REAL-TIME IN-SITU CHEMICAL AND LOCALIZATION SENSORS INTEGRATION IN HUMAN OCCUPIED SUBMERSIBLE FOR STUDYING HYDROTHERMAL VENTS

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Abstract

In June 2006, a research program was undertaken to investigate areas of suspected hydrothermal venting at the Greek islands of Milos and Santorini. This program utilized the two person research submersible *THETIS*, equipped with a high precision navigation tracking system and in-situ mass spectrometer, along with commercially available conductivity and temperature sensors, water, biologic, and geologic sample collection systems. This paper describes a novel integration of the sensor payload on the submersible which successfully demonstrated real-time *in-situ* analysis and mapping of hydrothermal venting.

Keywords: Hellenic volcanic arc, mass spectrometry, underwater navigation.

1. Introduction

The Hellenic Volcanic Arc is a 500km long southward-concave active volcanic system developed in the Southern Aegean Sea. Active hydrothermal venting has been observed on shore on most of the volcanic islands (Georgalas, 1962; Fytikas, 1977) while active seafloor hydrothermal venting sites are found near Milos, Santorini, and Poros. Active venting has been discovered recently (Sigurdsson *et al.*, 2006) at about 500m depth in the Columbo submarine volcano.

A research program part of project *PHAEDRA* investigated suspected hydrothermal venting sites, ranging in depth from 90 to 350 meters, near Paleochori Bay and within the north basin of the Santorini caldera using the Hellenic Center for Marine Research (HCMR) *Thetis* human occupied submersible equipped for the first time with a suite of *in-situ* chemical sensors, a precision navigation system and a novel network integration allowing real-time mapping and analysis of scientific data. This paper describes a novel integration of the sensor payload on the submersible which successfully demonstrated real-time *in-situ* analysis and mapping of hydrothermal venting. The chemical and geological analysis of the collected data will be addressed by the authors in a future publication.

2. Methods

Survey operations were conducted using the HCMR *Thetis* which is capable of operating up to 610 meters depth for up to nine hours mission duration. *Thetis* is typically equipped with obstacle avoidance sonar, two hydraulic manipulator arms (5 and 3 degrees of freedom respectively) and a vacuum sample collection system. Visual survey is accomplished by an external digital video camera mounted on the technical bar directly forward of the cabin, as well as a high definition video camera and multiple still cameras within the crew cabin. Illumination is provided by two 400 Watt HMI and six 150 Watt halogen lights.

For this research program *Thetis* was also equipped with an acoustic navigation tracking system and a payload of *in-situ* water column chemical sensors. By measuring the vehicle location in real-time, scientific survey can be conducted in a controlled, systematic fashion. Additionally, the chemical measurements can be more precisely georeferenced, providing information on spatial distribution and in some cases temporal variability. This approach also provides the pilot and observer in the submersible with real-time estimates of Thetis position via an onboard graphic and text display. The real-time display improves the overall efficiency of survey operations, enables the pilot to execute organized survey patterns, and permits revisitation of specific sites even when visual references are poor. Upon completion of a dive these position estimates can be made more accurate using post-processing techniques.

2.1 NAVIGATION AND POSITIONING IN THE SEA FLOOR

Human occupied submersible vehicles are conventionally tracked from the surface vessel using ultra short base line acoustic (USBL) navigation systems (Kinsey et al., 2006). Prior to this research program the main navigation system for the Thetis submersible was a USBL tracking system. Such systems fulfill operational and safety requirements by permitting personnel on the support vessel to keep track of the submersible position. But for scientific mapping purposes, this type of system has several drawbacks. First, the position fixes are available on the surface vessel but not in the submersible unless they are telemetered via an acoustic modem or relayed via underwater telephone. Second, USBL systems have limited accuracy, with error growing as a function of slant range from the ship to the submersible. Finally, USBL systems are vulnerable to erratic fixes and dropouts caused by acoustic or electrical noise induced by the vessel and to assumption that the sound velocity will be constant in all the water column.

Therefore, the approach for this research program combined several complimentary navigation sensors. This technique fused long baseline (LBL) navigation and Doppler velocity log (DVL) dead-reckoning. The DVL provides a smooth, continuous bottom track and the LBL system provides less frequent fixes, but those fixes are accurately registered to the seafloor (Whitcomb et al., 1999a). The DVL and LBL systems are complimentary, therefore, a composite estimate can utilize the high-update rate and precision of the DVL estimate with the long-term stability of the LBL estimate. This combination has previously been used to provide real-time navigation on a variety of human occupied and robotic platforms including AUVs, ROVs, and human occupied submersibles (Whitcomb et al., 1999b). The resulting high level of accuracy enables closed-loop near-bottom dynamic positioning and precise survey of the seafloor (Kinsey et al., 2006) and has proven highly useful for deep-sea science (Yoerger et al., 2007).

For this research program a 1200 kHz DVL was integrated under the *Thetis* cabin to improve XY position accuracy (0.3% precision, 1 – 5 Hz refresh rate at ranges up to 25 meters from the seafloor). In addition, a WHOI micro modem (Freitag et al., 2005) was integrated onto the submersible, just above and aft of the portside vertical thruster (Fig 1). This micro modem interrogated a 10kHz (Benthos) LBL transponder grid that was placed on the seafloor (consisting of two transponder beacons at approximately 300 meter spacing) and surveyed in by the R/V *Aegeao* prior to dive operations. Position estimates from each system was combined via a common software interface – DVLNAV (Kinsey and Whitcomb, 2003). DVLNAV software provided the submersible's pilot and scientist with real-time XY navigation temporally synchronized with payload sensor data.

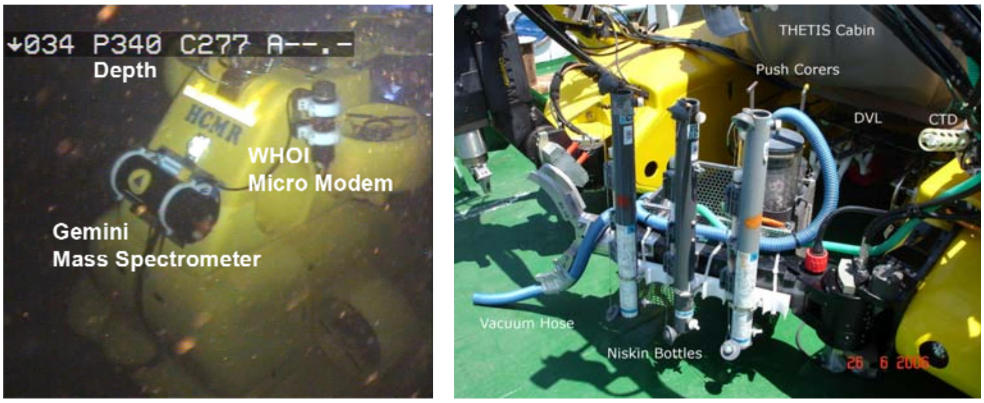

Figure 1: (left) Photo taken from the Achilles ROV of the Gemini mass spectrometer operating aboard the *Thetis* submersible at a depth of approximately 340 meters in the Santorini caldera. The micro modem is visible in the upper right of the photo, just aft of the portside vertical thruster. (right) The front of Thetis equipped with a vacuum and sample collection system, CTD, three Niskin bottles, four push corers and DVL.

This navigation system utilized RS232 serial communication protocol to transmit navigation data to a laptop computer inside the cabin; all other sensor data was transmitted to the laptop via a novel 10 Mb/s Ethernet developed on this project specifically for *Thetis*. This Ethernet communication system was crucial, as it allowed a large number of sensors to be integrated with high data rates without exceeding the limited number of available through-hull penetrations on the submersible and without violating the electrical isolation and ground-fault detection system critical to safe operation of the submersible.

2.2 SAMPLING, MEASUREMENTS, DATA COLLECTION AND TRANSFERRING

Vent chemistry analysis was carried out using a Gemini in-situ mass spectrometer (MS), conductivity temperature and depth sensor (CTD), and Niskin bottles for water sample collection and post-dive gas chromatographic (GC) analysis. Geologic sampling was carried out using the submersible's manipulator arms to collect rock specimens and a rack of four push corers and a vacuum "slurp" sample collection system, (Fig 1).

The Gemini MS was developed in 2004 at the Woods Hole Oceanographic Institution (WHOI) for in-situ analysis of trace dissolved gases and volatile compounds in the marine environment. It is capable of measuring analyte molecules from mass 2 to 290 AMU and operates to a maximum depth of 1,000 meters. For these operations the mass spectrometer was mounted to the submersible's aft exterior surface, directly behind the crew compartment and lateral thruster during deployments onboard the Thetis vehicle, (Fig 1).

The MS employs a continuous flow sample introduction with inline CTD (Seabird model SBE43). CTD data is conveyed directly to the mass spectrometer computer, permitting real-time interpretation of MS data as well as external supervisory input to adapt Gemini operating parameters. The MS provides satisfactory measurement stability across its full spectral range for durations of up to tens of hours. (Camilli et al., 2006).

Water samples were collected during dive missions and subsequently underwent shipboard analysis using a Shimadzu 14B extended gas chromatograph (GC), equipped with multiple columns, as comparative ground-truth for the mass spectrometer data.

3. Results

A total of three study sites were investigated with Thetis and the payload sensors; two sites along the southern coast of Milos, and one within the Santorini caldera. Dive operations typically lasted from 40 minutes to three hours and ranged in depth from 60 to 350 meters. For this paper, we focus on the technical and operational results of this work. Further discussion on chemical and geological analysis is out of the scope of this paper and they will be addressed by the authors in a future publication.

3.1 SE MILOS ISLAND

The first dive mission of the program was an operational test of the sensor systems onboard Thetis in a hydrothermally inactive area near the southern coast of Milos at a depth of approximately 60 meters. As a safety precaution, the dive sequence was initiated with all science payload sensors power off. Upon the submersible's arrival to the seafloor, payload sensor electronics underwent systems checks, followed by the standard startup sequence and operation. The Gemini MS and CTD recorded data for the remaining duration, including ascent to the surface. The study site for the second dive mission was in an area southeast of the Fyriplaka volcano containing suspected hydrothermal vents at depths of approximately 115 meters. During this and subsequent dive missions the Gemini mass spectrometer was started in advance of the dive. The sensor payload provided evidence of small scale but active hydrothermal venting (Fig 2).

3.2 NE SANTORINI CALDERA

The third study area was at an area of suspected active hydrothermal venting at the northeastern part of the northern basin of Santorini caldera at approximately 340 meters depth. The site is located on the 'Columbo Line', a SW-NE running zone of brittle deformation and faulting, which extends towards the NE in the Amorgos basin. Real-time mass spectrometer data gathered during this dive did not indicate any significant variation in methane, oxygen, or carbon dioxide levels, nor any sulfides or other dissolved gases associated with volcanic venting.

4. Discussion

This research program was the first time that a suite of *in-situ* chemical sensors and precision navigation system was used aboard the *Thetis* vehicle and was also the world's first successful deployment of a mass spectrometer payload onboard a human occupied submersible.

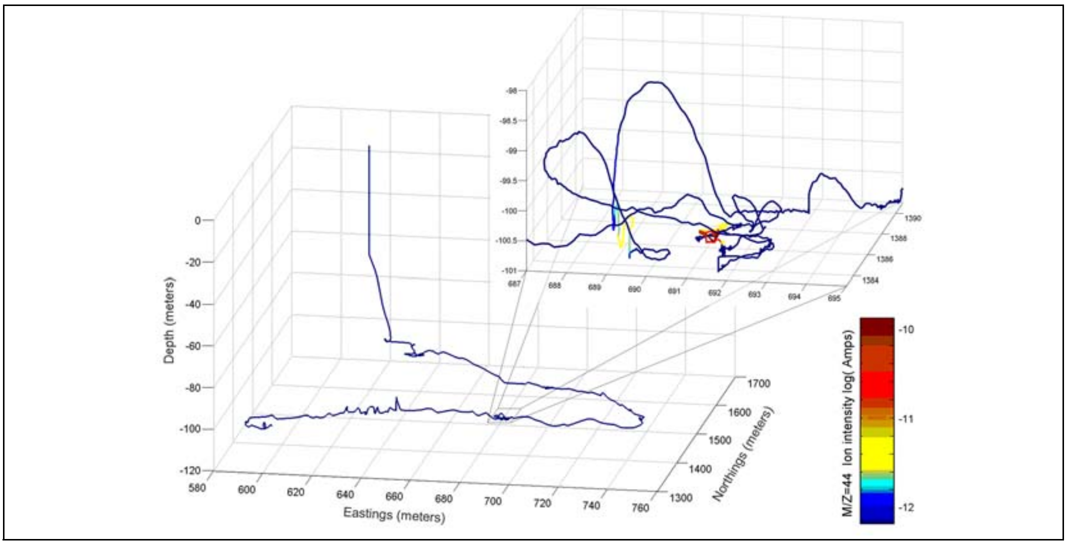

Figure 2: Gemini mass spectrometer estimates of carbon dioxide levels merged with Doppler velocity log x-y position estimates and CTD depth data collected during the second Thetis dive in a hydrothermally active area of Paleochori Bay. Inset plot shows detail of CO2 anomalies detected in a highly localized area of the seafloor.

The Gemini MS reliably collected data at spatial and temporal scales which are orders of magnitude greater than traditional means. The submersible's 10Mbit/second Ethernet system enabled a scalable and rapidly reconfigurable (i.e. between dive operations) sensor payload to transmit data and be controlled by the crew in real-time. Accurate instantaneous estimates of vehicle position and tracklogs of the dive missions enabled efficient identification of active hydrothermal vents and repeatable survey operations at study sites in bathymetrically rugose areas with visibility less than two meters.

The coverage area and spatial resolution provided by in-situ mass spectrometry in combination with precise navigation demonstrates the utility of real-time chemical mapping for efficient and repeated geochemical investigations of seafloor hydrothermal venting. The methods described here are also suitable for other types of underwater platforms such as AUVs (Camilli, 2004; Yoerger et al., 2007) and ROVs (Camilli and Duryea, 2007) in investigations of hydrocarbon cold seeps, brine pools, deep ecosystem biochemistry, point source pollution detection , and air-sea gas exchange. In particular, these methods may be appropriate for assessing green house gas contributions from shallow submarine hydrothermal venting and their distributions.

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