Report to BSEE:

HC-Sentinel: An AUV Glider for High Endurance Subsea Hydrocarbon Detection

Final Report

Work Performed Under Contract
E14PC00017

Submitted by:

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Executive Summary

HC-Sentinel is an AUV glider equipped with a mass spectrometer which was developed as a low operational cost, long-range platform for detecting hydrocarbon pollution in marine environments. Its minimalist architecture decreases its operational costs to orders of magnitude lower than conventional subsea leak detection vehicles. Additionally, because the HC-Sentinel can operate longer durations than conventional AUVs and without an attending surface vessel, leak inspection and survey can be conducted continuously for extended periods, including in sea states where surface ships could not operate (i.e., severe storms and hurricanes).

HC-Sentinel weighs 85 kg in air and can be deployed/recovered by two people from a small rigid inflatable boat. This vehicle platform is capable of operating up to 1,000 m water depth. Its payload mass spectrometer has a useful mass range of 7 to 200 AMU and is capable of detecting hydrocarbons at trace levels. In its current configuration can operate continuously for approximately 4 days (130 km or 70 nautical miles) before recharge of the mass spectrometer payload battery is required.

Demonstration operations were conducted during September 2016 in the Santa Barbara Basin, off the coast of California. During the course of these operations the HC Sentinel glider conducted a total of 160 dive cycles to a maximum depth of 570 meters (1,860 ft) covering 25 km, at an average speed of 37cm/s. The web-based software provided real-time control and data viewing, enabling useful situational awareness.

In-situ mass spectrometer data collected during demonstration operations consists of more than 170,000 georeferenced chemical measurements recorded during more than 20 hours of operation. The instrument’s expert system identified water column petroleum hydrocarbon anomalies, at levels down to parts-per-billion, with meter-scale georeferenced accuracy. Comparative analysis of these anomalies indicates that they correlate closely with published historical data and maps of known seafloor hydrocarbon seep sites in this area.

Further development of the HC-Sentinel design, particularly through the development of vehicle pressure hulls with increased depth capability, modification of the vehicle battery power system to make it fully rechargeable, integration of an underwater acoustic system, and the augmentation of the buoyancy engine with a hybrid thruster will greatly enhance the system’s utility. Specifically, deeper pressure hulls will enable the vehicle system to operate in deeper offshore areas of oil and gas production (i.e., 1,000 to 3,500 m) within the United States exclusive economic zone. A fully rechargeable battery system will extend the endurance of the vehicle to approximately two weeks between recharge, increasing coverage distance to more than 450 km (250 nautical miles) between recharge. The addition of an underwater acoustic modem/location transponder would enable the vehicle to send data and receive mission

plan updates without delay, allowing it to spend more time collecting data, and minimizing the danger of being struck by a vessel while surfaced. Finally, the addition of a hybrid thruster would enable the vehicle to conduct survey and monitoring operations that require close terrain following, such as benthic environmental assessment and infrastructure inspections (e.g., pipelines and wells).

Overview of the HC Sentinel

The HC Sentinel is a modified Slocum electric glider [3, 4] equipped with an ultra-low power mass spectrometer payload. The vehicle and payload system has an overall weight of 85 kg in air and length of 2.5 meters (fig 1). The vehicle is designed to operate to a maximum water depth of 1,000 meters (3,281 ft), with a maximum endurance of 3 days before requiring recharge.

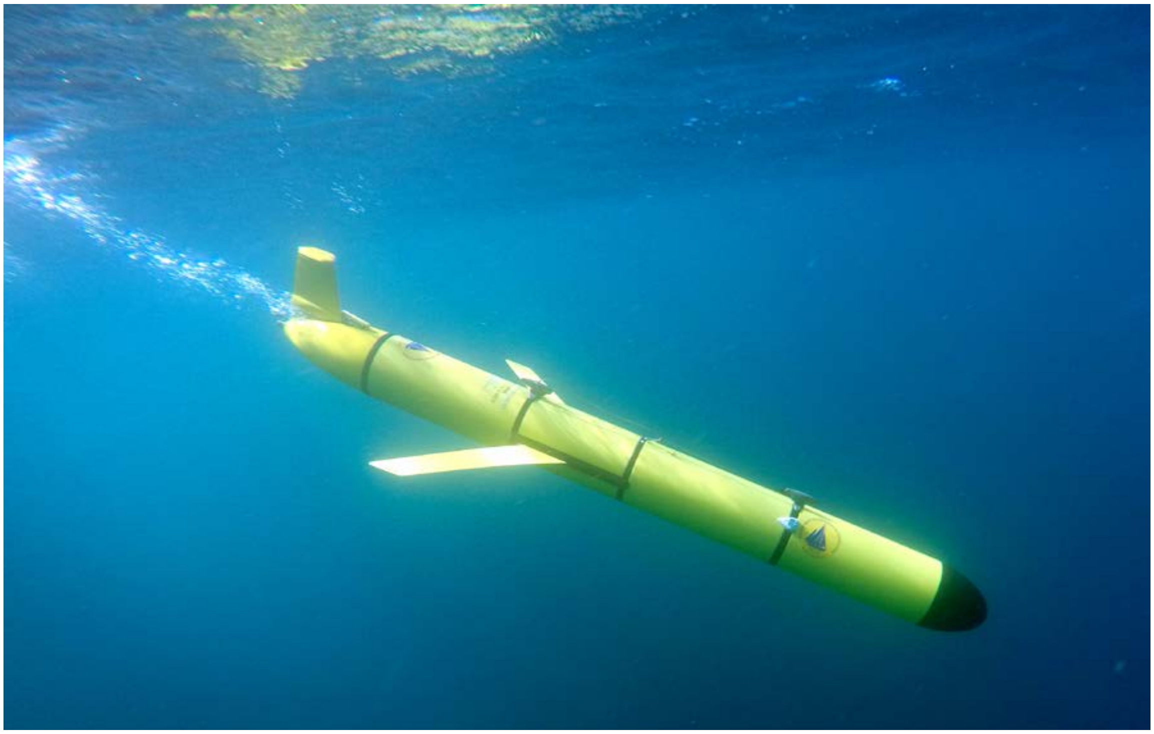


Figure 1: Underwater photo of HC-Sentinel on initial descent after being deployed from a surface vessel during demonstration operations in the Santa Barbara Basin.

Vehicle propulsion is provided by a buoyancy engine which, by changing the vehicle's displacement, causes the vehicle to move forward in an undulating saw tooth glide pattern, alternating between +/- 28 degrees from horizontal. The density difference provided by the buoyancy engine and coupled with the lifting surface of the vehicle wings and body enables the vehicle to generate a speed through water of roughly 0.42 m/s (0.85 kts). This translates to an average speed over ground (X-Y plane) of approximately 0.37 m/s or roughly 0.7 kts.

Payload hardware

The payload mass spectrometer uses a miniaturized double focusing prolate trochoidal analyzer [5], measuring 5 × 4 × 2 cm (fig 2). Embedded within the analyzer volume is a dual electrometer faraday cup, and frequency modulated electron impact ionization source. The analyzer's magnetic focusing is achieved using a 5000 Gauss rare-earth magnet which has been designed to minimize external fringing fields. Although this magnetic field is approximately 10,000 times stronger than the Earth's magnetic field, the instrument's magnetic field is more than 99% contained within the instrument. The instrument’s stray magnetic field intensity decreases to less than the Earth's magnetic field at distances greater than 0.2 m (approximately 8 inches) from the magnet (fig 3), enabling the vehicle system to use a low-power fluxgate compass heading reference for navigation. Vacuum pressure (below $2\times10\text{-}6$ μTorr) is maintained by an ion pump and ultra-high-vacuum valves, which automatically close on loss of power, are actuated via the instrument's embedded computer and enable the analyzer to maintain vacuum in all states (e.g., operational, standby, failsafe).

The payload mass spectrometer weighs 9 kg in air and occupies a volume of 7 l. The analyzer and ion pump are located in the forward payload bay section, and the 780 WHr rechargeable Li-ion battery pack is located in the aft payload bay section (fig 4). The mass spectrometer, battery pack and associated electronics serve as structural elements of the instrument's mounting frame in order to minimize weight and size. The assembly is fixed to a 0.05 kg aluminum frame spanning the fore and aft stiffener rings within the vehicle's pressure housing. The frame's design allows the payload to safely tumble in the water column (when swept by a breaking wave at the sea surface) and passively damp shock and vibrations of up to 10G. Accelerations recorded during shipping indicate that the frame assembly has survived accelerations exceeding 25G.

The mass spectrometer sample inlet, which is mounted to the vehicle’s forward stiffener ring, relies on the vehicle's movement through the water to generate a passive flow through the mass spectrometer inlet. The passive flow is designed to preferentially exclude buoyant gas bubbles and oil droplets while providing sufficient water flux to analyze dissolved gases and volatile chemical in the water column (fig 5). This approach eliminates the power requirement of active pumping and the inlet is shaped to minimize power loss caused by vehicle drag. A medical-grade high precision thermistor is embedded within the inlet, which measures inlet temperature in real time as the vehicle transits through the water column.

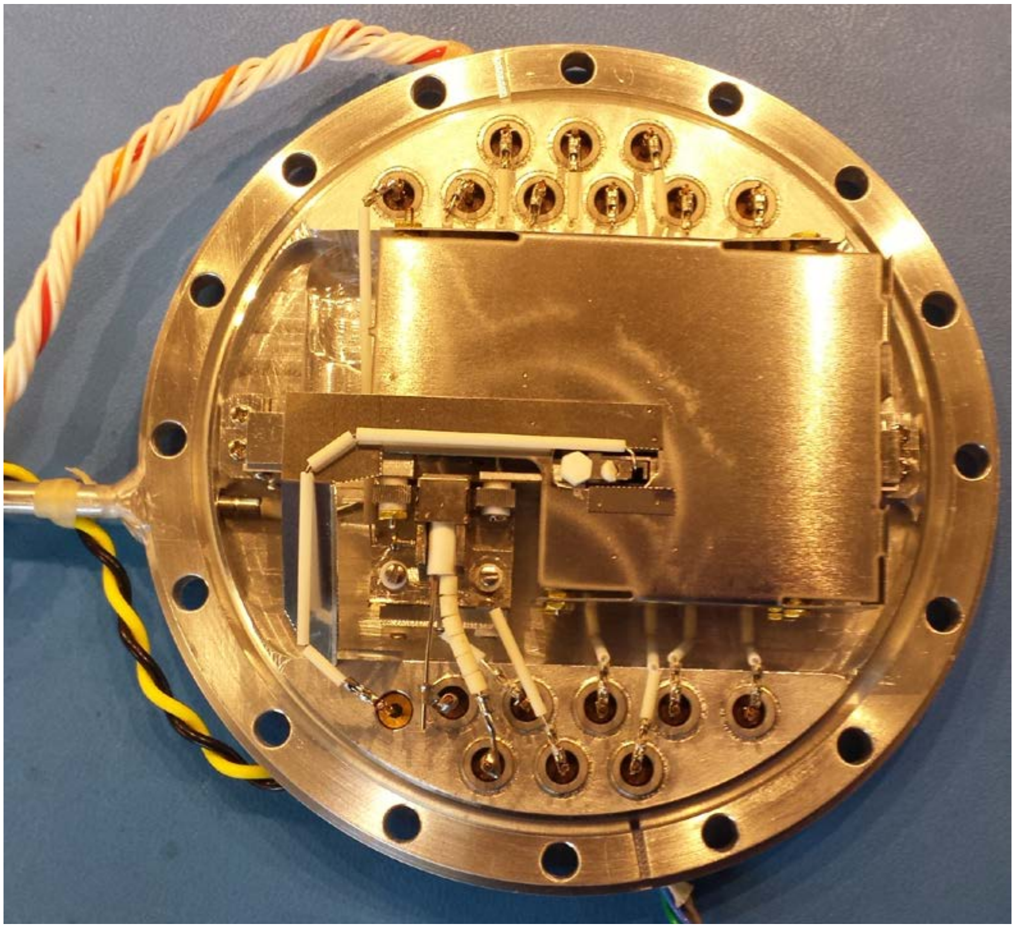


Figure 2: Photo of Sentinel mass spectrometer.

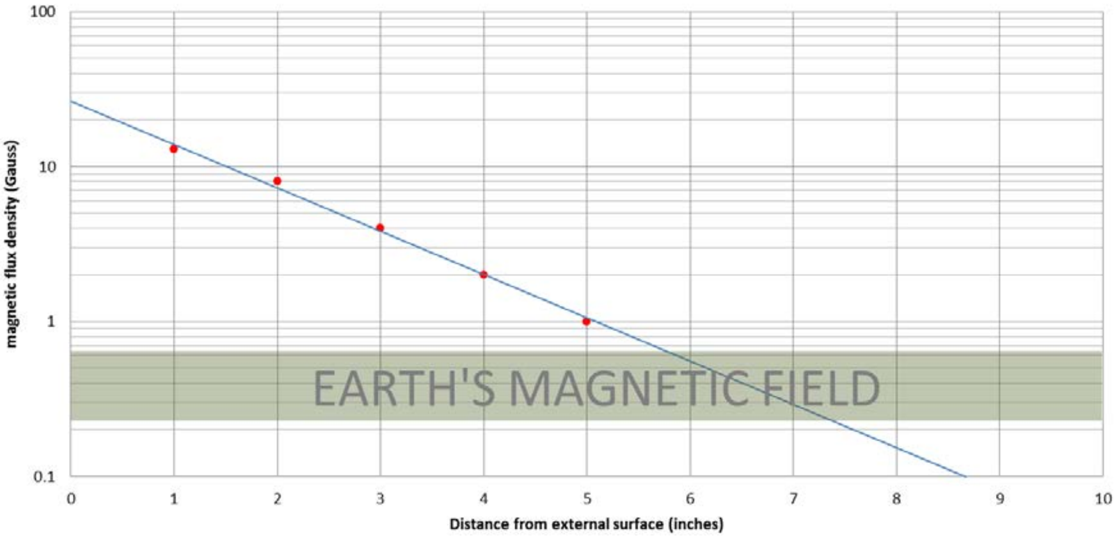


Figure 3: Measurement of stray magnetic field flux density recorded external to the mass spectrometer magnet.

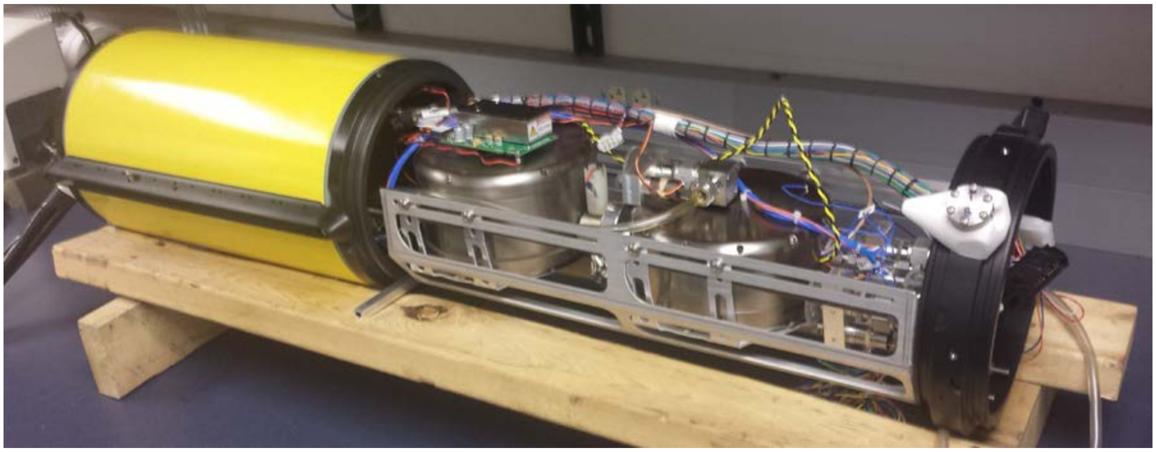


Figure 4: Photo of the payload bay sections. The forward pressure hull is removed showing the mass spectrometer.

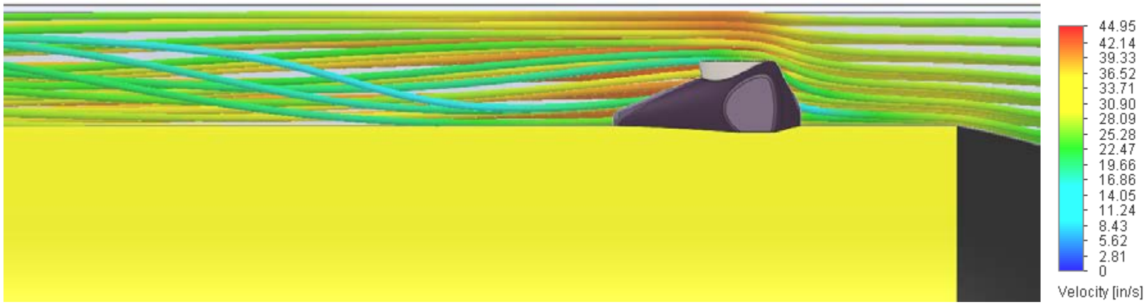


Figure 5: Profile view showing FEA model of water velocity vectors at the inlet region. The shape of the inlet cowling helps to maintain relatively laminar flow aft of the inlet, decreasing vehicle drag.

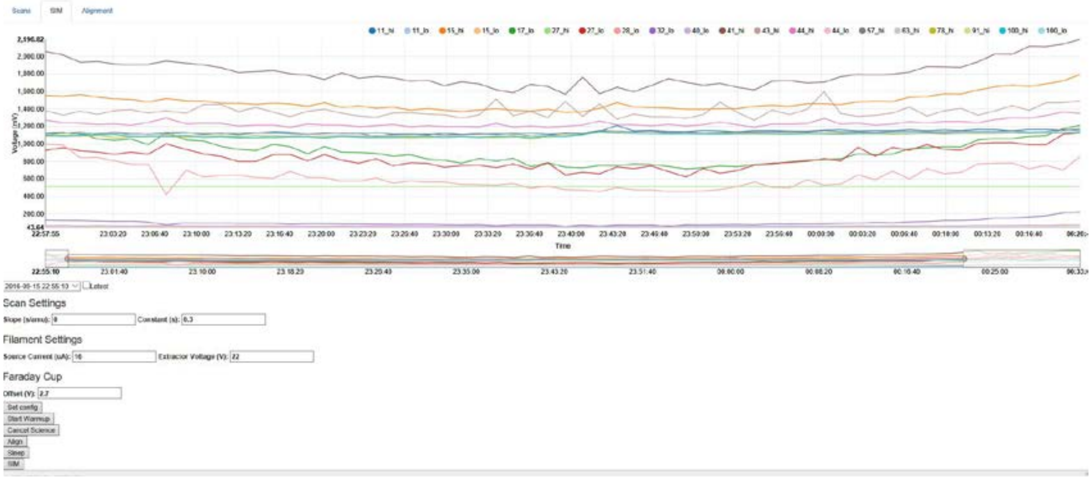
Mass Spectrometer control

The vehicle system uses a distributed computing architecture using five embedded processors and a PC-based remote dockserver [6] and mission planner. Embedded microcontrollers handle low-level mass spectrometer operations and report to an ARM-7 payload processor, which runs on a Linux operating system. The mass spectrometer and its PIC microcontrollers can be placed into low power standby, or turned off in software by the payload processor.

Mass spectrometer operation is controlled by a software daemon which enables the automated recover from hard reboots by the payload processor. The mass spectrometer is capable of four states: standby, emergency shutdown, and two operating modes: selected ion monitoring (SIM), spectrum scanning. Mission plans are transmitted from the dockserver to the vehicle via a 900MHz radio or RUDICS satellite link. Prior to entering an operational mode, the daemon performs a diagnostic assessment of subsystem component states. If a subsystem is determined to be out of normal operational range, the instrument will either enter a recovery standby mode, or in the case of a severe malfunction, the will trigger an emergency shutdown that requires a manual override.

In SIM mode the payload computer steps through electric field set points corresponding to the centers of individual ion peaks. In spectrum scanning mode the instrument steps through an electric field potential range at an increment defined in fractions of AMU. The mass value is calculated using a non-linear curve fitting equation of common atmospheric gas ion peaks. During low power standby as well as SIM and spectrum scanning modes the daemon monitors the analyzer's magnet temperature and performs an automated electric field adjustment to compensate for thermally-induced deviations in the analyzer's magnetic flux density. Alignment calibration tests of the analyzer indicate a monotonic ion optic response across a mass range from 7-200 AMU.

Instrument data can be transferred in a highly compressed format over WiFi (100 m range) as well as lower bandwidth Freewave radio (2 mile range) and Iridium satellite (worldwide) data links. The user interface is web-based, allowing multiple users to simultaneously view data and control the glider from a standard web browser on most computers and smartphones (fig 6).



2016-06-15 22:55:13

Scan Settings

Slope (s/amu): 8 Constant (s): 6.3

Filament Settings

Source Current (uA): 16 Extractor Voltage (V): 22

Faraday Cup

Offset (V): 2.7

Figure 6: Screen capture of web-based mass spectrometer controller and data visualizer, showing SIM data collected during glider dive operations and transmitted over radio link while the vehicle was surfaced.

Sea Trials

Following single day trials in Buzzards Bay, MA the initial glider design was during a cruise of opportunity in the Timor Sea (fig 7). The AUV glider was tested with its ARM-7 computer architecture in advance of integrating the full MS payload. Initial dive operations revealed a power instability caused by back EMF generation by the buoyancy engine pump when operating in waters deeper than 30 m, causing the processor to glitch. This problem was corrected by building an additional power stabilization circuit. Following this hardware modification, testing of communication between the vehicle flight computer and the payload computer demonstrated continuous vehicle computer operation without failure. The HC-Sentinel was deployed for multiple dive missions over 7 days, with a total operation time of approximately 36 hours.

Following integration of the mass spectrometer payload sections and compass calibration the glider underwent final sea trials in the summer of 2016 in Buzzards bay and Nantucket sound. During these sea trials ARGOS beacon, WiFi, Freewave radio, and Iridium satellite communications were demonstrated. Dives consisted of shallow ~10 meter deep dives along constant headings. Vehicle operation data collected during these dives indicate that the glider's horizontal velocity is approximately 35 cm/s (0.7 kts) and that a buoyancy engine inflection (from diving to ascending) requires about 2 minutes.

Figure 7: Test deployment of HC-Sentinel with modified computer architecture during a cruise of opportunity in late March-early April, 2015.

Mass spectrometer data collected during sea trials in Nantucket sound indicated that temperature variations in the water column do cause variation in field strength of the analyzer magnet. Although the mass spectrometer's rare earth magnets do create measurable biases in the vehicle's measured fluxgate compass heading, data indicate that this bias was fully corrected using a standard compass calibration routine following vehicle assembly and ballasting.

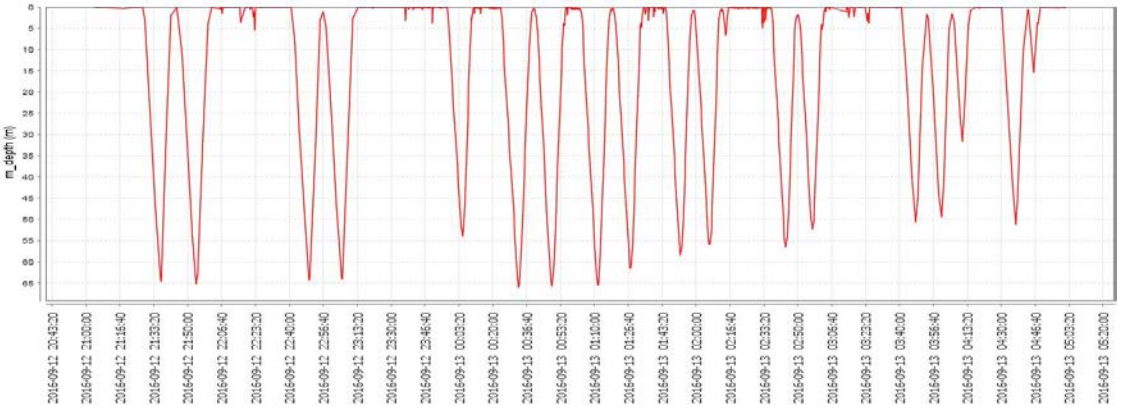
Demonstration operations

Demonstration operations in the Santa Barbara Basin were conducted from September 5-16, 2016 aboard the *M/V Truth* (fig 8). The glider arrived damaged from shipping. Following mobilization, the glider and mass spectrometer underwent major repair, requiring complete disassembly of the glider and mass spectrometer. Repairs included a rebuild of the ion pump, and replacement of the ion source. Following repair and re-assembly (Sept 7 -9) the Sentinel glider progressed through deck and shallow water testing (Sept 10-11). Although the damage to the vehicle and mass spectrometer caused a scheduling setback, the repairs were successful and demonstrated that the system is field repairable.

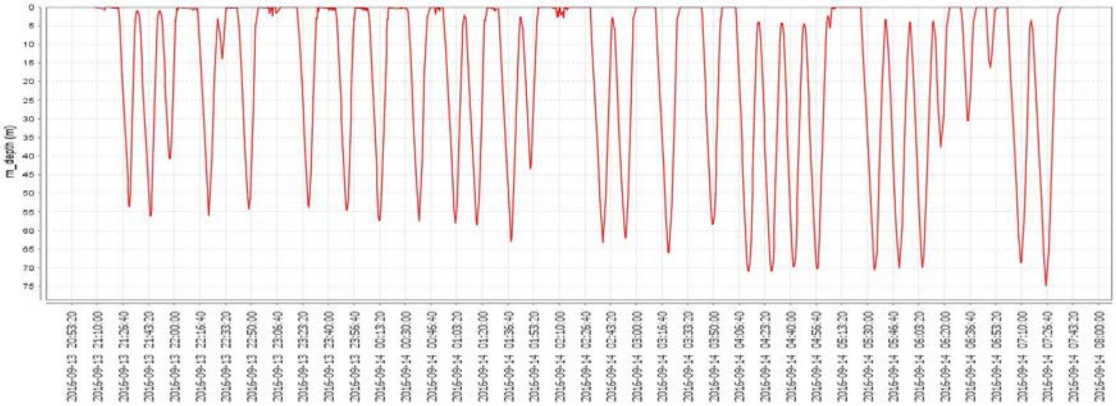
Figure 8: Photo of Demonstration Operations group with HC Sentinel glider following completion of operations.

Vehicle operation and data collection

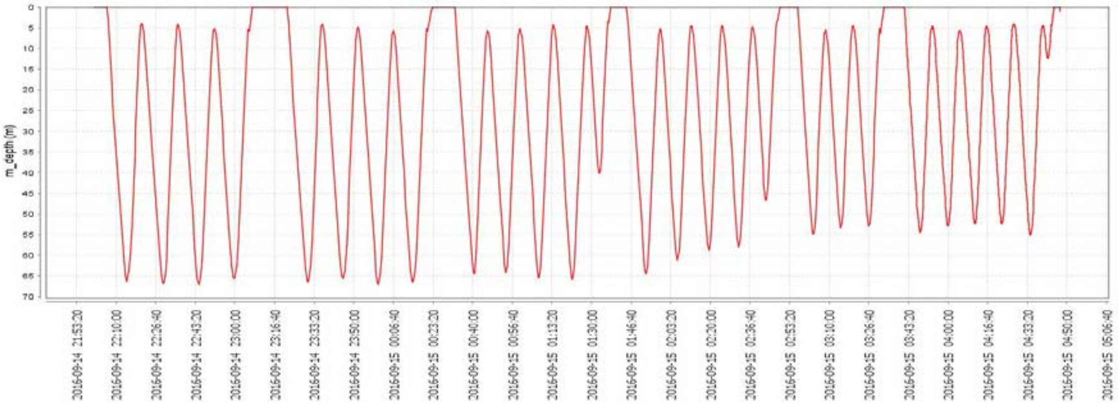
Following shallow water checkout dives, demonstration operations were conducted from Sept 12-15 (fig 9). From Sept 12-14 dive operations were focused on the coastal shelf areas with the glider completing dives of up to 75 meters (246 ft) water depth. On Sept 15 the field of operation shifted to the deepest region of the Santa Barbara Basin, where the glider completed two dives to 570 meters (1,870 ft). Each shallow water dive (coupled descent and ascent) lasted approximately 20 minutes, while each deep water dive lasted approximately 2 hours. Over the course of these operations the HC Sentinel glider conducted a total of 160 dive cycles, covering 25 km, at an average speed of 35cm/s. During these 20 cumulative hours of operation, the vehicle’s in-situ mass spectrometer recorded over 170,000 georeferenced chemical measurements. During these demonstration operations significant water column currents were encountered in the coastal areas, with maximum currents exceeding 25 cm/s during the full moon.



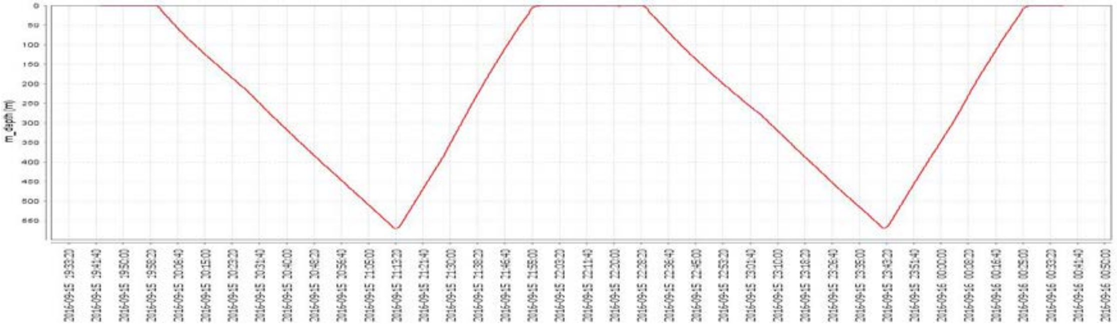
Sept 12 depth time series



Sept 13 depth time series



Sept 14 depth time series



Sept 15 depth time series

Figure 9: plots of recorded depth of vehicle during dive operations from Sept 12-15. Depth records are expressed in meters and date/time in UTC.

Geospatial hydrocarbon analysis

Mass spectrometer data recorded during the demonstration operations reveal elevated hydrocarbon concentrations, such as methane and benzene in localized areas around the Patch and Goleta cold seep sites (fig 10), with subsea concentrations in excess of 145 ppb and 2.5 ppb, respectively, near these seeps. Data recorded in the near shore area of demonstration operations reveal a general trend of decreasing hydrocarbon concentrations with increasing depth (fig 11), with water column hydrocarbons typically greatest near the sea surface in areas of known seeps, presumably due to the presence of oil slicks/sheens.

Processing of these data using an expert system for automated classification and clustering identified 31 target locations associated with hydrocarbon compositions indicative of close proximity to a source location (fig 12). These anomalies align well with previously located seafloor source locations in the area of the Golita and Patch seeps.

Mass Spectrometer data collected from the deep basin dive series indicated significantly reduced hydrocarbon levels compared with the coastal area described previously. A brief hydrocarbon anomaly was observed during the start of the deep dive sequence which is associated with the engine exhaust of the surface vessel. Concentrations of methane and benzene are characteristically less than 75 ppb and 1ppb, respectively. Although increased hydrocarbon concentrations were recorded in the surface waters, and are thought to be associated with drifting surface sheens. Curiously, a small, but significant increase in benzene concentration (increasing to approx. 2ppb) was identified during both deep dives at 570m water depth (fig 13). The initial hypothesis is that this benzene increase may be due to diffusive input from nearby asphalt volcanos and/or from fallout of weathered oil mousse slicks that are transported down from the sea surface. Further investigation of the other is required to understand this benzene anomaly.

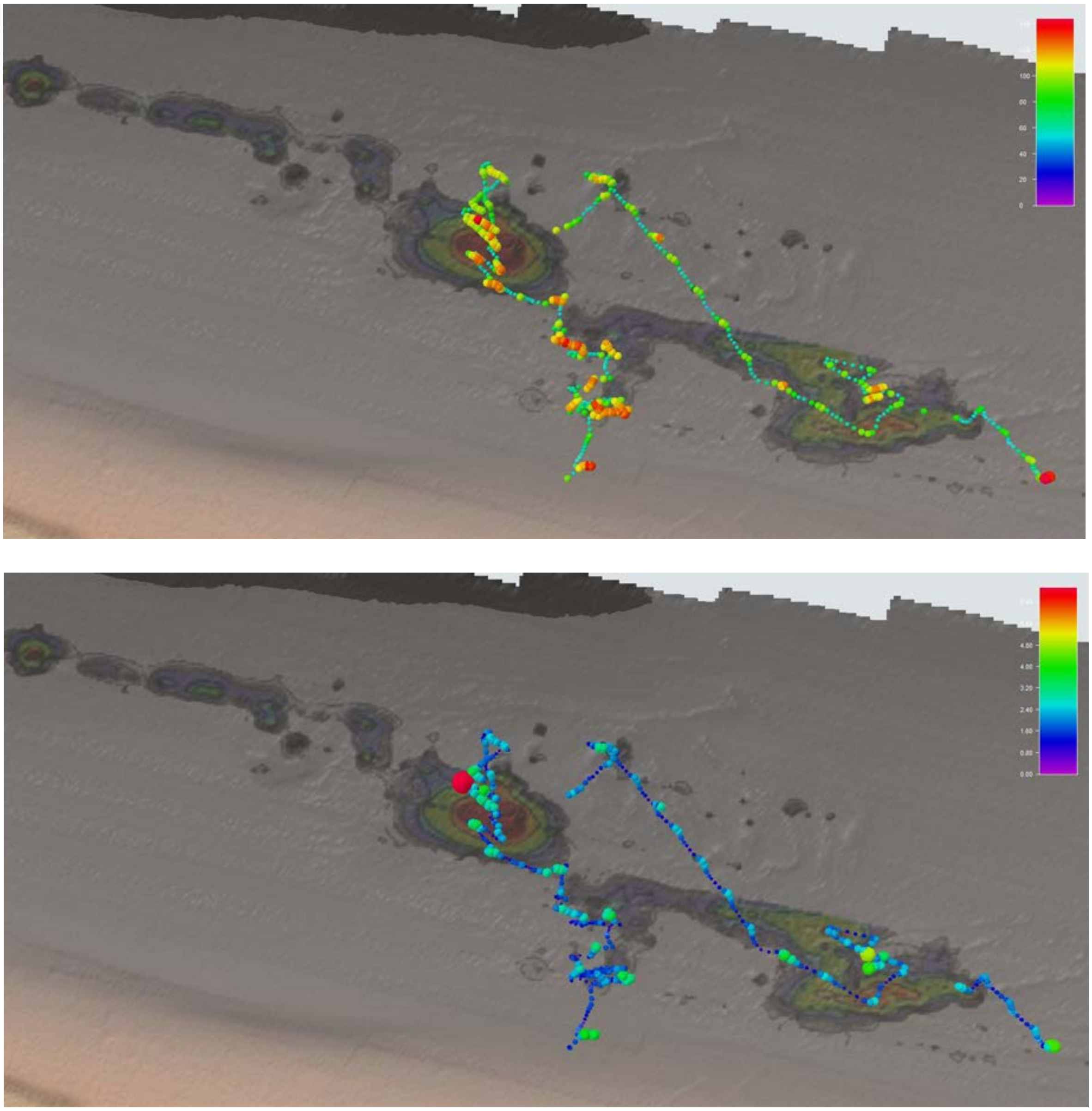


Figure 10: Plan view of methane (upper panel) and benzene (lower panel) distributions recorded during dive operations in the vicinity of the la Golita and Patch hydrocarbon cold seeps. Concentrations are expressed in ppb. The contour image layer shows areas of historically active seepage areas adapted from [1] and overlain onto a multibeam digital terrain map, courtesy of [2].

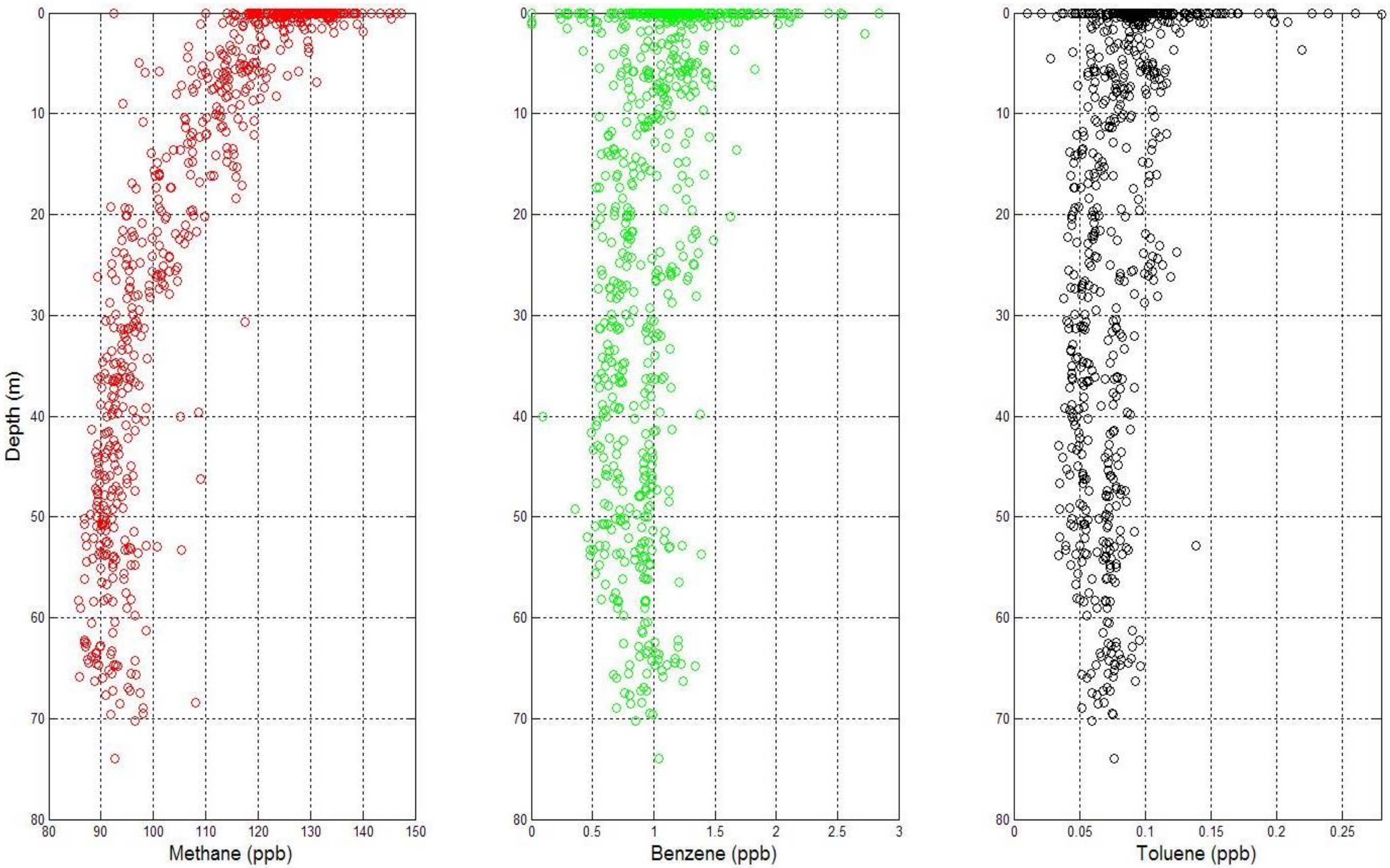


Fig 11: Water column profile of methane, benzene, and toluene concentrations in the near-shore region of the la Golita and Patch seeps.

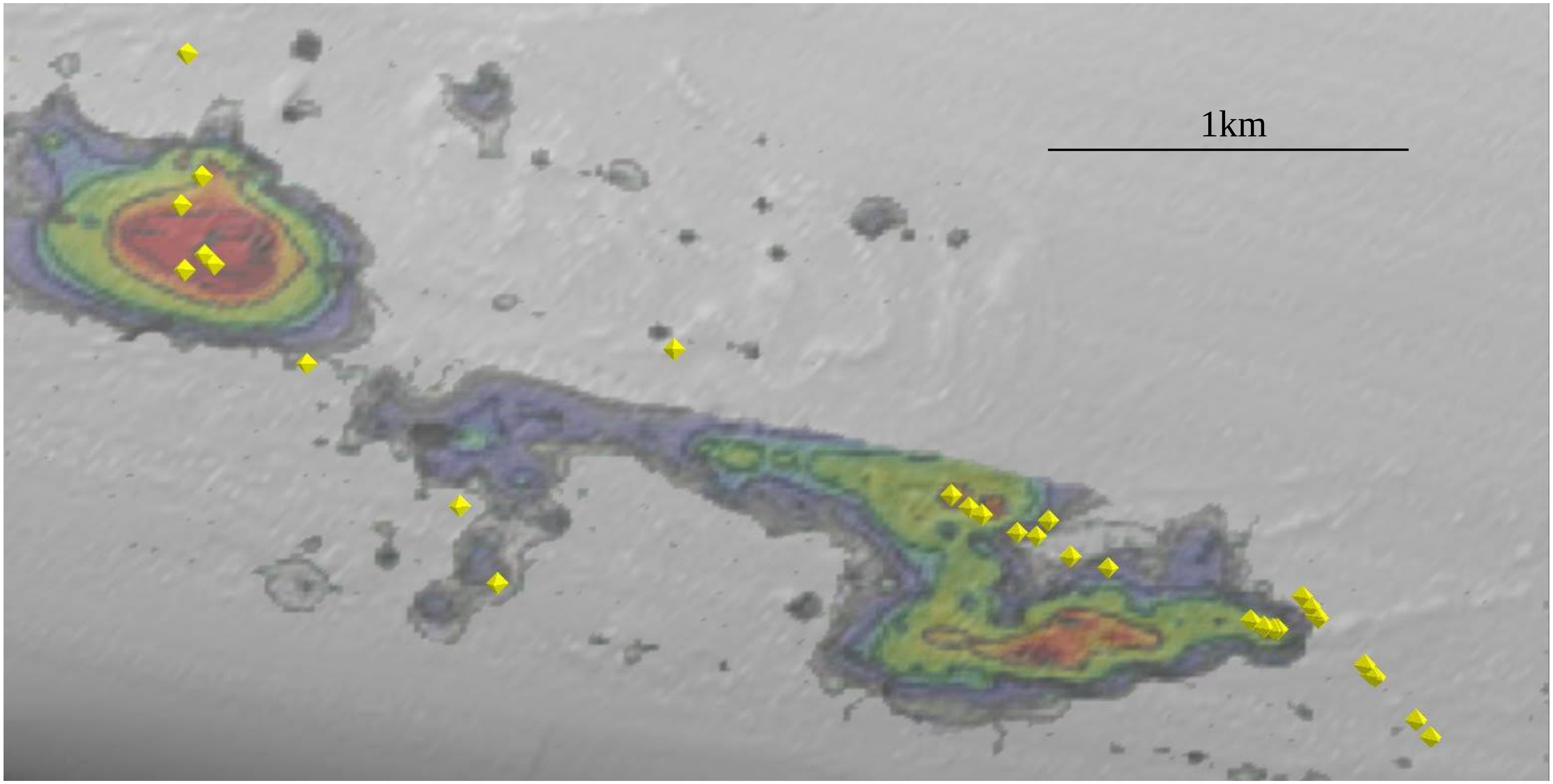


Figure 12: Plot of hydrocarbon anomaly locations (expressed as yellow diamond icons) . . The contour image layer shows areas of historically active seepage areas adapted from [1] and overlain onto a multibeam digital terrain map, courtesy of [2].

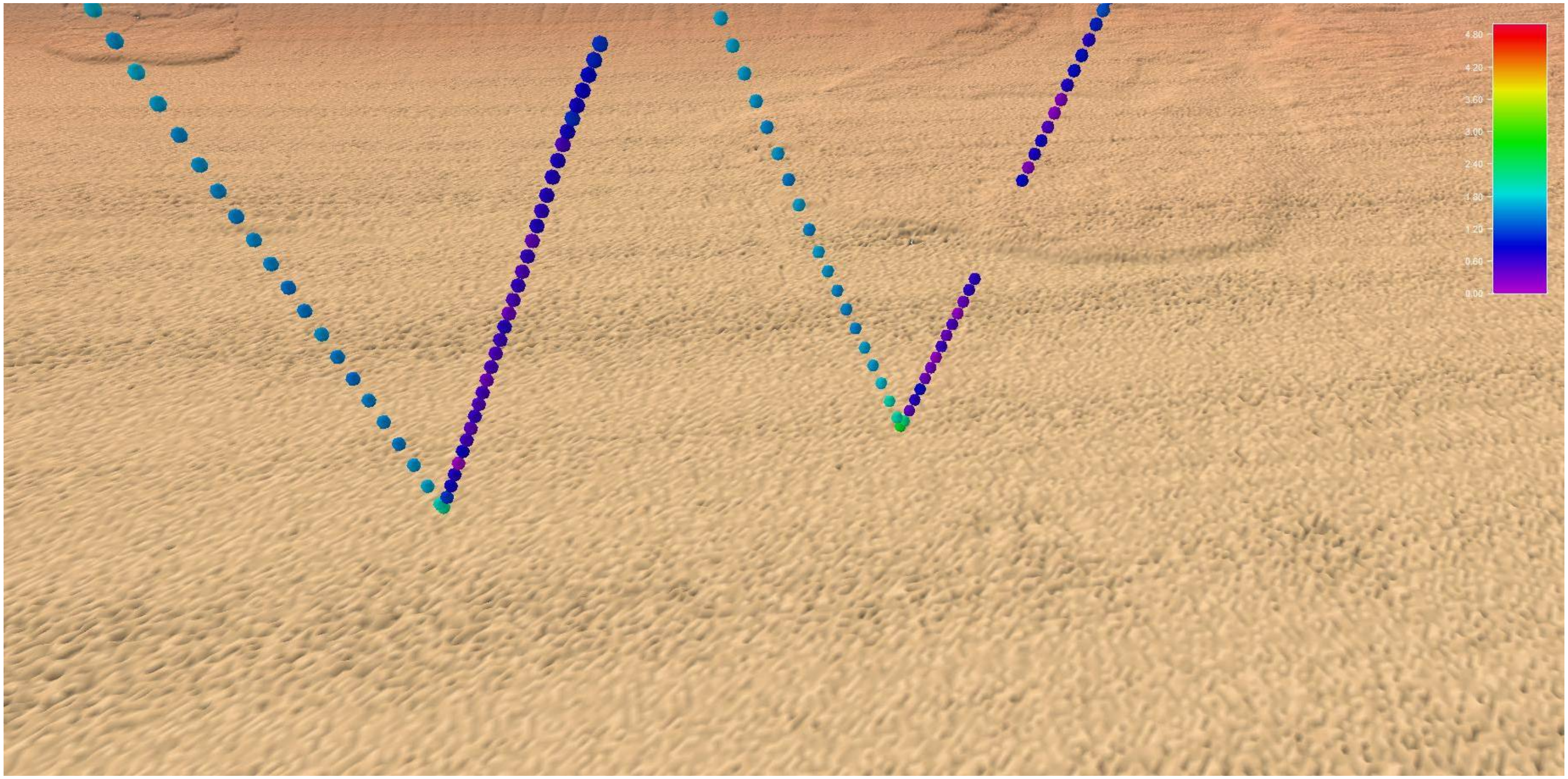


Figure 13: Magnified perspective view of hydrocarbon data recorded during dive operations to the deepest region of the Santa Barbara Basin. Consistent increases in benzene concentrations to approximately 2ppb are visible in the range of 560-570 meters water depth during both dives. The vehicle's dive inflection points are approximately 2 km away from each other and 15 meters above the seafloor.

Future work

Further development of the HC-Sentinel design focusing on improving the system's ability to operate 1) for extended periods, 2) at greater depths, 3) with variable velocity, 4) underwater acoustic telemetry and, 5) in close proximity to seafloor infrastructure will greatly enhance the system's utility for subsea hydrocarbon leak detection.

Fully rechargeable battery system

Preliminary calculations indicate that a fully rechargeable Li-ion battery system could be developed for the HC-Sentinel that would carry at least 3.2 kWHr of energy and be approximately 5kg lighter than the current battery system which is a combination of alkaline primary (vehicle flight battery) and Li-ion secondary (payload battery) packs. The redesigned Li-ion battery would allow approximately 2 weeks of operation between recharge, extending the system's range to more than 450 km (250 nautical miles) between recharge.

Transition to a fully rechargeable system would enable the vehicle to be recharged while at sea. At present, the non-rechargeable alkaline vehicle flight battery must be physically replaced and the vehicle re-ballasted in a motionless ballast tank, requiring that the vehicle be transported back to shore for this procedure. Replacing these non-rechargeable alkaline batteries with rechargeable Li-ion batteries would enable the vehicle to be fully recharged within a few hours while at sea (potentially without requiring physical recovery of the vehicle), saving both time and money by avoiding the return to shore for maintenance. This factor is increasingly important as the HC-Sentinel operates further from its maintenance port. As can be seen in fig 14, a fully rechargeable battery system would be able to support a significantly higher duty cycle/operations tempo than the non-rechargeable system. This would be an important consideration if the HC-Sentinel were called upon in response to a petroleum spill in the arctic, or a large-scale release such as occurred in the aftermath of Hurricanes Katrina & Rita, or the Macondo well blowout.

The decreased weight of this battery design would provide additional benefit by allowing for more payload carrying capacity and/or allowing for a slightly smaller subsequent generation of vehicle design. A particularly useful modification that would be enabled by the lower weight battery system would be the addition of a hybrid thruster.

Hybrid thruster

At present the HC-Sentinel must move through the water column in an undulating motion. Modification of the vehicle to include a hybrid thruster would enable the vehicle to move through the water horizontally in addition to its normal saw tooth motion. This would enable the vehicle system to conduct close bottom following surveys of seafloor infrastructure such as pipelines, jumpers, and wells. Configuring the thruster to provide variable velocity, would enable the vehicle system to safely operate in closer proximity to infrastructure than what is now possible (>70 meter standoff distance). This would be particularly important when inspecting complex infrastructure in areas with high water column currents (e.g., Gulf of Mexico loop current). The addition of a hybrid thruster would also assist with detailed assessment of natural seeps as indicators for the federal government to better establish the value of lease particular blocks prior to auction, and for baseline environmental assessment of areas prior to their development.

Acoustic modem/location transponder

A second modification that would be enabled by the lighter weight battery pack would be the addition of an underwater acoustic modem/location transponder. This communications system would enable the HC-Sentinel to transmit data in real time while still under water and to receive periodic position updates to correct for navigation error. The addition of an acoustic telemetry system would increase the support infrastructure requirements, entailing surface vessels, or underwater communications nodes. However, autonomous surface vessels, such as Wave Gliders [7], have been demonstrated as a low cost (~$1k/day) option for mobile node communication to satellites while a vehicle is underwater [8]. This capability is particularly useful when operating in deep regions ~1,000 m because the transit time for the vehicle to surface can be several hours, which delays data and mission plan updates. By increasing the speed/frequency of these communications and navigation updates, the vehicle has less need to surface, allowing it to spend more time collecting data, and minimizing the danger of being struck by a vessel while surfaced (this safety concern is particularly important in areas with high traffic shipping lanes.

Deeper pressure hulls

Finally, modification of the HC-Sentinel's pressure hulls to allow for a 3,500 m operational depth would enable the system to survey the all areas of deep water production facilities within the Exclusive Economic Zone of United States. At present these facilities are only accessible by work class ROVs and large-displacement AUVs, which require an attending surface ship and have an associated rate in excess of $100,000/day. The HC-Sentinel design would lower the cost of operation by roughly 100 fold, while allowing the survey and inspection to be conducted continuously, including in sea states where surface ships could not operate (i.e., severe storms and hurricanes).

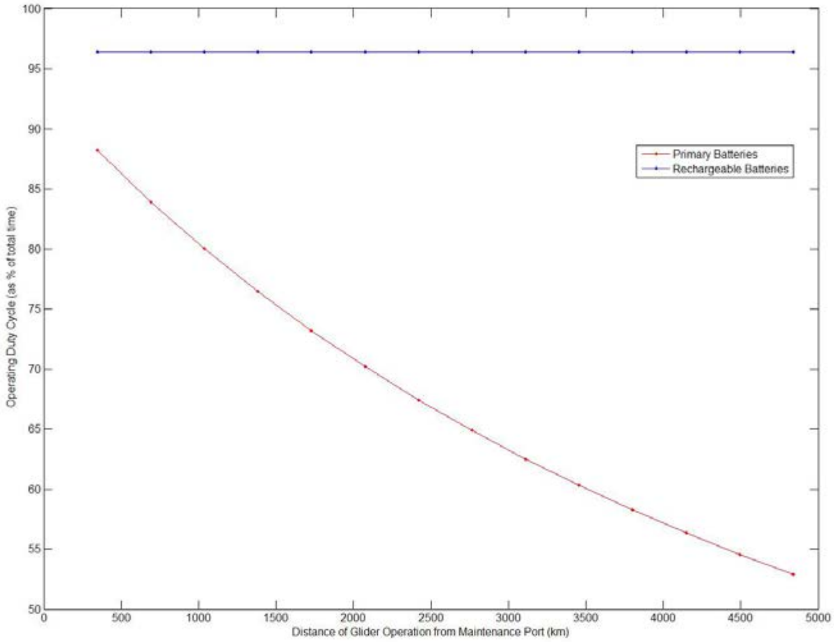


Figure 14: Plot showing the operational duty cycle when factoring in shipping transit time for a non-rechargeable vehicle to be brought back to shore for battery replacement and re-ballasting. This is calculation assumes a surface vessel transit speed of 10 kts, and one full day for battery replacement/re-ballasting, vs a 12 hour in-situ recharge.

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