# Hadal Landers: the DEEPSEA CHALLENGE Ocean Trench Free Vehicles

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*Abstract*— **Unmanned free vehicles, using kerosene-filled envelopes for lift, have been used since the late 1930's to deliver scientific instruments and samplers to the seafloor. Recent advances in glass spherical housings have provided a cost-effective option for operations into ocean trenches. During his 2012 DEEPSEA CHALLENGER Expedition, Explorer James Cameron pushed the design limits with both manned submersible and unmanned lander designs. This paper describes the unmanned lander design and operational experiences during that successful expedition.**

***Keywords—free vehicle; hadal exploration; lander; imaging; video camera; digital camera; acoustic communication; flotation; glass sphere; underwater connectors; pressure compensated; LiPO battery; LED light; sampling; sensors***

## I. INTRODUCTION

Virtually all oceanography has been done in the upper 6km of the ocean, and very little in the 5km that exist below 6km, the region known as the hadal zone, created by the titanic planetary forces of subduction. This is not because of a lack of interest, but a lack of access, living in our common language as something "unfathomable". Earthquakes, volcanoes, tsunamis, and unknown species are born in the subduction zone. Early attempts at probing the hadal depths used long pieces of wire and chain dredges to bring up rocks, but couldn't recover the most fragile sea creatures who live in the great vastness of the far removed ocean depths.

Credit for the first use of free vehicles in deepsea scientific study belongs to Maurice Ewing, Lamont, and Allyn Vine, WHOI [1]. Inspired by Professor Auguste Piccard's proposal for what became the bathyscaphe, Ewing and Vine used rubberized float bags filled with kerosene for flotation to lift their geophysical instruments. With that fundamental design innovation, instruments and samplers began arriving on the floor of the deep sea. Later the bags were replaced with plastic jugs, and the technique has persisted into the 21st century, despite advances in syntactic foam and glass spheres, plus the real problems of handling inflammable fluids during shipment and at sea. Later free vehicle design approaches were described including John Issacs [2], [3], Charles Phleger [4], Ken Smith [5], Kevin Hardy, [6], [7], and Alan Jamison [8].

In 2001, Hardy, then at Scripps Institution of Oceanography and Gerald Albich, of Nautilus Marine, a German manufacturer of large hollow glass spheres rated for abyssal depths, resolved what was needed to modify the production tooling to create thick-wall glass spheres capable of reaching the ultimate deepest depth of the Mariana Trench. Glass spheres have the dual advantage of providing both buoyancy and an instrument housing. The German glass optical quality made it a perfect camera housing once polished. Lessons were learned in the first few attempts. Further, glass is invisible to IR and radio waves, providing other design opportunities. With some unexpectedly good timing, just after the final thick-wall manufacturing plan was described, Japan's JAMSTEC offered to pay for the tooling modifications, and the plan was put into action.

To make a functioning hadal depth system other component technologies required similar improvement, including through-glass bulkhead connectors. Engineers and their companies inspired by the challenge, created, piece-by-piece, the key components able to survive the ambient pressures of 1,100 atmospheres. Their combined solutions opened hadal exploration and discovery to all interested research institutions, not just the largest, as small ships of opportunity became useful for reaching the trenches, many found within 8 hours of port. Small free vehicles, some light enough to be lifted out of the ocean with one hand, have made

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repetitive dives into the Puerto Rico, Aleutian, and Mariana Trenches. Dubbed "landers", in a nod to the lunar landers of the 1960's and Mars landers of the 1970's, these vehicles have begun the routine exploration of the most remote and alien environments of planet Earth.

In the run-up to James Cameron's DEEPSEA CHALLENGE Expedition, which concluded in March 2012 with a successful manned dive to the floor of the Challenger Deep in the Mariana Trench, Cameron challenged a handpicked hadal lander design team to build a remote camera, sensor, and sampler platform. The lander incorporated the latest components and thinking in autonomous free vehicles. The expedition demonstrated the practicality of interchangeable component technologies shared across multiple undersea vehicle types: landers, ROVs, and manned submersibles. Pressure-compensated batteries and LED lights, stereo camera systems, and syntactic foam originally designed for the DEEPSEA CHALLENGER submersible were incorporated into the lander. A separate L3 Nautronix communication system was adapted for camera and light control functions. Additional commands through an Edgetech BART system provided redundancy to the command capabilities of the L3 unit.

The Landers were developed under a very restricted time schedule. Interchangeable payload modules were in concurrent development, requiring flexibility in the payload bay of the free vehicle. The vehicles became known internally as "Alpha Landers" for their size. Previously described free vehicles were mission specific, while the Alpha Landers were designed from the outset to be reconfigurable for different mission profiles. After successful at-sea testing off San Diego, CA, USA, the lander development project was moved to Sydney, Australia for further outfitting of the imaging payloads, submarine communication systems, and sampling arm. Further sea trials of the Alpha Landers were performed in conjunction with the submersible, DEEPSEA CHALLENGER, and independently inside Sydney Harbor.

Checklists were developed to assist in the repeated opening, closing, refurbishment, launch and recovery procedures. Details of each launch were carefully logged.

## II. Benefits of Free Vehicles

Each of the several unmanned undersea vehicle types has its advantages and disadvantages. ROVs have imaging, tactile ability, and some payload capacity, but are tethered to a ship. The deeper the ROV can go, the larger the winch needed, increasing the minimum ship size needed. Expensive Dynamic Positioning (DP) and heave compensation systems are needed to overcome wind, current, and waves. AUVs are untethered, and may roam unattended to any depth. They have finite battery capability, do not provide real time imaging, and have limited payload capacity for both deployment and sample collection. Gliders have range and persistence but are limited by depth, speed, and communication intervals.

Seafloor packages, or more popularly "landers," in the manner of the NASA unmanned interplanetary descent spacecraft, do not generally have mobility, nor the ability to recognize their immediate environment in detail and selectively sample it. They do have numerous offsetting benefits to oceanographic exploration, research, commerce, and defense, many of which were described by Ewing and Vine in 1938, and are still very much true today.

These include:

- Flexible Configuration: A lander can be sized and configured to whatever ship-of-opportunity presents itself.

- Interchangeable payloads: Like a pick-up truck to the deep sea, if a payload fits within physical, weight, electrical, and control parameters, it can be delivered to any place in the ocean, and recovered safely.

- Ships-of-opportunity: A less specialized but appropriately-sized seaworthy vessel may be found in a smaller harbor closer to the point of operation, during a more advantageous time, at a more modest cost.

- Test bed: Free vehicles may be used as test beds to verify operation of components for other vehicles in development, including pressure compensated systems, lights, cameras, batteries, motors, flotation, materials, acoustic systems, drop arms, and location beacons. Lander operations provide deck crews operational training on launch-and-recovery techniques for larger systems, and provide ocean engineers the confidence and competence that comes from a successful field deployment and recovery.

- Length of time: A lander can remain on the seafloor for an entire year or much longer if needed. The lander can be used to lure animals towards its position by the use of bait. Low-light cameras using red LEDs can image animal behavior without detection by most animals of the deep sea. A baited lander can act as a Fish Aggregation Device (FAD), awaiting the arrival of an ROV or manned submersible.

- Any depth: As shown in this expedition to the Mariana Trench, there are no depth limitations. Landers can be used from shallow water to 11,000m.

- Scout: Landers can precede a manned submersible or ROV operation to determine a specific area of interest. Multiple landers allow a large area to be surveyed from a small vessel.

- Samplers: Any number of water, sediment or animal samplers may be attached. Burnwires, solenoid-driven actuators, shape memory releases, Galvanic Time Release (GTR), or other pressure tolerant mechanisms can trigger sampler actuation.

- Sensors: numerous and complementary chemical, geophysical, physical, biological, acoustic, and imaging sensors can all be carried by landers.

- No HazMat: A shipment of lander components can fly Priority on passenger aircraft from point-of-origin to point-of-operation, and assembled pier side, allowing rapid response to a sudden event or discovery. Small landers have been flown as check-on luggage.

- Cheap Expendable Anchors: Only scrap iron is needed for anchors, so the ballast weight may be purchased in the port of operation, saving the cost of shipment. Old engine blocks from a scrap yard, or barbell weights from a sporting goods store are all low cost-per-pound options.

- Disruptive Technology: Landers are simple, cost-effective, and accessible to any size institution. Their use in the ocean to any depth provides immediate observational or sampling capability.

## III. FRAME AND FLOTATION

### *A. Basic Description*

The Alpha Lander vehicle body was designed tall (approx. 14-ft) with a narrow width and depth (approx. 2.5-ft x 3-ft ) with buoyancy high and weight low, resulting in excellent upright stability. (Fig. 1) The resultant small frontal projected area on descent and ascent provided directional stability. The box structure made in-field adaptations simpler. Use of low specific gravity materials such as extruded fiberglass shapes, HDPE sheet, and 6061 aluminum plate minimized in-water weight, decreasing buoyancy requirements. Consideration was given to metacentric stability on descent, at the seafloor, on ascent, and at the surface.

### *B. Frame*

The vehicle frame was built in two sections to allow disassembly for transport. HDPE doubler plates at the mid-section joint reinforced the frame during the transition from horizontal to vertical during deployment and recovery operations.

Alternate, interchangeable payload modules were in concurrent development. The Alpha Lander's payload bay was designed with generous volume, standardized mechanical mounts, and accessible cableways.

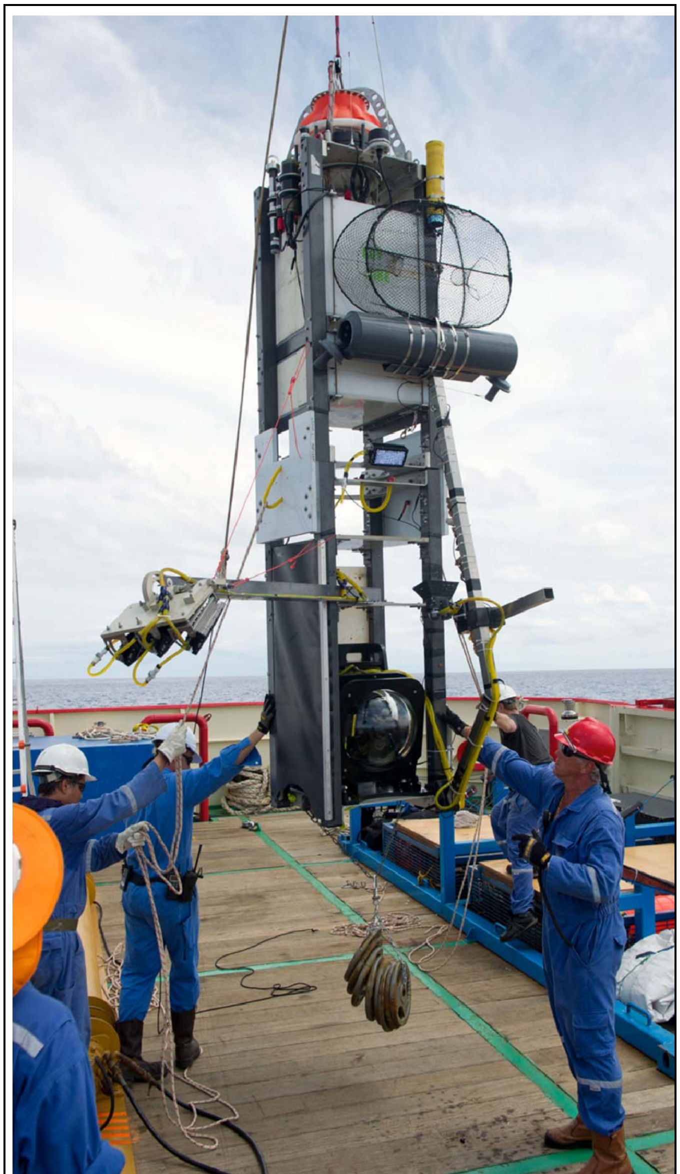

*Fig. 1. The Alpha Lander, DOV MIKE, is lifted by crane during deployment. Steel barbell weights are the clump weight. The drop arm, retracted against the face of the lander during deployment, holds a Niskin bottle rigged as an animal trap, and a net fish trap. A stereo camera pair is mounted to the drop arm, and looks upward in this view. The polished glass camera sphere is located at the bottom. Small barbell weights are fixed to the underside of the aluminum deck below the camera housing to negate the buoyancy of the camera sphere for overall vehicle stability. A fixed light arm holds the 3-element key light to the right and forward of the camera. A single-element fill light is positioned mid-body directly over the camera sphere. Fixed and variable buoyancy modules made of syntactic blocks are located above this. The Command/Control sphere tops the stack, with an aluminum lifting bale and hardhat segment providing cover and protection. (Photo used with permission, Earthship Productions.)*

The vehicle was intended to be laid flat on deck during transport, pre-launch preparation and post-recovery servicing.

Because of the vehicle's overall size and weight, use of a crane or A-frame was mandatory.

A 6061-T6 welded and heat-treated aluminum lifting bale was placed at the top. The SolidWorks design was evaluated using FEA, and validated by physical testing. An HDPE Vitrovex hardhat segment provided a protective cap over the upper Command/Control sphere.

Dual pelican releases were located at the bottom of the frame, providing release redundancy.

*C. Flotation*

To minimize implodable volume, syntactic foam developed for the DEEPSEA CHALLENGER submersible was used for the primary fixed buoyancy (FB), and variable buoyancy (VB). Blocks were fabricated in Sydney, AUS and shipped to San Diego, CA, USA for incorporation. The VB allowed for different weights of alternate payload modules. The frame construction accommodated in-field adaptation, including addition of supplemental syntactic as needed to offset in-water weights of later add-ons.

*D. Command/Control and Camera glass spheres*

Glass spheres have the dual advantage of being both a source of flotation and an instrument housing. Glass spheres are lightweight. They can be drilled and spotfaced with diamond tools for electrical and fiberoptic bulkhead connectors, or polished for optical clarity. IR and light waves, magnetic fields, radio waves, and wireless signals pass through glass with little attenuation, allowing control and viewing of interior electronics and components. LCD displays, mechanical gauges, and strobe lights can be seen.

Two 17" x 23mm thick Nautilus Marine (Buxtehude, Hamburg, Germany) Vitrovex glass spheres were used, one for the Command/Control sphere at the top of the frame, the other for the Camera sphere, located at the bottom of the frame.

The command/control sphere housed acoustic transceiver circuitry, recovery beacons, and batteries. A lower camera sphere housed a Canon 5D still/video camera, a programmable camera/light controller, and the recorders for the external stereo camera pair, described in detail below. To negate the buoyancy of the camera sphere, barbell weights were attached to the frame below the sphere.

The implodable volume of the two spheres was minimized by use of sealed bags of syntactic microspheres mixed with mineral oil. As many bags as would fit were secured to the interior of both the command/control sphere and the camera sphere.

*E. Acoustic Receiver*

An Edgetech (West Wareham, MA, USA) BART Board was selected for acoustic command and control. The BART system was successfully tested in August 2011 in the Mariana Trench Sirena Deep at 10,800m using the topside Edgetech Model 8011M Acoustic Tranceiver deck unit. The smaller topside Edgetech PACS Portable Acoustic Command System is of limited use at great depths as the slant range is fixed in firmware at something close to 7.5km. While topside commands will travel to the trench floor, and replies will still be heard on the deck unit, there is a heart-stopping moment when the display reads "No signal received" while the sinking vehicle passes the pre-set max depth range. Then a moment later, the reply is heard.

The basic Edgetech BART Board has two release commands. The addition of an optional daughter board provided four additional commands. These proved invaluable at-sea. An alternate daughter board provides a limited ascii character set, which can be adapted for a large array of commands and controls, but was not used on this mission.

A suggested improvement to the Edgetech BART board for ultra-deep deployments would be to provide for power and sensitivity adjustment in the seafloor BART unit, or connect the BART board through a secondary power booster. During ocean trench operations, reception of the acoustic replies from the lander was sometimes difficult, though it was clear the Model 8011M commands from the surface were always received at the seafloor on the first try. The operator of the topside Model 8011M deck unit can manually adjust power output levels and incoming signal gain/sensitivity. It would be useful if the seafloor BART board had the same adjustment capability through either a manual pre-set adjustment on deck, or by remote command.

*F. Connectors and Cabling*

MacArtney SubConn® connectors, including modified 1.5" shank length LPBH glass sphere bulkhead connectors, were used to interface modules within the two unmanned robotic landers. The need for additional connectors, and the lack of time to drill additional though holes in the glass hemispheres, was solved by use of a 10-pin glass BH connector that plugged into a trench-depth rated 7075-T6 aluminum junction box where additional connectors could be easily added. SeaCon (El Cajon, CA, USA) provided the single pin metal shell connectors used with the burnwires and related cathode. An external MetOcean/Novatech (Dartmouth, Nova Scotia, Canada) pressure switch was adapted to the Command/Control sphere to switch on the recovery beacons at the surface.

The camera payload team, in close proximity to the Acheron submersible development team, preferred the use of SubConn PBOF connectors on their LED lights, pressure compensated LiPO batteries, and the L3 comm controller. A special high pressure fitting was made by the Lander Team to adapt a high-pressure fiberoptic feedthrough, designed by Acheron, to the lander camera sphere.

### *G. Ballasting and Release mechanism*

A clump weight was made of 85-lbs of cast iron barbell weights. A chain was slung through the middle hole, and fastened back on its self, making a closed loop through the weights. The loose end of the chain is shackled to a 5" Dia x ¼" thick welded ring. Through this ring a second length of chain is passed. Each end of the second chain is held by a pelican hook release mechanism located on either side of the base of the Alpha Lander. Each pelican hook release is held closed by an Edgetech burnwire element. One Edgetech burnwire is connected to the Command/Control sphere, where it may be directed by acoustic command to corrode and release it's chain end. The second Edgetech burnwire is connected to an independent, stand-alone count-down timer. Should the acoustic command release system fail for some reason, the back-up countdown timer will initiate the burn of the second burnwire after a pre-set time interval of up to 99-hours.

GTRs, or Galvanic Time Releases, were sometimes used as a third release means for drop arms or even the main anchor. These were only coarsely accurate, and varied for a number of reasons including instantaneous load, temperature, available oxygen, and anode-cathode ratio, modified by attachment to steel chain.

Loop burnwires, used on the drop arm and Niskin bottle closure, are made at American Rigging (San Diego, CA, USA) to custom design specification. Each cost under $10 and are individually load tested to 500-lbs.

## IV. GLASS HOUSINGS

### *A. Glass housing design and manufacture*

Nautilus Marine (Buxtehude, Hamburg, Germany) supplied the 17-in OD x 23mm wall glass housings. The company also drilled and spot faced the penetrator holes. Some refinement continued on the size and shape of the edge chamfer to minimize spalling. Some exterior surface spalling as evident after the deepest dives as well. It is speculated this may be due to residual stress created by localized cooling during the manufacturing process. The spheres were tested to 1,000 atm at Vitrovex plant in Germany. Later testing was done to 1,225 atm at Deep Sea Power & Light (San Diego, CA, USA).

Provision was made for two bulkhead connectors and a single purge port. The purge port is used to cycle air over a desiccant to dry it prior to deployment, preventing condensation on electronics or camera lenses at the cold temperatures found at depth.

### *B. Command/Control Sphere*

A PVC ring mount was bonded to the interior surface of both hemispheres of the Command Control sphere using 3M (St. Paul, MN, USA) Fast Cure 5200 Polyurethane marine adhesive. The ring mounts provided excellent mechanical attachment to the glass, while still providing some compliance for movement of the glass under pressure. A 1/8" aluminum plate is then bolted in 6 places to each ring mount. The upper one holds the recovery beacons and their battery. The lower one holds the Edgetech BART board acoustic command board and related battery packs. Below the lower plate, the bulkhead connectors bring their wires to be tied into the BART board, and other electronics.

Acoustic Command/Control was accomplished using the EdgeTech BART board, as described above. The BART was selected for the acoustic command and control system based on number of features, reputation, and proven effectiveness for trench depth operations in a cruise the prior August 2011.

The landers recovery beacons adapted COTS MetOcean/Novatech strobe lights (ST-400) and RDF (RF-700) beacon boards. Novatech provided the boards without the standard housings as these were to be mounted inside the glass sphere, and switched on at the surface by a Novatech external pressure switch. An additional RF-700AR, a COTS RDF with remote antenna, was pressure tested to full trench depth and used as a back-up external RDF beacon without problem. An additional ST-400 strobe with a custom strobe head modified by Acheron, provided a back-up external strobe.

A MetOcean/Novatech Iridium beacon was also added to the interior. Lander operations never required the use of this device, as the lander rose to a predictable location within view of the ship. The satellite link from lander to shore, and back to our Iridium phone typically took 90 minutes. That would be helpful if we were onshore and needed to know our unit had surfaced, but in our application, we always had the lander strapped down on deck and were under way to the next site by the time we received notice from Iridium the lander was on the surface.

Duracell alkaline cells supplied Battery power for the Command/Control sphere and back-up timers. The camera used rechargeable LiPO camera battery packs. The pressure compensated LED cinemagraphic lights were powered by Acheron pressure compensated LiPO battery packs made for the DEEPSEA CHALLENGER submersible.

A pocket altimeter was used to indicate interior pressure to provide visual confirmation all seals were working prior to deployment. The altimeter can be viewed through the glass, allowing controlled purging and confirmation the seals are holding. Digital units are fine for short duration deployments, or can be modified to run off a larger system battery pack for longer durations. Mechanical Bourdon Tube gauges are harder to find, but require no power to operate. An internal pressure of approximately 10 psi is preferred.

*C. Camera Sphere*

A PVC ring mount was bonded to the interior surface of the lower, unpolished hemisphere using 3M Fast Cure 5200 Polyurethane marine adhesive. The ring mount provides excellent mechanical attachment to the glass, while still providing some compliance for movement of the glass under pressure. A 1/8” aluminum plate is then bolted in 6 places to each ring mount. The camera, the controller, and all other recorders and components, are mounted to one hemisphere. The matching hemisphere is the polished dome and is mounted once the detailed pre-cruise checkout is complete.

## V. IMAGING SYSTEM

The DEEPSEA CHALLENGE Expedition required imaging systems far superior to any ever utilized at record-setting depths. James Cameron demanded the lander capture both high quality 3D video for his 3D Imax film and, simultaneously, National Geographic-worthy high resolution still photos. Just as with any of his feature films, Cameron knew precisely the images he wanted to capture: a bait lure in the foreground swarming with never-before-seen fauna, and the DEEPSEA CHALLENGER submersible hovering in the background, observing the feeding frenzy. He was very specific as to the best angle on the sub, the need for proper theatrical lighting, even anticipating bottom currents and the need to insure that stirred sediments would not block the camera's view.

Capturing the images he envisioned became the task of engineers utilizing a radical new set of components. With prior work, two 17" OD x 23mm thick borosilicate Vitrovex glass spheres with optically-polished front hemispheres were produced and delivered by Nautilus Marine to the Lander Team in San Diego. The ability to take high quality images directly through the glass walls of a Vitrovex pressure sphere is transformative. After exhaustive comparison tests, a Canon 5D Mark II DSLR was selected by Larry Herbst, a seasoned underwater imaging expert, for its high resolution sensor and low-light capabilities. The camera was mounted inside the sphere -- and an imaging system was born. (Fig. 2)

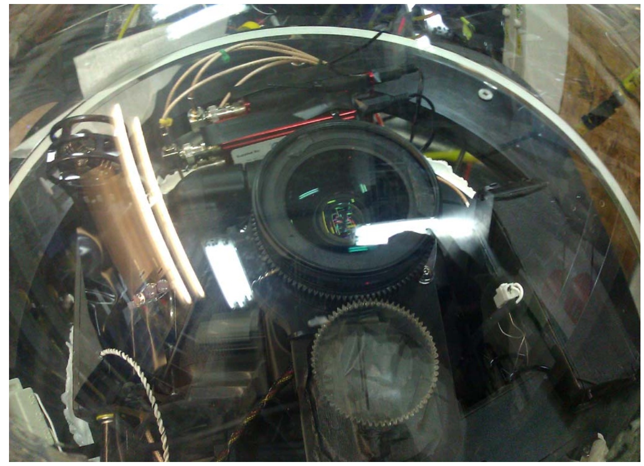

*Fig. 2. A Canon 5D camera is seen through the optically polished Nautilus Marine Vitrovex glass housing. The focus adjust gear is seen below the lens. Inside the sphere the pressure remains at 10psi, while external water pressure could approach 16,500 psi. (Photo used with permission, Earthship Productions.)*

In the black depths of the sea, the camera would need to shoot with the lens nearly wide open--resulting in extremely limited depth-of-field. Accurate focusing becomes paramount. A one-foot-deep fifty-foot-long focusing trough was built to gather focusing data through a horizontal water column. With the camera lens positioned close to the nodal point of the sphere, shooting images through the curved glass sphere proved similar to filming through a dome port, and the focus marks on the lens were immediately seen to be irrelevant. New focus measurements were taken. To focus at a distance of two meters (the anticipated distance from the camera to the end of the lander's bait arm), the lens needed to be set at 0.65 meters according to the barrel markings. To focus at eight meters (the closest approach of the DEEPSEA CHALLENGER submersible), the lens had to be set at 0.7 meters. Thus an almost imperceptible lens adjustment resulted in a large shift in actual focus. In order to hit both of these focus marks accurately (and thereby insure capturing both the sub and the bait in precise focus), a precision servomotor focusing system was designed and implemented to repeatedly and reliably shift between the two lens settings. An Arduino-based microcontroller was employed to control the camera and its focusing system, and was programmed for a variety of mission profiles and dive times. (Fig. 3)

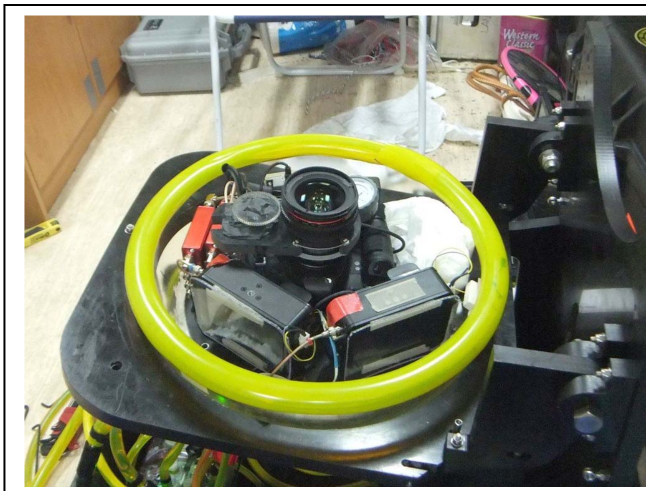

*Fig. 3. With the upper polished hemisphere removed, the interior is easily seen. The Canon 5D camera is centered on apex of the dome. The focus gear is to the left. Two Atomos Samurai video recorders, located at the bottom of the image, capture the images from the stereo camera pair located on the baited drop arm. (Photo used with permission, Earthship Productions.)*

For lighting, the lander was outfitted with four pressure-compensated LED light bricks made for the DEEPSEA CHALLENGER submersible. Three were positioned on a two-meter light boom extending to one side, allowing the key light to rake across the foreground from the far right. The fourth light was positioned high above the camera, offering fill light for shadows. To conserve energy on missions expected to last as long as 48 hours, the lights were programmed at a duty cycle of 50%, with a 3+ hour period of darkness during initial descent. Originally the camera was to take photos only when the lander lights were on -- after all, there's no point in taking photos in pitch darkness. However, unlike traditional sea-bottom surveys, the DEEPSEA CHALLENGER submersible provided a brightly lit subject, and should it approach the lander -- even during the lander's "dark" period -- it would provide more than sufficient self-illumination for a stunning self-portrait. So on sub dives the camera was programmed to cycle non-stop, at times capturing images of the illuminated bait lure and, at others, pitch blackness... until the brightly-lit submersible descended into frame. The camera was then set to bracket exposure by two stops over and under the chosen exposure, allowing the camera to capture additional shadow detail in the low light while also preventing over-exposure when the sub entered frame.

Capturing 3D Imax-quality video footage provided its own set of challenges. The mini-dry cameras, developed by Acheron (Sydney, Australia) camera technician Adam Gobi, were small cross-section HD camera units individually housed inside precision titanium shells capable of withstanding full ocean trench depth. The titanium housings are small enough to be mounted side-by-side for standard 3D interocular distance. The pair were attached to a pressure-compensated stepper motor that provided dramatic tilt-ups and tilt-downs from bait lure to submersible and back. The cameras' HD video signals were exported via optical fiber through a specially-built Acheron fiber penetrator into the Vitrovex payload sphere, where they were recorded on twin Atomos (South Melbourne, Victoria, Australia) Samurai HD video recorders sheltered within its low-pressure environment. To safeguard video data in case of power failure, the Samurai's hard drives were formatted FAT32 -- the 4gb maximum file size forced the recorders to save a new file every few minutes, thus insuring that we wouldn't lose more than a few minutes of data if something went awry.

The lander switched on the video cameras in sync with the lights, and the Samurai recorders began recording each time they detected video signals coming through the fiber. The stepper motor would then begin its pre-programmed tilt motions every 30 seconds. The plan was that, as the sub approached, the 3D video cameras would perform multiple tilts to dramatically reveal its presence. In practice, unfortunately, the stepper motor proved to be troublesome, destabilizing the camera signals and causing the Samurais to intermittently switch off. Repeated efforts to isolate the grounding issues and power spikes proved infuriatingly fruitless. The first rule of deep ocean operations -- equipment will NOT operate the way you expect it to -- eventually forced its retirement. But even as stationary cameras, the footage from the 3D cameras was exceptional, capturing the sub's activities with extreme clarity.

Together, the still and video camera systems delivered some of the clearest and most stunning images of the deepest realms of the ocean ever captured. Their relatively small size, robustness, and simplicity of operation make them ideal components of future deep sea payloads, and offer opportunities for future high quality surveys of unseen ocean depths.

Looking forward, there are several areas we are continuing to refine. The 3D video cameras offer depth and size information that can be particularly useful for measuring sea life without the need for laser guides or other virtual yardsticks. But many scientific missions can be successfully accomplished with purely 2D imagery. In these circumstances we are devising a new system that employs the HD video capabilities of DSLRs, allowing the cameras to do dual duty as both still and video cameras. This simplifies the camera payload by eliminating roughly half the equipment and allowing all of the gear to reside inside the Vitrovex sphere. Another area we are refining is the ability to service the camera and its controller from outside the sphere -- downloading imagery, wiping data cards, updating controller mission profiles and so forth -- all via WiFi, bluetooth and other wireless methods. By eliminating the need to open the sealed sphere after every dive, we hope to reduce turnaround time between dives and eliminate much of the labor and risk that comes with sealing and resealing the glass spheres. Ideally, future generations of this camera payload system will be easier to service in the field and make simultaneous deployment of large numbers of landers a far simpler operation.

We are also exploring a simple method for greatly increasing the camera system's field of view. On the DEEPSEA CHALLENGE Expedition, some of our most exciting discoveries came when the lander brought back images from the side of an undersea mount. How fortunate the camera was pointing towards the rocky outcroppings, instead of 180 degrees the other direction! Which of course highlights the need to capture ALL the surroundings of the lander, a full 360 degrees. On the final lander drop in the Siren Deep of the Mariana Trench, the anchor slipped off a rocky outcrop putting a half twist in the chain and causing the lander to make a slow half rotation due to the torque. Cal Tech's Dr. Kevin Hand used images captured by the Canon 5D over several minutes to stitch together a wide-angle panoramic view of the bottom, with startling result. We plan to do something similar on future dives, incorporating a method to deliberately rotate the lander through a full 720 degrees after landing, perhaps through as simple a mechanism as a couple of twists placed in the anchor chain and a timed release. By insuring the camera will point in all directions during the dive, we will be able to capture a full 360 degree panoramic view of the landing site. Only then will a bait arm or other anchor be allowed to lock the lander's orientation into a single position.

## VI. L3 COMMUNICATION SYSTEM

The L3 Nautronix (Perth, Australia) unit is a long-range acoustic modem that transmits and receives both voice and data communications, and can calculate total distance (range) between modems. The L3 was initially envisioned to provide 2-way data and communication between the triad of vehicles: the DEEPSEA CHALLENGER submersible, the M/V Mermaid Sapphire, and the unmanned Landers [9]. It was an early goal for the submersible to acoustically navigate to the landers on the sea floor, and, once in sight, control the landers' cameras, pan-and-tilt, and lights from an in-situ vantage point using several switchable circuits to turn relays on or off. The original L3 package specification also included an acoustic release, which was not ultimately implemented. The sub-to-lander tracking feature was also not implemented, though the air-filled spheres provided an excellent acoustic target for the submersible's sector scanning sonar.

The L3 Nautronix system – acoustic modems - operated between 8 and 12 KHz, and could transmit voice, theoretically, further than 15km. This had been tested at horizontal distances, but never to depths of 11km. Thermoclines, haloclines, varying densities, and surface noise all affect the performance of the system. As the project progressed to deeper depths, the methods of operating the system changed empirically to improve the odds of success.

The transmitted source level is attenuated significantly through 13 to 15km of slant range, therefore the L3 Nautronix was designed with a very sensitive receiver. In the field, this sensitivity made background noise the largest problem, mainly that generated by ship's propulsion and machinery noise picked up by the topside transceiver module.

Eventually the topside transceiver module had to be placed in a RHIB (Rigid Hull Inflatable Boat) boat with its dunking transducer suspended on a long cable, increasing the distance from the ship's noise, to clearly resolve the attenuated signal from DEEPSEA CHALLENGER.

The modems could also switch to data mode and transmit short text messages. This mode was less susceptible to noise than pure voice, making it a useful back-up plan for communication. The control system of DEEPSEA CHALLENGER automatically used the data modem to transmit measured depth, $O_2$ and $CO_2$ levels inside the hull, battery voltages, and other critical information. For this mode, a PC running a small application was connected to the L3 acoustic modem. The operator topside or the pilot in the submersible could type text messages into a window, and receive text messages in the receive window.

The ranging feature is based upon a high precision timing circuit in both the submersible and the topside transceiver module that are synched with each other after power up. Each message transmitted contains the precise instant it was sent, so the receiver can calculate the time-of-travel through the water column. With the measured speed-of-sound throughout the water column provided by the CTD, a very good estimate of the range between modules was determined.

This "ranging" feature was also applied to interrogate the submersible from two different surface vessels (Mermaid Sapphire and Prime RHIB). By using the intersecting range rings from the two vessels at different locations at the same instant, a reasonably accurate position for the submersible was obtained.

For use on the Landers, the L3 acoustic modems had one shortfall – there was no PC running the text application, and there was no person to send and receive the texts.

In practice, the L3 Nautronix team was on a very tight schedule to deliver the basic system, and the system was having some unforeseen delays.

With an already tight delivery schedule, technical challenges in the principle communication and ranging features demanded the attention of the engineering team. As a result, L3 was unable to work on the acoustic release and additional relay functions in time for the planned dives. This was a big problem, as the original intention was to use the L3 control functions for the landers' anchor drop, and as a back-up to drop the submersible's ballast weights in the event its pilot was disabled.

Working with L3, the Indepth Marine Ltd. team outlined two solutions: the first was to build a PBOF circuit board as an interface to the L3 Nautronix modems, and the alternative, the same circuit in a pressure resistant housing. Either would communicate from the lander or submersible to the topside transceiver module to control lights, cameras and drop weights.

Identifying and qualifying pressure tolerant electronic components in the short time frame was becoming problematic, so the alternate solution, the pressure resistant housing, was chosen. Nicknamed the "Bulman Bottle," it was designed and built by the Acheron engineering team. The full ocean depth titanium pressure housing enclosing the electronics, and was filled with 3M (St. Paul, MN, USA) Fluorinert, an electrically insulating, stable fluorocarbon-based fluid, to minimize implodable volume near the submersible. Fluorinert has a specific gravity of 1.9, adding in-weight to the lander, which had to be offset by additional syntactic foam.

An Arduino board was used for the controller. During the development, interface questions arose. James Lumsden, the L3 Nautronix engineer who had programmed much of the modems was on hand for testing and integration. Since he had developed much of the communication protocols for the L3 modems, he offered to program the board that would communicate with them. He was able to get the boards performing well within 3 days.

During early testing, there was a power issue – each time the modem transmitted at the power level required for full ocean depth communication, the power would cut out and then return to normal voltages. Subsequently, the modem would lose its timing sequence, canceling time of flight through water, making ranging meaningless. The problem was bench tested over and over, but it only seemed to happen during real dives, when the fault was diagnosed after it surfaced. The L3 team was later able to resolve the issue, and when it mattered most, on the DEEPSEA CHALLENGER's Deep Dive, the ranging and communication systems worked flawlessly down and back again.

The Alpha Lander received the submersible's back-up L3 system, which had not been entirely de-bugged. Most lander command/control was done with the Edgetech communication system, countdown timers, and on-board Arduino-based camera controllers. The final two lander deep dives, one in the Challenger Deep, and one in the Sirena Deep, had the L3 system removed from the lander.

## VII. Samplers and Sensors

Samplers included water sampler Niskin Bottles, fish net traps, and sediment corers. The fish traps worked well for amphipods. An additional Niskin bottle was mounted on the drop arm to lay on the seafloor and capture animals. This worked well. The sediment corers, using core catchers recovered some material, but not the undisturbed 10" long cores hoped for.

RBR Ltd. (Kanata, Ontario, CA) supplied DR-1050, a self-contained, submersible depth recorders, housed in a small separate Ti 6-4 cylinder (38mm diameter, 220mm long). Pressure measurements are made to 24-bit resolution. The DR-1050 is calibrated to an accuracy of ±0.05 % full scale using NIST traceable standards. The data was recorded in solid-state memory and read using RBR's RUSKIN GUI software. The data provided insight to the landers' fall rate, bottom time, release time, and rise rate, and to correlate the high definition stereo images of the life forms and geologic features with the extreme depths where they were found.

## VIII. Testing

Testing of the lander proceeded in stages. A saltwater basin at Scripps main campus was used to check air and water weights of unassembled components.

Underwater connectors were individually tested to 18,000psi in a pressure chamber at Scripps Institution. Several fully assembled glass spheres were pressure tested at Deep Sea Power and Light (San Diego, CA, USA)

Load tests were performed on critical load-bearing components.

The first assembled lander was lifted by a crane and tested off the Scripps Nimitz Marine Facilities wharf to check in-water stability and ballast. An anchor release test was also performed. A chartered vessel was hired to take the system off shore. A release test pierside validated all release and recovery systems. Then, offshore, a tethered 30m tested was performed. With all systems functioning, a final 1,200m untethered test was performed successfully.

## IX. Operation

The lander lay on it's back on deck to make access to all segments convenient, and the platform more stable on deck in transit. Lander operations were moved from the main vessel, the MV Mermaid Sapphire, to a separate vessel, the M/V Barakuda, which had a moveable A-frame and winch. A numbers of cleats were added to the stern bulwarks in Guam.

With multiple dives, the deck crew became quite adept at handling the large lander. The launch sequence of raising the lander, moving it over water, slipping the anchor, clearing taglines, lowering the lander, and pulling the quick release would take just 3-1/2 minutes.

The Lander dove pretty much straight down and back as expected. The fall and rise rates were high enough that little time was spent in any current, and minimizing lateral offset. The Edgetech comm system provided good slant ranges. We would nudge the ship towards the anticipated surface arrival point. On the final two lander deep dives, the vehicle broke surface within 50m of the vessel. It was important to the biological samples to get them aboard and out of the warm surface water as soon as possible.

On recovery, the vessel approached from downswell. The ship then worked against the swell, providing better steerage, and precluding the ship being pushed over the floating instrument.

## X. Conclusion

The DEEPSEA CHALLENGE Alpha Landers demonstrated their capability as payload haulers and autonomous robotic camera platforms. The speed with which the lander project was completed was due in part to the utilization of common tested components used across several vehicle platforms, including the landers, an ROV, and the DEEPSEA CHALLENGER manned submersible.

The DEEPSEA CHALLENGE Alpha Landers became an important exploration, research, and engineering platform.

The DEEPSEA CHALLENGE Expedition Alpha Landers collected biological samples, including giant amphipods at depths greater than ever seen before. Some photographed were astounding for their massive size. The landers also gathered sediment samples, water samples, sensor data, and high-resolution still images of animals and video sequences of their behavior in the manner of Schwartzlose and Shutts [10].

The final dive in the Sirena Deep of the Mariana Trench, arguably the second deepest place on Earth, culminated the lander ops. Dr. Patricia Fryer, University of Hawaii, speculated on a number of geologic conditions with potential biologic results, and selected the site for the exploratory dive. A twist of fate was a twist in the anchor chain, and as the vehicle rotated with the torque, it took a panorama shot looking up slope then across. Dr. Fryer's entire string of hypothesis, each one built on the last, was seen in that one photo sequence.

Following the DEEPSEA CHALLENGE Expedition, James Cameron donated the Alpha Lander, spares and topside command gear to Scripps Institution to establish a multi-user Lander Lab. The shared resource will broadly benefit the institution by providing numerous Scripps scientists and their colleagues with the proven ability to explore the deepest regions on Earth.

In addition, Cameron donated one of the polished Vitrovex camera spheres, with a Canon 5D camera, logic board and servo focus unit, to the Hadal Ecosystems Studies (HADES) Program of Woods Hole Oceanographic Institution (Woods Hole, MA, USA), contributing to their collaborative investigator efforts to explore the deep sea with lander systems.

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The lander team, led by "Lander Commander" Kevin Hardy, expresses their most profound gratitude to James Cameron for the extraordinary opportunity, backed by his true commitment, to demonstrate the functionality of the deep sea lander system. Cameron's passion for exploration, blended with his natural mechanical aptitude and team building skills, pushed the design field ahead 10 years, and then a little more.

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