fins and propeller shaft.

The ACTV displaces 9,500 cubic centimeters (8.9 centimeters in diameter and 160 in length). The payload section contains the electronics from a repackaged Sea-Bird SEACAT CTD instrument mounted on a 9.5-centimeter aluminum extension attached to the underside of the main hull. The electrical leads to the conductivity and temperature sensors run through an O-ring seal and a Morrison seal, respectively. For accurate conductivity measurements, the water entering the cell (protected by an aluminum guard) should be perturbed as little as possible by the vehicle. Positioning the cell this far forward presents a yaw stability problem for the vehicle but is essential for accurate measurements.

The slightly smaller ALDV displaces 8,700 cubic centimeters (8.9 centimeters in diameter and 152 in length). In this configuration, a flooded payload section is inserted close to the vehicle's longitudinal center of gravity. The spool is oriented such that the line reels off forward and is routed through a 180° turn before exiting the hull and running aft along the keel. A tail stinger with a fishing rod ferrule completes the line-deployment system.

Beneath the 7.6-centimeter-diameter line spool are two wire conduits for passing electrical signals between the two hull sections. An additional vent plug in the transducer section is used to check seal integrity forward of the line-deployment section. The standard Mk 38 hulls were thinned to remove weight from the vehicle, resulting in a collapse depth rating of 110 meters. The cruising depth of the ALDV is typically 20 to 25 meters. Tests show an additional drag of 30 grams at typical forward speeds.

Electrical, Electronic Design

The two stacked circuit boards contain all the electronics for guidance and control, sensor data acquisition, and data logging. Two serial communication channels link the guidance and control microprocessor with an external computer and with the internal payload section. The channel to the external computer is used for predeployment configuration, calibration, test diagnostics, and post-deployment data readout. The other channel is used to control and/or communicate with instruments in the payload section.

The homing system, consisting of electronics, hydrophones and an external, acoustic beacon, is designed to allow the vehicle to determine range and bearing to the beacon once every 2 seconds. The guidance computer determines the bearing to the homing beacon by the phase difference between the signals received by two nose-mounted hydrophones.

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.

The vehicle also uses the synchronized clock to transmit an acoustic tracking pulse. An APL-UW designed tracking range (it tracks the vehicle and the homing beacon) receives this pulse on an array of fixed hydrophones. The vehicle tracking pulse repeats once every 2 seconds as does the homing beacon, but the signals are offset by 1 second, thus allowing the two systems to work at the same frequency without interference.

The SeaShuttle is powered by a lithium/sulfur-dioxide battery pack with a capacity of 5.4 ampere-hours and a nominal output of 30 volts. The battery pack provides approximately 3 hours of vehicle run time at a maximum speed of 1.8 meters/second.

Software, Run Programming

SeaShuttle software consists of vehicle and DOS-based support software. The vehicle software, interrupt-driven, real-time, assembly language program executes active guidance and homing algorithms and collects all vehicle sensor information. A run log for sensor readings and computed algorithm results is maintained in a battery-backed RAM. The program accepts commands and outputs system status information via the external serial communication channel reserved for vehicle configuration, diagnostic, calibration, and data extraction functions.

User-friendly one and two letter commands provide the user with real-time readouts of sensor values, control surface movement, motor control, and automated calibration procedures.

The support software program (DOS-based), menu-driven, allows the user to configure the vehicle for a run and then upload run data at the end. It also provides a terminal-emulation mode for working with the vehicle at the direct command level. Other programs are used to analyze the data collected by the SeaShuttle during a run (i.e., sensor information, control surface positions, and homing data) to determine vehicle performance.

Runs generally consist of a launch segment, a dead-reckoned segment, and a homing segment—algorithms are available to support recovery. For the ACTV application, which uses the barb/net method as the primary recovery system, the software detects when the vehicle has entered the net by looking at the history of the homing range values. Motor shutdown occurs when the range is small and is not changing. In the event the vehicle misses the net, a re-attack mode is initiated—it moves away to a distance sufficient to make a full 180° turn and tries again.

For the ALDV application, the vehicle is operated exclusively in the homing mode since the run geometry is always a straight line. This mode is very reliable, since the accuracy of the fluxgate compass (which is poor at high latitudes) is not a factor. Run segments can also be made on fixed yaw-rate values, allowing an initial straight-line segment (the launch angle must be accurate).

Launch and Recovery

Separate launch and recovery systems have been developed for the ACTV and ALDV for arctic operations utilizing the vehicle's ability to be launched and recovered from small-diameter holes. In both systems, the vehicle is lowered in a vertical position for launch and utilizes a collapsible recovery system.

The ACTV launch system (a simple spring-loaded, hinged aluminum box held chosed by an electromagnet) swivels on a short pipe section that slides on the wire used for the recovery net. The vehicle is lowered to the top of the recovery net by the wire used to control the launcher's electromagnet, with the vehicle's center of gravity positioned forward of the center of the launcher box. The vehicle swivels to the horizontal position when the lowering wire is relaxed. Removing power to the electromagnet opens the box and launches the vehicle.

The ACTV recovery net consists of three 2- by 2-meter panels 120° apart attached by hinges at the top and bottom to a central pipe. Floats attached to the top ends of each panel open the net upon deployment into the water. The net collapses when the structure is removed from the water.

The ALDV launcher (a combined hydraulic, pneumatic, and electric system weighing about 15 kilograms in air) consists of a metal ring (in a fixed position around the ice hole) topped by a triangular support from which hangs a 2.5-centimeter-diameter hydraulic hose culminating in an articulated launcher mechanism at a depth of 23 meters. The pyramidal structure on top of the ring both supports the launcher hose and is used to orient the launcher toward the recovery hole. The hose, when pumped to 4,000 pounds/square inch, becomes torsionally stiff and effectively allows the launcher mechanism to be rotated from the surface. Electrical wires inside the hose operate the launcher. A pneumatic tube spiraled around the outside provides abundant surface air to pneumatic actuators on the launcher mechanism. One actuator orients the launcher to a horizontal position after it has been deployed through the ice hole, and a pair of actuators, plumbed in opposition, rapidly flings the vehicle vertically after its motor is powered on. This launch method was chosen to allow the use of elevators and rudders larger than the body's diameter.

The recovery system is an extension of the net and barbed nose system used on the ACTV. The ALDV uses the towed Kevlar line to its advantage. By homing on a beacon positioned just below it, the vehicle swims through a 3-meter-diameter hoop positioned at the steady-state run depth of the vehicle enabling the capture of the line. The hoop consists of four 5.2-meter, 1-centimeter-diameter aluminum tent poles arranged in a cross when viewed from above when deployed. Each pole is attached to a fixed yoke at the bottom and a similar yoke at the top that slides on the beacon cable, permitting the hoop to collapse to a 13-centimeter diameter during deployment and recovery.

The SeaShuttle AUVs (possibly the smallest operating AUVs in the world) are easily handled, shipped, and maintained. Operational since 1988, both have made hundreds of runs in a variety of environments, including through small-diameter ice holes in the arctic, without a loss.

Simple run programming from any DOS-based computer makes the vehicle easily programmable in the field. The ease of launch and recovery allows a fast turn-around and operation by only two people.

Programs in the proposal stage include ACTV operation in Antarctica in 1994, a microstructure conductivity/temperature version of the ACTV, and a SeaShuttle equipped with an upward- and downward-looking radiance/irradiance spectrometer to study the optical properties of seawater. /st/

Russell D. Light received his bachelor's degree in electrical engineering from the University of Washington in 1982. He has been responsible for the electrical and software design of naval electronic targets, oceanographic data collection systems, underwater tracking ranges, and the SeaShuttle AUV. He is currently the technical manager and lead electrical engineer for the SeaShuttle, the Diver Exercise Unit (a mine simulation device for training Navy divers), and a recording system for the Navy's Mk 60 CAPTOR Mine.