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Autonomous Transient Ocean Event Monitoring (ATOEM)

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Abstract— A novel conceptual design is presented for a research platform for Autonomous Transient Ocean Event Monitoring (ATOEM). In simplest form, ATOEM would be an autonomous diesel-electric submarine of conventional design, but stripped of all of its requirements for human occupation and life support, and whose "torpedo" tubes would instead be loaded with a variety of AUV configurations (*e.g.*, benthic, photic zone and midwater) capable of autonomous docking with the "mother ship". Global deployment of a large fleet of modular, low-cost, highly manufacturable ATOEM platforms has the potential to transform oceanographic research by providing coordinated, comprehensive, time-series, spatiotemporal measurements of all key ocean properties on an unprecedented scale.

Keywords— transient ocean event monitoring, ocean observation, unmanned underwater vehicles, and docking.

I. INTRODUCTION

A variety of transient events occur throughout the world's oceans that may warrant detailed monitoring over both a large areal extent and throughout the entire water column from the sea surface to the sea floor, and often over extended timeframes. Among these are naturally occurring events such as volcanic eruptions, both land based and subsurface; continental slope failures and slides; methane release from sediment-buried hydrates; subsea oil and gas seepage; major river flooding or discharge events; and large plankton blooms, including toxic events. Man-made events include oil spills or other significant pollution discharges as well as deliberate ocean fertilization experiments. Recent examples illustrated in **Figure 1** include: (a) the mobilizations following the Deepwater Horizon oil spill in the Gulf of Mexico [1], (b) the eruption of Eyjafjallajökull in Iceland [1] and (c) the Fukushima nuclear reactor releases [3].

Despite best efforts, however, it is often impossible to capture the critical early history of such events and a more rapid deployment capability is clearly needed. In addition, practical station keeping limitations permit only limited observation periods, while long term continuous monitoring would be far preferable. The typical sampling requirements for comprehensive monitoring of such events would often require the deployment of a small armada of ships and AUV/ROV platforms fitted with a diverse array of samplers, sensors and profilers, which is both expensive and logistically complex.

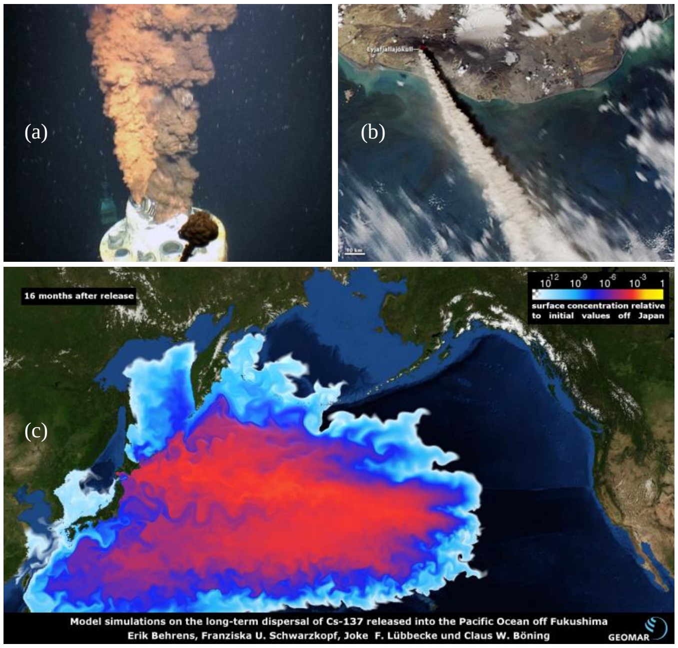

Figure 1 Examples of Transient Ocean Events. Credits: (a) U.S. Geological Survey, (b) NASA, (c) [4]

A. *Ocean Observatories*

Existing distributed sensor arrays such as the ARGO floats [5] still lack both the spatial resolution and sensor complements that are required to capture such transient events, despite their considerable numbers and global distribution. Other ocean monitoring networks currently in deployment or still under development, such as the Ocean Observatories Initiative (OOI) [6] and the proposed Global Biogeochemical Flux (GBF) extension of OOI [7], while incorporating a vastly greater variety of samplers and profilers, rely largely on fixed mooring arrays and will be limited in number. Although some of these arrays will also incorporate gliders and other AUVs, they will still be largely restricted to observing events that happen to pass through the array carried by ocean currents and will be incapable of actively tracking random events that might occur anywhere.

B. *A Shrinking and Ever More Expensive Research Fleet*

The White House recently released the Federal Oceanographic Fleet Status Report for 2013 [8], which documents both the continuing decline in the number of research vessels as well as the rising costs of ship operations that

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is rapidly approaching $50,000 per diem for Global Class ships such as the *R/V Atlantis*. The two newest additions to the UNOLS fleet now under construction, the *R/V Neil Armstrong* (AGOR 27) and the *R/V Sally Ride* (AGOR 28) are only Ocean Class vessels compared with the Global Class veterans they will eventually replace, *i.e., R/V Knorr* and *R/V Melville* [9]. The estimated cost of construction is $75 million each, exclusive of scientific equipment fit out.

On the other hand, advances in robotics and autonomous systems continue apace. For example, the Monterey Bay Aquarium Research Institute (MBARI) has developed the long-range *Tethys* AUV and is pushing endurance from days to weeks [10], while the Rutgers University glider *Scarlet Knight* crossed the Atlantic in 2009 [11] and Liquid Robotics' Wave Glider traveled 9,000 miles across the Pacific in 2012 [12]. However, each of these platforms is currently limited in the types of measurements and/or samples that they are capable of acquiring in transit, and are further limited in their flexibility for accommodating changing mission plans and courses. For the most part, AUVs continue to require relatively frequent human support between sorties, with all its associated costs, constraints and logistics.

These realities are continuing to drive the scientific debate over the need for a manned presence both *in* the sea and even *at* sea [13]. Perhaps this is best highlighted by James Cameron's recent dive to the Challenger Deep in his privately funded *Deepsea Challenger*, a feat unmatched by any government in 50 years [14], but also accomplished by the hybrid AUV *Nereus* in 2009 [15]. Somewhat ironically, Cameron has subsequently donated the *Challenger* to the Woods Hole Oceanographic Institution (WHOI), where it is unlikely that she will ever dive again, and has agreed to serve as an advisor to WHOI's new Center for Marine Robotics [16].

II. THE ATOEM CONCEPT

One solution to this dilemma would be to eliminate people from the deployment, recovery and servicing of AUVs and instead employ a fully autonomous diesel-electric "mother ship" to perform those functions typically requiring a manned support ship. While a variety of autonomous surface craft have been developed, largely for military and surveillance applications, they would be at the mercy of the sea state, greatly limiting their operational capabilities. On the other hand, an autonomous submarine could operate submerged and largely immune to sea state, surfacing and/or using a snorkel as needed to charge batteries, transmit data and receive updated mission profiles and make weather observations. Docking with its complement of smaller AUVs would be facilitated by the ability to hover submerged with minimal pitch, yaw and roll, which would be a far greater challenge for a surface platform. Submerged operation would also minimize the chances for collisions with surface vessels.

The *Proteus* platform illustrated in **Figure 2** was developed by Battelle, Bluefin Robotics and The Columbia Group as a "mothership testbed" that embodies many of the elements required for ATOEM, while lacking a diesel-electric power plant [17]. Technology for coordinated control and communication among "swarms" of AUVs and the ATOEM "mothership" is evolving rapidly [18] including novel acoustic and optical modems for longer range and higher bandwidth data transfer [19].

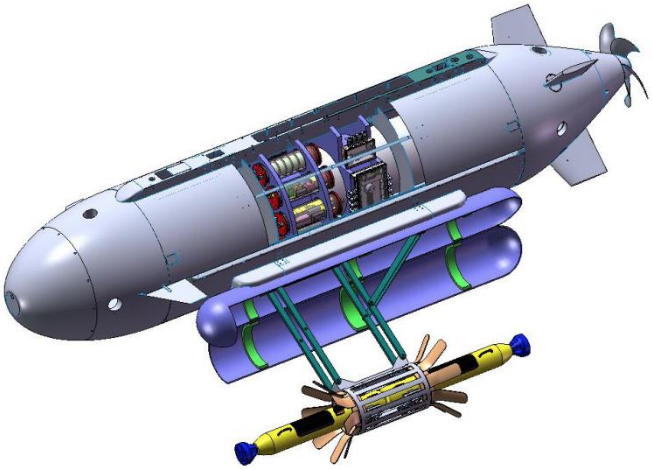

Figure 2 *Proteus* is a "mothership testbed" (reproduced from [16], Copyright American Society of Naval Engineers)

A. Large Displacement Unmanned Underwater Vehicles

The largest Unmanned Underwater Vehicle (UUV) currently is the LSV II *Cutthroat*, illustrated in **Figure 3**, a quarter-scale version of the *Virginia* class New Attack Submarine with a displacement of 185,520 kg and a length of 33.8 m [20]. At roughly one-half the size of a typical WWII submarine, *Cutthroat* illustrates that size *per se* should not be a constraint for the development of ATOEM and that technical solutions for autonomous submerged propulsion, buoyancy control, navigation, and power management are in hand for vessels at this scale.

Figure 3 The *LSV-Cutthroat* is currently the world's largest AUV

The U.S. Navy currently has a program for the development of Large Displacement Unmanned Underwater Vehicles (LDUUV) like *Proteus* [21], but their requirements are vastly different from ATOEM's as highlighted in Table I. As with many military platforms, stealth is of critical importance, while ATOEM would only need to be "silent" to the extent that it is employing sensitive sonar for various purposes. While submerged and operating on batteries, ATOEM would likely be a very quiet platform to begin with due to the lack of auxiliary machinery needed to support a crew, who are also a source of noise. Because of this stealth requirement for the LDUUV, the Navy is particularly interested in novel energy sources, whereas

ATOEM would achieve maximum range and duration employing the century-old technology of diesel-electric propulsion.

Table 1
Differing requirements

Property	ATOEM	Military
Theater of Operation	Deep, open ocean	Littoral
Critical Features	Range & duration	Stealth
Cost	Primary	Secondary
Measurements	Ocean observation	Intel

Autonomous navigation is also a considerably greater challenge for the LDUUV, which is expected to operate in shallow littoral waters that are crowded with other vehicles and obstacles. In contrast, ATOEM would operate primarily in the deep open ocean, although advances from the LDUUV program might allow for coastal operation in the future. Given that self-driving cars capable of navigating city traffic or off-road courses are now a reality, and autonomous jet drone aircraft are capable of taking off and landing on aircraft carriers, and Martian rovers have been operating continuously for a decade would all indicate that such autonomous control is well in hand.

B. *Diesel-Electric Power Plant*

While a typical military diesel-electric submarine requires a relatively large crew to operate, "miniature" versions have been developed that require only a few individuals to operate, such as US Submarine's two-man S-101 [22][23] as well as several large "amateur-built" subs such as the Danish *UC-3 Nautilus* [24] and the German *Euronaut* [25]. Modern diesel-electric power generation plants are able to operate for a year or more without servicing in remote areas [26] and should be adaptable for ATOEM. One of the first milestones in ATOEM's further development will be the proof-of-concept demonstration of a small, fully autonomous diesel-electric submersible capable of repeated cycles of submerged operation at depth running on battery power and transition to surface or snorkel operation where the diesel will recharge the batteries.

Diesel fuel has a volumetric energy density of 35.86 MJ/L (10 kWh/L) compared with rechargeable lithium ion batteries 2.23 MJ/L (0.625 kWh/L). Each liter of fuel would thus allow for >10 recharges of a one liter battery depending on charging efficiency. The battery capacity for an ATOEM platform would be designed to provide the power needed for submerged operation (*e.g.*, ≥ 24 hours), which would include the hotel load for onboard automated laboratory operation (see below), autonomous controls and propulsion at an average submerged cruising speed (*e.g.*, ≤ 10 kn). The generator would be designed to operate at full power and efficiency and rated to charge the full battery capacity in a few hours of surface or snorkel operation, including the batteries of the complement of smaller AUVs. The diesel fuel capacity would then be scaled for the desired duration of autonomous operation between fuelings (*e.g.*, ≥ 6 months). As a point of comparison, a WWII German Type XXI U-boat could remain submerged for 2-3 days traveling at 5 kn on batteries that could be recharged in 5 hours. Total range was >15,000 nmi at 10 kn with a maximum submerged speed of >17 kn.

Such a propulsion system would allow active tracking of the "center of gravity" of even the most rapidly moving and/or expanding transient events by integrating remote sensing and shore-based instructions with its own real time measurements, unlike simple neutrally buoyant drifters, and the fleet of AUVs would be capable of sampling to the event's horizons. A small fleet of modern submarine "oilers" could refuel and service some ATOEM platforms at sea while others could return autonomously to the nearest port.

III. ATOEM DESIGN REQUIREMENTS

A. *Modular Design*

ATOEM can take advantage of the same modular design strategy employed by many smaller AUVs and even MSubs' 24 m, 64 ton Mobile Anti-Submarine Training Target (MASTT) [27]. Standard modules required for all configurations would include:

- Propulsion and power generation
- Buoyancy and trim control
- Fuel storage
- Batteries
- Control, navigation and communication

Vendor-specific modules would accommodate AUV's from different manufacturers and include their specific docking mechanisms. Autonomous docking of AUV's to recharge batteries, download data and upload new mission profiles has already been demonstrated [28][29] and could be extended to include offloading of water samples and replenishment of consumable reagents and supplies (*e.g.*, preservative solutions, filters and membranes, *etc.*) for the next generation of biological and biogeochemical samplers [30]. "Gulper" samplers have already been demonstrated by MBARI [31] and by the Alfed Wegener Institute [32]. ATOEM-specific AUVs might take advantage of a "Russian Doll" approach employing nested AUVs that might facilitate fractal sampling methods [33]. The ATOEM "mother ship" would deploy a fleet of larger AUVs, each of which would in turn deploy a number of smaller AUVs.

The ability to separate modules would provide access for servicing of internal equipment without the added volume required for manned access to such compartments during operation. Standardized interfaces between modules will need to be well defined to provide maximum flexibility and versatility. Reliability of machinery will be of critical importance for long duration, unattended operation.

B. *Design for Large-Scale Manufacturing*

Perhaps the most important design criteria will be standardization of components and subsystems and choice of materials and manufacturing techniques to achieve a viable design for low-cost, large-volume production. Military platforms tend to make use of more exotic materials and construction methods and cost typically takes a back seat to performance. Composite materials incorporating closed cell polymer buoyancy foams such as Divinylcel HCP [34], and fabrication methods like casting, molding and "additive manufacturing" or 3D printing, rather than traditional welding of steels or titanium will be explored. The volumes of the pressure hulls should be greatly reduced compared with manned submarines, resulting in a commensurate reduction in buoyancy requirements. If prototypes demonstrate the anticipated performance, one could ultimately envision a fleet of >1,000 ATOEMs deployed throughout the world's oceans. If a target cost of $1 million, exclusive of its complement of AUVs, can be achieved, such a fleet would cost far less than, *e.g.*, NASA projects such as the James Webb Space Telescope, whose budget is now approaching $9 billion.

C. Novel Sensors, Samplers and On-Board Laboratory

While some of the retrieved samples could be archived for later shore based analysis in onboard freezers or refrigerators, others might be analyzed by shared onboard instruments to allow for nearly real time reporting of data. This will require the development of novel, robust, raw-sample-to-result instrumentation and processing protocols for a host of analytical methods.

IV. AIRBORNE DEPLOYMENT

ATOEM configurations could span the historic range of lengths and displacements of manned diesel-electric submarines. The larger vessels would have greater operational range and/or duration, and/or a larger complement of AUVs, and/or a larger onboard laboratory, and might require customized versions of submarine tenders for refueling, reconfiguration at sea, and rapid transport to and from areas of operation. Rapid deployment could be achieved with system configurations that would meet the dimensional and weight limitations of large cargo planes capable of precision, GPS-guided, parachute assisted descent. Single payloads of 18,000 kg have been successfully deployed from C-130 aircraft, whose cargo bay measures 17 m long and 3 m in diameter [35]. The larger C-17 boasts a 72,000 kg payload 20 m long and 5.5 m wide, while the C-5 tops out at 130,000 kg and 37 m long by 5.8 m wide, and successfully air launched a Minuteman ICBM [36].

V. SAFETY, SECURITY AND LEGAL ISSUES

A large, autonomous vessel like ATOEM might be a target for vandalism or piracy on the high seas, especially when surfaced. In addition to providing ATOEM with a standard marine Automatic Identification System (AIS) to avoid collisions [37], it would therefore be prudent to equip the vessel with a threat recognition and avoidance capability. If approached by an "unauthorized" vessel that does not provide the necessary identification, ATOEM would submerge and hide or flee after transmitting an appropriate distress signal. Similar behavior could be adopted to avoid collisions, but the legal requirements for deploying large, autonomous platforms like ATOEM in international waters, especially in large numbers, will need to be established. However, the risks compared with operating driverless cars in urban locations would appear to be minimal.

VI. PLANKTON BLOOMS – A UNIQUE APPLICATION

Tracking the full history of a large plankton bloom like one illustrated in **Figure 4** is a formidable challenge particularly suited to ATOEM. By the time a natural bloom is observable via remote sensing, much of its early history will have been missed, compounded by the delay before a manned vessel could be on station to follow its further development. The large areal extent of such blooms is also problematic for comprehensive sampling and the full history of the bloom includes the fate of the fixed carbon as it is transformed and transported to the deep ocean over the course of many months. ATOEM platforms could be deployed in those regions of the ocean and during those seasons where blooms are to be expected to detect the earliest signs of bloom formation and then follow its evolution from "start to finish".

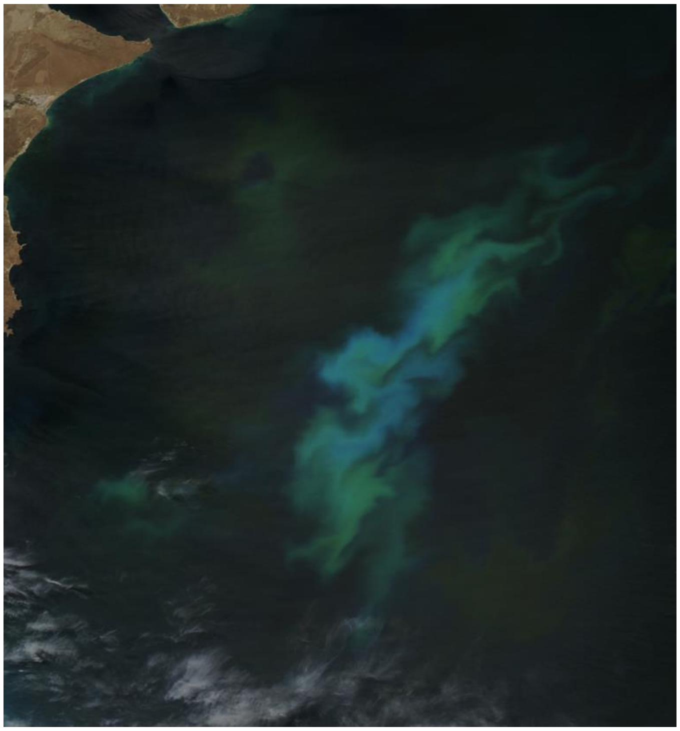

Figure 4 A large plankton blooms off Argentina (NASA)

In addition, ATOEM could monitor deliberate ocean fertilization experiments [38] designed to test the sequestration of atmospheric CO_2 in the deep ocean to partially mitigate global warming and/or to assist in the restoration and maintenance of marine fisheries. Only a dozen or so of such fertilization experiments have been conducted over the past 20 years, and while there have been some promising results, considerable additional research is required. Future experiments must be conducted on a far more frequent basis at ever increasing scale and with rapid data reporting, while capturing the full spatiotemporal history of the bloom with measurements of all the critical parameters throughout the water column [39]. A fleet of ATOEM platforms configured specifically for such a purpose would provide a unique capability to rapidly and comprehensively assess the potential for ocean fertilization in high-nutrient, low-chlorophyll (HNLC) regions throughout the world's oceans.

VII. CONCLUDING REMARKS

ATOEM represents a potentially transformative oceanographic research platform that combines the best of modern autonomous systems technology concepts with the rich history of diesel-electric submarine design and development. The next stage will involve detailed design specification and evaluation of materials and manufacturing options, as well as discussions with AUV manufacturers concerning interface standards and docking requirements, leading to the fabrication and testing of initial basic modules for proof-of-concept.

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