Design and Initial Results of a Bottom Stationing Ocean Profiler†

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***Abstract*-The benefits of untethered or drifting buoys and platforms have been well documented over the past decade. Study of physical, chemical and biological processes in the ocean can often be optimized using systems that profile and/or drift. However, it is at times useful to station a sensing system so that measurements are made only after or during specific conditions, e.g. a storm, an algae bloom, or underwater geologic event. A new autonomous platform has been developed that can provide the benefits of an untethered drifter while also providing the benefits of a stationary buoy. The Bottom Stationing Ocean Profiler (BSOP) is an instrument platform that stations itself on the sea floor and ascends and descends autonomously to gather water column profile data. While at the surface the BSOP transmits acquired data via the ORBCOMM satellite system to provide researchers a near real-time observation of the study area.**

The BSOP unit is designed to remain at sea for extended periods up to several months. It uses an oil-based buoyancy control system to ascend and descend at speeds up to 0.5 meters per second. The unit is low cost, easy to deploy and recover using only light duty gear and can support a wide variety of sensors. Command scripts are downloadable while the unit is in communication with a satellite ground station; this permits reprogramming of mission parameters if needed. The unit has an integral global positioning system receiver to accurately identify surface position. This is important to the scientific mission but is also used for recovery operations. BSOP design and early results are presented.

I. Introduction

The ability to synoptically gather ocean data throughout a large (cubic kilometers) water column is a significant need in modeling and prediction of ocean physical processes. Prediction models for circulation, and properties dependent upon the circulation (such as primary productivity, sediment resuspension, inherent optical properties), require adequate initialization of the large-scale density field *and* regular timely assimilation of density field information. Density data, however, are difficult to come by. Ship surveys are costly, slow, and manpower intensive. The need for more convenient, cost effective, and timely data acquisition is a driving reason for the development of the bottom stationing ocean profiler (BSOP).

The BSOP platforms described herein are designed to provide regular density information, as well as other data, for mapping and assimilation into models. Because of its versatile design the BSOP platforms can carry multiple sensors for a variety of marine research and/or monitoring applications: 1) low cost, low maintenance, surveillance or monitoring for security of coastal, harbor or port waters; 2) monitoring of marine temperature gradients, currents, optical characteristics and chemical or biological characteristics, and; 3) measurements during storms or other events where manned ship borne instrumental deployments are not practical.

II. Design of BSOP

A. BSOP Basic Design

The Bottom Stationing Ocean Profiler is a vertically profiling, untethered, autonomous platform. It is designed to carry a sensor payload, gather sensor data and store and/or transmit the data to the user via a bi-directional RF satellite link. The intended application of BSOP is on shelf margins or where water is generally no deeper than 250 meters. As such, the basic design, aluminum pressure vessels, syntactic foam, etc., is optimized for shallow water. The design is similar to previously developed drifting systems [1][2]; the significant difference being an ability to hold general position by stationing on the sea floor. There are two types of BSOP platforms: 1) a modular design, and; 2) a much simpler unitary version. Both designs are comprised of: a 1) buoyancy system; 2) power source; 3) communication system, 4) system monitor-unit locator, and; 5) control system. The modular BSOP has additional components; a drop weight and syntactic foam floatation.

The modular BSOP consists of several physically-separate sections. The sections are mechanically connected forming a contiguous tube that minimizes hydrodynamic drag

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and allows for ascent and descent at reasonable rates with minimal drift.

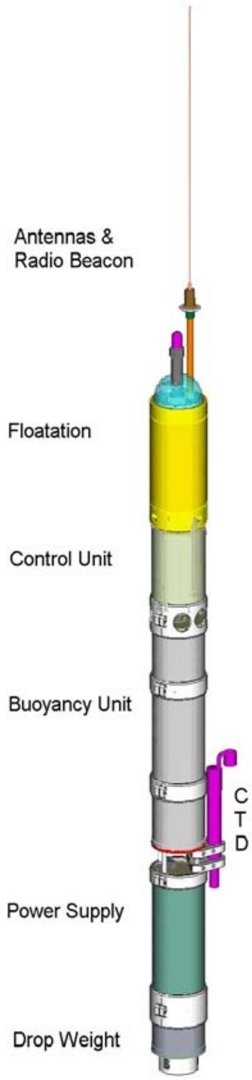

Fig. 1 Modular BSOP design.

The assembly is configured so that the center of gravity is far below the center of buoyancy. This, along with the tubular low drag construction, allows the unit to maintain a vertical orientation at the surface or while ascending or descending.

Syntactic foam floatation is used in the top section to maintain high center of buoyancy and cushioning in case of contact with a sea-going vessel. This foam section consists of epoxy-paint-coated 4Kg foam, and is an assembly of four, 25cm diameter by 20 cm long cylinders. These cylinders are bored with a 2.5cm diameter center hole and are held to the BSOP assembly by a treaded rod and endplate. Individual cylinders can be added or removed to accommodate the buoyancy needed by a variety of payload configurations.

The modular BSOP weighs 84 Kg in air and has 25cm maximum diameter and length of 325cm (excluding antennas or protruding sensors).

The unitary BSOP design differs from the modular design in only a few respects: it has 1) no drop weight; 2) no syntactic foam, and; 3) single body, rather than modular, construction. The objective in development of the unitary BSOP is cost reduction while maintaining the intrinsic qualities of the modular BSOP. The design is intended for a single sensor, although additional sensors could easily be added if their size were sufficiently small (less than 100 cubic centimeters). In addition to reduced size and cost the advantages of the unitary BSOP are: 1) improved launch and recovery; 2) reduced maintenance, and; 3) minimization of losses in event of no-recovery.

The fixed sensor used in the unitary BSOP is the Applied Microsystems Micro CTD (http://www.applied-microsystems.com/index.html). This CTD is integrated into the top endcap of the pressure vessel. Since the CTD is the only sensor and the drop weight is not included, the unitary BSOP needs no syntactic foam and weighs only 38.6 Kg in air. Fig. 2 illustrates the simplified design.

Fig. 2 Unitary BSOP Design

Launch and recovery of the BSOP is relatively straightforward requiring only light onboard gear. The BSOP unit has been successfully deployed using several methods including a simple hand operated davit, knuckle crane, ship-based U-frame and even by hand. A goal is to ruggedize the design of the unitary BSOP to withstand deployments from airborne aircraft.

Fig. 3 A unitary BSOP is deployed for testing.

B. BSOP Buoyancy System

The buoyancy system consists of: 1) a sealed oil reservoir; 2) a nitrile bladder; 3) a pump (for oil evacuation), and; 4) a motor-actuated valve (for flooding). The pump and valve are controlled by the BSOP's central microcontroller system. The oil reservoir (approximately 3.8 liters) is able to provide approximately 3.0Kg of adjustable buoyancy for the BSOP. For ascent, the gear pump (Marzocchi model 1A) is used to transfer oil from the reservoir to the nitrile bladder. The nitrile bladder is housed within a seawater-flooded cylinder; large holes in the cylinder allow for easy displacement of seawater as the bladder fills. (The creation of an evacuated volume and displacement of the seawater creates the buoyancy change.) An in-line check valve assures no backflow from the bladder once the pump stops. Complete fluid transfer, which is accomplished in about 60 seconds, provides sufficient buoyancy to ensure a minimum 0.5-meter per second ascent rate. For descent, the motor actuated valve (KZCO model 88B) is opened, allowing the oil to return to the reservoir under the weak pressure of the bladder and increasing hydrostatic pressure resulting from the descent; no pumping is required.

C. Intelligent power source

The power supply uses lead acid batteries configured in an isolated "multibank" arrangement, where each bank is used in sequence over the duration of the deployment. The central microcontroller monitors the status of each bank via a network communication system within BSOP (LONWorks, described below in *BSOP Control System and Software*). A network node dedicated to monitoring battery status initiates switching to the next bank when the in-use bank becomes exhausted. BSOP is designed with four banks, each consisting of two, 12 volt, 5.0 amp-hour batteries. The total energy stored, 480 watt-hours, is sufficient for approximately 150 ascent-descent cycles. A "mission abort" message is transmitted to the central microcontroller by the battery node when the last battery bank drops below a pre-programmed threshold voltage.

D. Satellite communication

BSOP's remote communication system is a bi-directional satellite link that uses the ORBCOMM low earth orbit constellation. Although several commercially available units were considered for BSOP, the Quake 1500 transceiver (http://www.quakewireless.com/) was chosen because of its small size and versatility. ORBCOMM provides 24-hour, (nearly global) daily coverage and allows rapid economical communication while the BSOP platform is on the surface. The Quake 1500 transceiver allows outgoing transmission of data and profiler status and provides GPS coordinates through its built-in GPS receiver. The bi-directional capability of the ORBCOMM system permits powerful features to be included in BSOP. As one example, internet e-mail messages from a shore-based operator can to be used to alter the profiler's operating characteristics (e.g. cycle frequency, profiling velocity, sample rates, etc.).

The Quake 1500 transceiver's internal microcontroller can be user programmed; a program can be written to cause the transceiver to respond to a variety of stimuli including state changes of externally accessible digital input/output lines. Through this capability the transceiver acts as a backup controller for BSOP. Failure of the main microcontroller to transmit a "heart beat" signal to the Quake 1500 transceiver will trigger the transceiver program to change to a mission-abort state (described below in *BSOP Control System and Software*).

The profiler is equipped with a 5/8-wavelength (137 MHz center frequency) dipole antenna for the Quake 1500 transceiver. A GPS antenna is also fitted to the BSOP platform; both are supported above the waterline when the unit is at the surface. The ORBCOMM and GPS antennas are commercially available antennas that are modified to withstand the 250m design-depth of the profiler. They are also rewired with custom Center for Ocean Technology-designed underwater RF coaxial connectors.

E. Locator system

A radio beacon/xenon flasher, Novatech RF-700C5 (http://www.novatechdesigns.com/RF-700C5.htm), is fitted to each BSOP to aid in recovery. This beacon is activated by the QUAKE 1500 transceiver when a special e-mail message is received. A homing beacon receiver on-board the recovery vessel provides the relative direction to the on-board BSOP transmitter. The beacon's integrated strobe lamp flashes when the unit is activated. This facilitates rapid location of the unit during night recoveries.

Emergency ascents are accomplished using a drop weight system (modular BSOP only). When any of a number of abort criteria are experienced, an energized electromagnetic coil cancels the permanent magnetic field of a magnet holding the 4.5 kg drop weight. The drop weight housing includes a backup 24V Ni metal hydride battery pack, which permits release of the drop weight in the event of main power supply failure. A pressure sensor in the drop weight pressure vessel also backs up the CTD pressure transducer in the case that BSOP descends below its design limit. A LONWorks network node in the drop weight pressure vessel monitors this pressure transducer and can independently activate the drop-weight. A corrodible link (100 day) between the drop weight and the magnetically coupled release plate serves as a final recovery mechanism in the event that one of the modular sections becomes flooded. Release of the 4.5kg weight creates sufficient positive buoyancy to overcome the flooding of one section.

F. BSOP Control System and Software

BSOP is controlled by the OSIS microcontroller system developed at the University of South Florida's Center for Ocean Technology. The OSIS system is based on the Motorola 68HC16, has up to 128 megabytes of internal data storage memory, a real-time clock, and a very low power sleep-mode. (A lithium coin cell powers the microcontroller's real-time clock and watchdog timer.)

The OSIS microcontroller interfaces to an intelligent distributed control network wired throughout the entire BSOP platform. This network, based on LONWorks (Echelon http://www-.echelon.com), enables communication with all components within the BSOP using only two conductors in a terminated or loop network topology. A significant advantage of this is that any connections through a bulkhead or to an external instrument requires only a two-conductor connector for communication and control. Reliability is increased compared to other methods that require multiple branches of several conductors from a central point, e.g. several RS-232 serial communication channels from a central controller.

LONWorks network nodes each handle a specific function under the supervision of the main microcontroller. However, each node also contains software that provides "intelligent" redundant control should communication with the central microcontroller be lost. Custom software is developed for each node; this effectively distributes the control of BSOP throughout the network, thereby increasing system reliability and improving the chances of recovery should a major microcontroller failure occur.

LONWorks nodes are flash-memory based; new software can be downloaded to each over the network without BSOP disassembly. In BSOP, the LONWorks network is used for both control and data acquisition. As configured in BSOP the network has a communications bandwidth of 78 Kbps, however, higher speeds are achievable with other components and cables. The network is low-power sleep mode enabled by the main microcontroller when it is not active.

The software that controls BSOP is a simple state machine. Software is written in C and is compiled using a floating-point compiler to the target 68HC16. Although the software state table is too large to present here, the basic states are: 1) sleep – on the bottom; 2) data acquisition during ascent; 3) surface data transmission and receipt of instructions; 4) data acquisition during descent, and; 5) emergency abort – transmitting position and listening for the locator beacon "recovery mode" command.

A 12-volt lead acid backup battery within the main control section provides power to the communications transceiver in the event of main power supply failure or exhaustion. This allows the profiler to continue transmissions, acquire GPS coordinates, and activate the short-range radio beacon during a retrieval emergency. The normal sequence of operation is as follows. At ascent/descent rates of 30m/min., CTD (and/or other payload) data are acquired at 2 m intervals and stored in internal memory. Once on the surface, the unit transmits acquired data and GPS location via the satellite communication link. Each transmission consists of data gathered from the previous descent-ascent cycle. Upon completion of data transmission, the unit floods its internal buoyancy canister and descends, gathering data until impact with the sea floor. The internal microcontroller then shuts down power and enters a "sleep" mode until an internal real time clock (or other programmed external stimulus) initiates wakeup and the cycle repeats.

The BSOP control program stores all gathered data in internal flash memory. In addition, failures in satellite link data transmission are noted. If a reliable transmission of data does not occurred within a pre-programmed time period, a BSOP platform will note the transmission error and descend. Unsent messages are queued for transmission during the subsequent cycle. While on the surface on the following cycle, the BSOP platform will attempt to transmit any data not successfully transmitted in previous attempts. Data that are not transmitted via satellite can be read from internal flash memory when the BSOP platform is recovered. Up to 16 megabytes of data can be stored, with the option of expanding to 128 megabytes.

The microcontroller hardware and associated software are designed to enter an abort state if any of a variety of problems are detected. In the abort state several actions are taken: 1) the drop weight is released (not applicable in the unitary BSOP); 2) the oil reservoir is evacuated, and; 3) a special abort message is transmitted by the satellite transceiver. (An abort messages contains the time and cause of the abort and the current GPS coordinates). Abort e-mail messages are transmitted at a preprogrammed period until battery power is exhausted. Once the retrieval vessel and crew are within range of the profiler, an e-mail message is sent to the BSOP via an on-board satellite transceiver, causing it to switch to a retrieval state. In this state the QUAKE 1500 transceiver activates the radio beacon/xenon flasher.

A number of events can trigger the microcontroller to enter an abort mode: 1) low battery power; 2) lack of communication with one of the profiler component modules; 3) failure to ascend/descend on command; 4) CTD depth data indicates profiler is below design depth, and; 5) the drop weight system indicates that the weight has been released (modular BSOP only). In addition to these standard abort conditions, the drop weight and /or the QUAKE transceiver can trigger an abort mode. The conditions under which the drop weight will trigger an abort are (modular BSOP only): 1) over pressure from the drop weight's backup pressure sensor signals that the unit has drifted below its design depth; 2) a periodic 'heartbeat' signal from the microcontroller is not received; 3) a predefined time in the powered-up (ON) state is exceeded, and; 4) the drop weight's backup power supply drifts below a pre-programmed working voltage. The QUAKE transceiver can trigger an abort mode when: 1) a direct e-mail message commands an abort, and; 2) there is a lack of communication with the micro-controller.

II. Initial results

A. Lab testing

The initial design required significant laboratory testing to ensure reliability. Through extensive experimentation, testing, and debugging several modifications to the original design were necessary. Those modifications included: 1) repackaging of microprocessor and satellite transceiver components to reduce RF interference; 2) antenna matching to improve satellite communications; 3) improving surface buoyancy characteristics; 4) improving the landing (sea-floor impact) characteristics; 5) improving RF connector design; 6) increasing the buoyancy bladder volume; 7) reducing the energy requirement of the buoyancy pumping system, and; 8) adding software to accommodate additional abort-initiation states.

Although several modifications were required, changes to the original design were minor. The improvements to the satellite communication system were necessary because of observed inconsistency in reliable communication. The RF network must be well designed to ensure reliable bi-directional communications.

B. Sea Trials

As of August 1st, 2002 at least 48 missions have been completed in Tampa Bay and on the West Florida Shelf. Offshore deployments have produced CTD profile data as shown in Fig 4. The data shown were acquired from a test station 64 kilometers west of Sarasota, FL. For tests at this location satellite transmission success rates approached 90%. However, initial communication testing in Tampa Bay showed diurnal variability, as illustrated in Fig. 5, and reduced communication success rates.

The diurnal variability and reduction in reliable communication are most likely due to RF interference from local sources, e.g. an active airport, Coast Guard station, major hospital and university research laboratory are all within 2 kilometers of the test area. The tests show, however, the robustness of BSOP's software; messages queued during unsuccessful communication periods were sent during subsequent successful communication periods. For this particular testing 84 of 85 attempted messages were transmitted and received successfully.

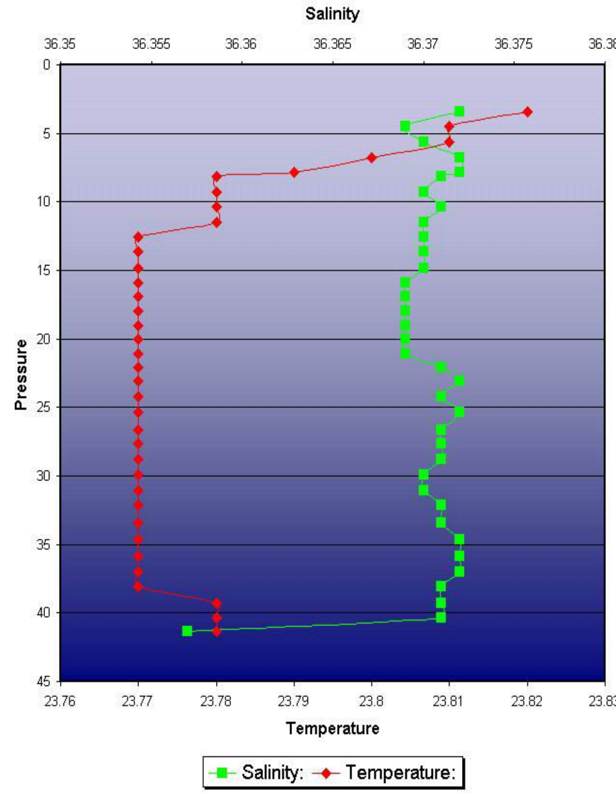

Fig. 4 Chart of BSOP acquired CTD data from a test station 64 kilometers west of Sarasota, Florida

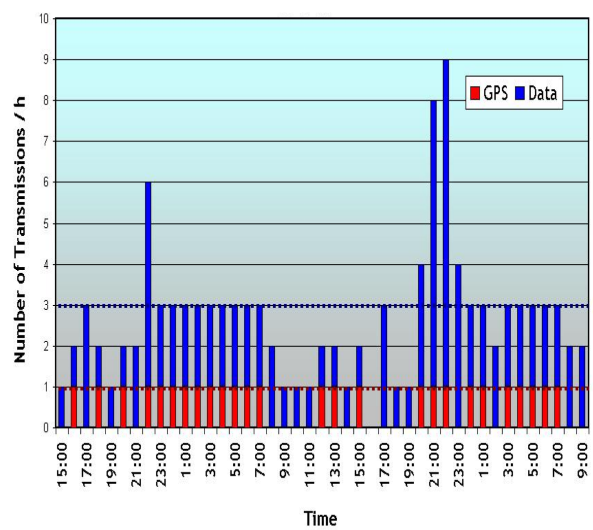

Fig. 5 Received BSOP transmission rate vs time of day. Note the increases in reliable communication near midnight.

Sea testing of the GPS and abort/retrieval systems has been completed. GPS fixes and transmissions are not only needed for scientific research but are also necessary for retrieving a free-floating mission-aborted BSOP. The ORBCOMM bi-directional satellite communication system allows versatility and flexibility in the retrieval process. As described earlier, when a BSOP has ended its mission, it periodically sends an abort notification message and GPS-acquired coordinates. The retrieval vessel transmits an e-mail message to the free-floating BSOP instructing it to increase its transmission rate to provide GPS coordinates (as many as 6/hr) and activate the radio beacon/xenon flasher described earlier. The transmission success rate of these e-mails is shown in figure 6. The "Pickup Script Sent" event indicates that a mission altering transmission was received by the BSOP. The increased number of GPS acquired coordinates from that point forward facilitates tracking of the BSOP by the retrieving vessel.

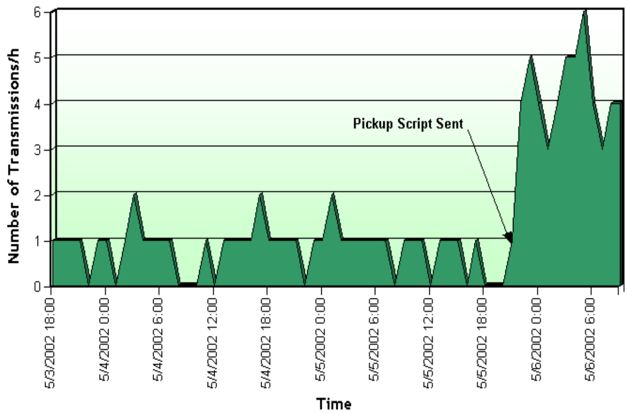

Fig. 6 Received BSOP transmission rate vs time of day. Note increase in number of receptions after the retrieval command is received by the BSOP.

III. Conclusion

The Bottom Stationing Ocean Profiler allows advanced autonomous data acquisition for ocean research. An array of BSOP platforms, equipped with appropriate sensors, can provide a synoptic data set for large areas of the coastal ocean. Future enhancements of the BSOP design will provide additional capability. Satellite communication using the IRIDIUM system will provide a "bent pipe" data channel, which will allow real-time bi-directional transmission and reception of information, commands and/or programs. Enhancements to the control system will allow depth keeping, which will facilitate "hot-air-ballooning" a BSOP for relocation or for drifting buoy related research. As miniaturized sensors become available continued improvements in the BSOP are envisioned. While maintaining reliability of the original design, future designs will be directed toward cost reduction, improved endurance, weight reduction and improvement in communication and control.

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