A New Navy Deep-Water Oceanographic Survey Vehicle: the Naval Oceanographic Office's Subsurface Autonomous Mapping System (SAMS)

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***Abstract*-The Subsurface Autonomous Mapping System (SAMS) is a full-ocean-depth (6000-meter) autonomous vehicle with integrated physical oceanography and bottom-mapping sensors. Developed for the Naval Oceanographic Office (NAVOCEANO) by the Woods Hole Oceanographic Institution Ocean Systems Laboratory, SAMS is a new NAVOCEANO capability for deep-sea oceanographic data collection. SAMS is equipped with a CTD, an optical backscatter sensor, an ADCP, and a side-scan sonar. The SAMS vehicle is designed to conduct two types of missions: independent physical oceanographic data collections and side-scan sonar bottom mapping surveys. SAMS can collect 10-12 hours of side-scan and oceanographic data or up to 16 hours of oceanographic data with the side-scan sonar disabled. At a cruising speed of 4 knots, the vehicle can survey more than 40 nmi during mapping missions and nearly 65 nmi during oceanography missions. The range of the vehicle, its ability to conduct preprogrammed and redirected missions, and its multipurpose sensor suite allow NAVOCEANO to conduct large-scale, deep-water oceanographic and ocean bottom feature exploration with greater efficiency and flexibility.**

I. INTRODUCTION

One of the primary missions of the Naval Oceanographic Office (NAVOCEANO) is “to conduct multidisciplinary ocean surveys and to collect and analyze all-source oceanographic data” [1]. To meet this tasking NAVOCEANO operates seven oceanographic survey vessels worldwide.

The goal of the NAVOCEANO autonomous underwater vehicle (AUV) program is “to multiply the effectiveness of oceanographic survey ships, allowing survey of larger areas in less time than with a ship alone” [2]. The Subsurface Autonomous Mapping System (SAMS), operated by the Ocean Projects Department within NAVOCEANO, is a new NAVOCEANO capability engineered to meet this goal.

This paper will provide an overview of the SAMS vehicle, with a limited discussion of its capabilities and limitations, and will also outline SAMS’ intended concept of operations. This paper will also provide some initial estimates of how the SAMS vehicle can multiply ships’ survey capabilities and also how it will increase data collection efficiency relative to existing survey instruments.

II. SAMS CAPABILITIES

SAMS was developed and built by the Woods Hole Oceanographic Institution (WHOI) Ocean Systems Laboratory (OSL) for NAVOCEANO. SAMS is built around the Remote Environmental Monitoring Unit System (REMUS) AUV software (another OSL product) and has many of the same sensors as that shallow-water system [3,4].

Engineering and specific technical details of the SAMS vehicle are provided in [5]. However, a brief overview of operating characteristics and vehicle sensors is included in this paper.

A. Vehicle Characteristics

SAMS is a free-swimming, programmable, and redirectable AUV. The SAMS vehicle is full-ocean-depth rated (6000 m; 20,000 ft) and has been tank-tested to that depth. Field testing to 5000 m (16,500 ft) was completed in March 2003.

SAMS is typically navigated using Long Base Line (LBL) techniques for high positioning accuracy; acoustic transponders are deployed and surveyed by the SAMS host vessel, and the SAMS vehicle computes its position based upon signal time-of-travel from the transponders. SAMS’ LBL navigation is essentially identical to that of the REMUS vehicle, described in [6]. SAMS is also capable of independent navigation, using global positioning system (GPS) positions at the surface and a high-accuracy internal gyroscope and acoustic doppler current profiler (ADCP)-determined bottom-track speed to estimate subsurface velocity and position.

The vehicle is both programmable and redirectable. A set mission is typically downloaded to the vehicle during topside workups, and if programmed correctly the vehicle will operate accordingly. However, the SAMS operator can also redirect the vehicle during a deployment, allowing for mid-mission changes in vehicle tasking. This allows for active investigations of unusual oceanographic features or of unusual bathymetric or geologic features identified during data playback and analysis.

SAMS is powered by two rechargeable lithium-ion battery assemblies. The batteries supply 8 kWh at 25 V and can sustain vehicle operations for at least 12 hours. After vehicle recovery the batteries can be completely recharged within 8 hours. NAVOCEANO deploys the vehicle with two pairs of battery assemblies, reducing turnaround time and therefore maximizing survey time.

A summary of vehicle characteristics is provided in Table I. The vehicle is usually deployed with a descent weight and recovered after dropping the ascent weight. These are the most efficient means of moving the vehicle vertically, although SAMS is capable of driving itself up or down as required.

TABLE I
VEHICLE CHARACTERISTICS

Capability	Specifications
Maximum Depth	6000 m (20,000 ft)
Endurance	
Oceanographic Survey	16 hrs[a]
Bottom-mapping survey	12 hrs
Descent Rates	
Self-Driven	24.3 m min^{-1}
Descent-Weight	46.5 m min^{-1}
Cruising speed	4 knots
Ascent Rate	
Self-Driven	41.3 m min^{-1}
Ascent weight released	134.7 m min^{-1}

[a]Estimated

The vehicle has three swimming modes: depth, altitude, and triangle. While in depth mode, the vehicle swims at a near-constant depth. In altitude mode, the vehicle maintains a certain altitude above the bottom (as determined by ADCP bottom detect). Altitude mode is used for side-scan bottom-mapping missions. In triangle mode, the vehicle cycles between two depths while moving along a transect line, thus collecting profile data while following a preset pattern.

Thus, the SAMS vehicle, at a 5000 m site, if most efficiently deployed (using a descent weight and releasing the ascent weight), could spend over 10 hours on the bottom conducting a mapping survey and would cover nearly 7.5 square kilometers (assuming 100 percent coverage of a 100 m-per-side swath width).

B. *Vehicle Sensors*

SAMS is intended to serve as a platform for multi-disciplinary survey missions. It has a full suite of oceanographic and bottom survey sensors, all of which are full-ocean-depth rated. The systems and manufacturers are listed in Table II.

The pressure, conductivity-temperature-depth (CTD), ADCP, and optical back scatter (OBS) sensor data are fed to the mission computer within the SAMS vehicle. The Marine Sonics sonar data are processed and stored on a separate, dedicated computer.

TABLE II
SYSTEM SENSORS

Sensor Type	Manufacturer
Pressure Sensor	Parascientific
CTD	Sea Bird Electronics
ADCP	RD Instruments
OBS	Sea Tek
Side-scan sonar	Marine Sonics

The vehicle software relies on data from the pressure sensor and the ADCP. Bottom detect data from the ADCP is used by the vehicle to determine vehicle altitude, which is integral to effective use of the side-scan sonar.

III. CONCEPT OF OPERATIONS (CONOPS)

The SAMS vehicle is intended to increase efficiency rates for deep-water oceanographic surveying and for bottom surveying/mapping. The CONOPS for both types of missions is detailed below.

A. *Oceanographic Surveying*

With the side-scan sonar disabled, SAMS has sufficient power to operate approximately 24 hours. During an oceanographic survey the vehicle can collect two water column profiles (one each during descent and ascent) and at least 14 hours (approximately 75 nmi) of linear oceanographic data. These data can be collected along a single trackline (in depth, altitude, or triangle mode) or in programmed missions at one or more depth planes.

Fig. 1 shows temperature profile data (deg C) collected during vehicle descent. The data are from the west-central North Atlantic Ocean from March 2003 and show the warm surface waters of the Sargasso Sea.

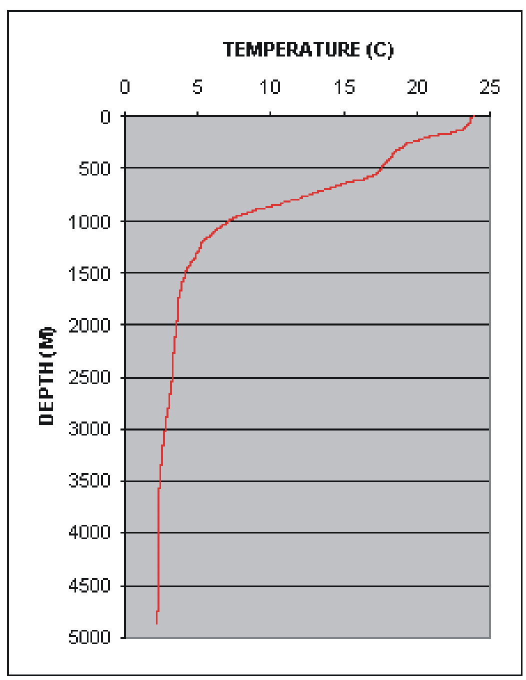

Fig. 1. Temperature profile collected by SAMS in the west central North Atlantic Ocean in March 2003.

Fig. 2 shows a plot (75-m grid resolution) of relative bottom sound speeds from the same mission; to maximize space the color legend has been omitted. The sound speed structure suggests a subtle sound speed front at the bottom. The data below were collected at 4950 m.

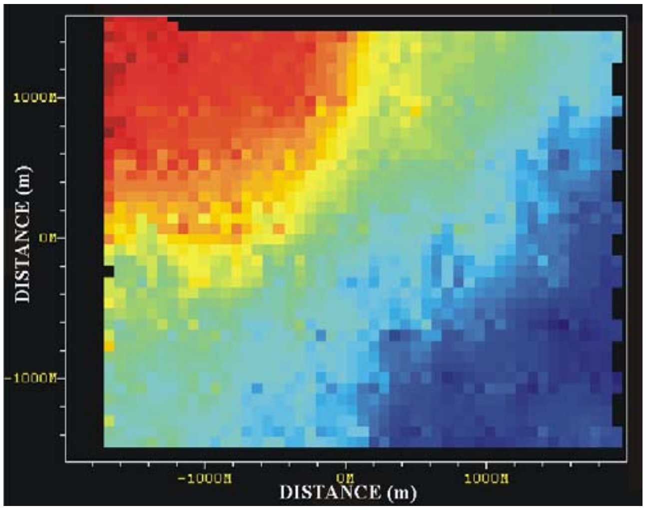

Fig. 2. Plot of bottom sound speed structure, western North Atlantic Ocean, March 2003.

During one of the test dives in March 2003, the vehicle was redirected (i.e., instructed to deviate from its programmed mission) to collect data in small areas at four depths: 1250 m, 1500 m, 1750 m, and 2000 m. Plots of the relative temperature grids produced from this mission are included in Figs. 3 through 6; the plots are gridded at 15 m resolution. The area covered was small, but SAMS required less than three hours to cover the four data planes. Although not originally intended as a rapid environmental assessment tool SAMS does have that capability.

B. Deep-water Bottom Mapping

Although the side-scan sonar is only one element of SAMS' functionality, the SAMS vehicle was engineered as a stable platform for bottom mapping. The Marine Sonics 300-kHz system, installed by WHOI during summer 2003, can cover swaths up to 250 m on each side. With the side-scan enabled, SAMS can be deployed for 13-hour missions and can collect at least 10 hours (at least 40 nmi) of survey data. Total area coverage depends upon swath width and degrees of coverage, but at maximum swath width with 100 percent coverage, as many as 18.5 km^2 can be mapped. Oceanographic data are also collected during a mapping survey, so near-bottom ocean physical properties are mapped at the same time.

No examples of collected side-scan data are shown. However, Fig. 7 shows a map of bottom bathymetry, computed from pressure depth plus ADCP altitude. The plot is gridded at 75-m resolution. To save space, the color legend was eliminated. The figure does highlight another capability and convenient use of the system.

SAMS could be directed to conduct a 16-hour bathymetry mapping survey if necessary; no side-scan

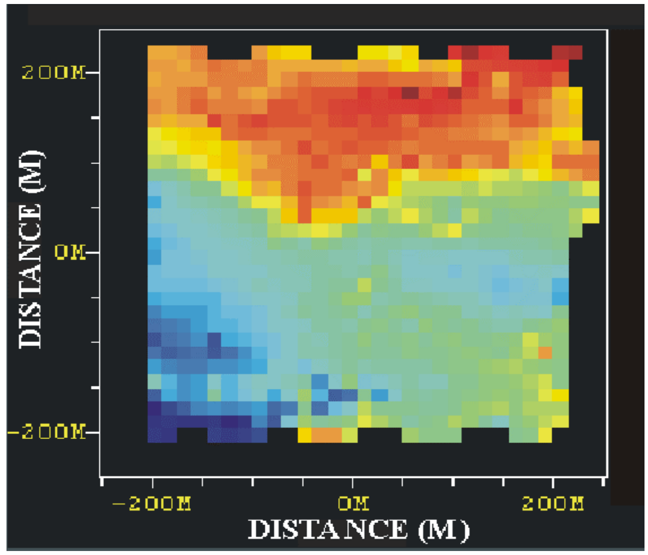

Fig. 3. Plot of gridded temperature at 1250 m depth, western North Atlantic Ocean, March 2003.

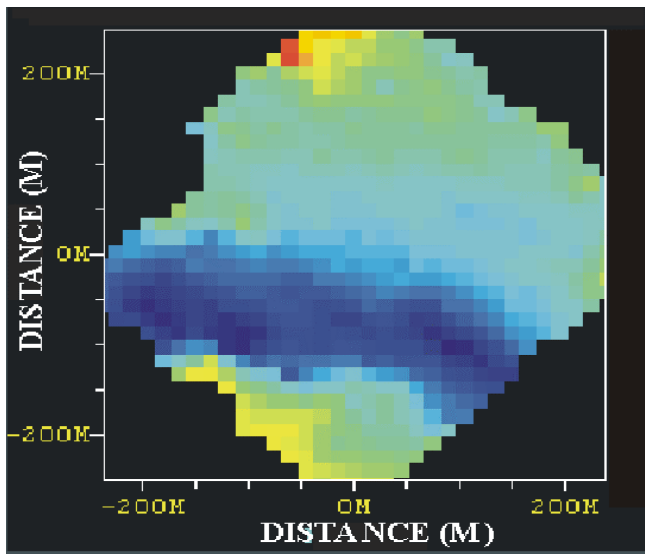

Fig. 4. Plot of gridded temperature at 1500 m depth, western North Atlantic Ocean, March 2003.

sonar data would be collected, but the additional mission time would allow for greater area coverage or higher spatial resolution.

IV. SURVEY EFFICIENCY

SAMS was developed to augment NAVOCEANO survey efficiency. We believe that the SAMS vehicle will supplement ship capabilities while increasing the efficiency of certain types of data collection. To highlight some of the benefits of SAMS, the system will be compared to two NAVOCEANO systems currently in use: traditional CTDs and the Towed Oceanographic Survey System (TOSS).

It is important to note that SAMS is a roll on-roll off (RORO) system that can be shipped worldwide easily. NAVOCEANO can deploy SAMS to any of its ships (or

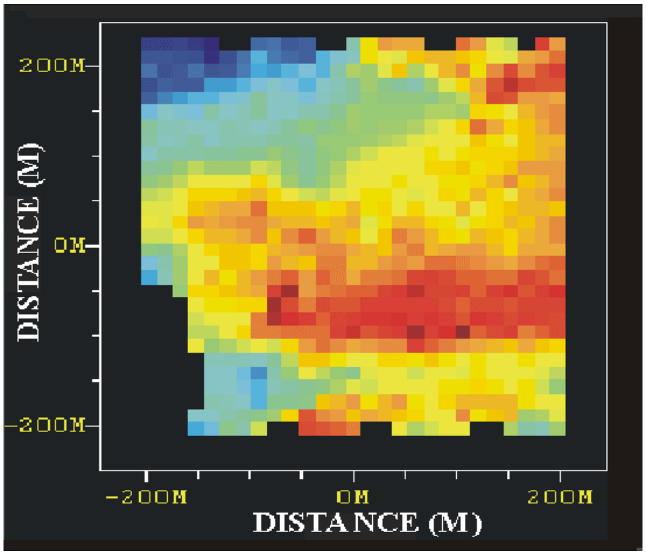

Fig. 5. Plot of gridded temperature at 1750 m depth, western North Atlantic Ocean, March 2003.

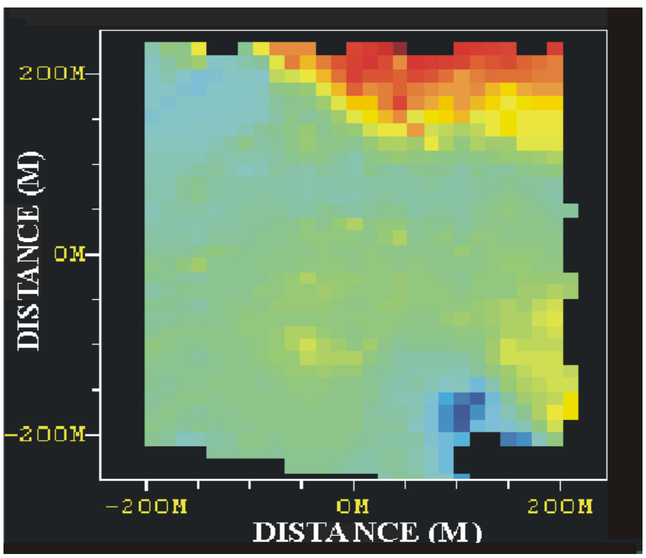

Fig. 6. Plot of gridded temperature at 2000 m depth, western North Atlantic Ocean, March 2003.

even to ships of opportunity) to meet immediate Navy requirements or needs. Therefore, there are no dedicated SAMS platforms; all of the ships can be leveraged as host vessels for the AUV, so all of the ships have host capabilities.

A. *Traditional CTD Systems*

SAMS compares favorably with traditional CTD units. At greater depths, SAMS matches them in terms of survey rate/efficiency but has additional organic sensor capabilities (side-scan sonar, OBS, ADCP) that traditional CTDs do not. CTDs are also restricted to z-axis sampling, whereas SAMS is programmable and redirectable throughout the water column.

Fig. 8 shows the number of CTD casts computed by depth per 19-hour SAMS mission (16-hour mission, 3-hour

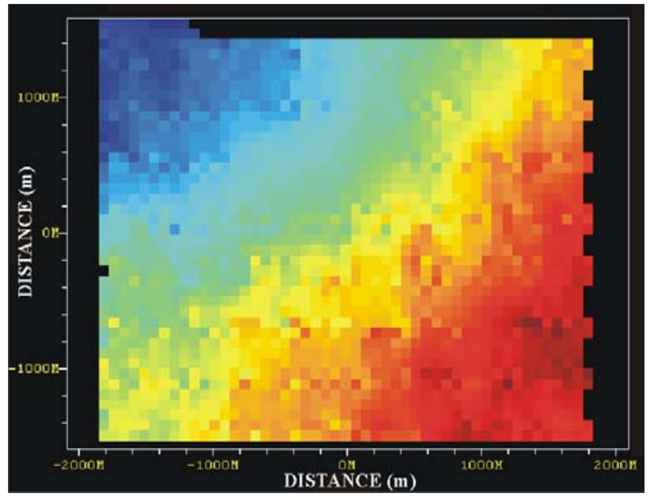

Fig. 7. Plot of bottom bathymetry, west central North Atlantic Ocean, March 2003.

turnaround). It was assumed that a relatively standard NAVOCEANO methodology for CTD casts was used (lowered at 20 m min^{-1} to thermocline, then at 60 m min^{-1}; recovered at 100 m min^{-1}; casts are conducted two hours apart; 20 min total preparation for each cast) [7]. The thermocline cutoff was assumed to be 400 m. Equation (4.1) computes the time (in min) to conduct an individual cast in water depths less than 400 m. Equation (4.2) computes the time per cast for depths greater than 400 m.

$$T_C = (\text{Depth}/20)+(\text{Depth}/100)+20+120 \qquad 4.1$$

$$T_C = (400/20) + ((\text{Depth}-400)/60) + (\text{Depth}/100) + 20 + 120 \qquad 4.2$$

The number of casts per 19-hour SAMS mission is therefore

$$N_C = (19*60)/T_C. \qquad 4.3$$

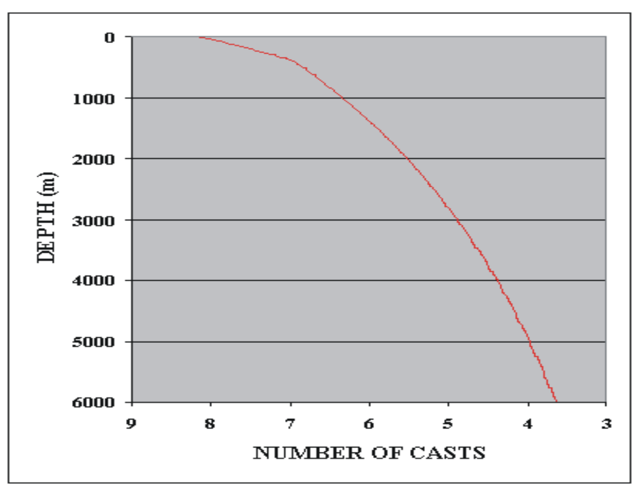

Fig. 8. Number of traditional CTD casts that can be conducted during a single SAMS mission as a function of depth.

Traditional CTDs are more efficient collecting temperature and salinity profile data, but the obvious advantage of SAMS is its additional sensor systems and its mobility. Another advantage is the fact that the ship can conduct other work—even take CTD casts—while SAMS is in the water.

B. TOSS System

TOSS is the precursor system to SAMS. TOSS, also built by WHOI OSL, is a towed, deep-water, oceanographic survey sled and has been operated by NAVOCEANO for nearly 10 years. A comparison of the two systems, including sensors, is provided in Table III.

TABLE III
CAPABILITIES AND SENSORS COMPARISON

Capability	TOSS	SAMS
Maximum Depth	6000 m (20,000 ft)	6000 m (20,000 ft)
Survey Speed	1.5 knots	4 knots
Towed	Yes	No
Endurance	Continuous	12 / 16 hrs
Navigation	RATS[a], Transponder	Transponder, Internal
Sensors		
Pressure Sensor	Yes	Yes
CTD	Yes	Yes
OBS	Yes	Yes
ADCP	Yes	Yes
Side-scan Sonar	Yes	Yes
ASCS[b]	Yes	No
Optics	Yes	No

[a]Relative Acoustic Tracking System
[b]Acoustic Sediment Classification System

The relative acoustic tracking system (RATS) is a high accuracy relative positioning system integral to the TOSS system. RATS computes the TOSS position relative to the host vessel and converts that to a real-world position using the known location of a topside GPS [8]. SAMS uses a REMUS derivative of the RATS system based on computed position relative to known transponder locations [9].

SAMS does have some limitations relative to TOSS, notably vehicle endurance and the lack of the acoustic sediment classification system (ASCS) and optical sensors. However, the SAMS survey rate is at least triple that of TOSS (it should be noted that TOSS tow speeds rarely exceed 1 knot). Furthermore, the table above does not include independent ship operations for 8-12 hours of the SAMS mission.

V. SUMMARY

NAVOCEANO's newest AUV, SAMS, has been engineered to serve as a multipurpose, multidisciplinary RORO survey tool. The combination of sensors; useful for physical oceanography, bathymetry mapping, or side-scan sonar mapping; allows for considerable flexibility when scheduling and planning missions.

The vehicle is intended to augment the capabilities of NAVOCEANO's ships while providing an efficient means of collecting relevant data. The SAMS vehicle is capable of independent operation for 8 to 12 hours of each mission, thus freeing the host vessel to conduct separate surveys nearby.

SAMS offers an alternative to the certain existing NAVOCEANO equipment. Ocean physical properties data can be collected more rapidly with traditional CTD rosettes than with SAMS, but the AUV can collect other data types that cannot be collected with a standard CTD (ADCP, wide-scale bathymetry, and side-scan sonar data). The TOSS vehicle, also full-ocean-depth rated, has more sensors than SAMS but has a much lower survey rate.

It can therefore be argued that the SAMS AUV offers a compromise between data collection and survey rate. However, the AUV also frees the host ship to conduct semi-independent operations during SAMS missions. These are the hallmarks of a successful AUV program: more data, collected faster, more efficiently, and independently. We are confident that SAMS will meet these benchmarks as it deploys.

Note: The inclusion of names of any specific commercial or academic product, commodity, or service in this paper is for informational purposes only and does not imply endorsement by the Navy or by NAVOCEANO.

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