# Autonomous Transient Ocean Event Monitoring (ATOEM)

Kevin M. Ulmer[†,‡]

[†]Seaquester, Inc., East Sandwich, Massachusetts USA

[‡]Woods Hole Oceanographic Institution, Woods Hole, Massachusetts USA

***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, 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 include the mobilizations following the Deepwater Horizon oil spill in the Gulf of Mexico Ref. [1], the Fukushima nuclear reactor releases Ref. [2], and the eruption of Eyjafjallajökull in Iceland Ref. [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.

### A. Ocean Observatories

Existing distributed sensor arrays such as the ARGO floats Ref. [4] 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) Ref. [5] and the proposed Global Biogeochemical Flux (GBF) extension of OOI Ref. [6], 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 Ref. [7], which documents both the continuing decline in the number of research vessels as well as the rising costs of ship operations that 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* Ref. [8]. 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 Ref. [9], while the Rutgers University glider *Scarlet Knight* crossed the Atlantic in 2009 Ref. [10] and Liquid Robotics' Wave Glider traveled 9,000 miles across the Pacific in 2012 Ref. [11]. 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 Ref. [12]. 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 Ref. [13], but also accomplished by the hybrid AUV *Nereus* in 2009 Ref. [14]. 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 Ref. [15].

## 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 "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. Submerged operation would also minimize the chances for collisions with surface vessels.

### *A. Large Displacement Unmanned Underwater Vehicles*

The U.S. Navy currently has a program for the development of Large Displacement Unmanned Underwater Vehicles (LDUUV) Ref. [16], but their requirements are vastly different from ATOEM's. 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. The 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.

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.

Military platforms also tend to make use of more exotic materials and construction methods and cost typically takes a back seat to performance.

## III. ATOEM Design Requirements

### *A. Modular Design*

ATOEM can take advantage of the same modular design strategy employed by many smaller AUVs. 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 Refs. [17-18] and could be extended to include offloading of 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 Ref. [19]. ATOEM-specific AUVs might take advantage of a "Russian Doll" approach employing nested AUVs that might facilitate fractal sampling methods Ref. [20]. 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. Composite materials incorporating closed cell polymer buoyancy foams such as Divinylcel HCP Ref. [21], and fabrication methods like casting and molding, 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 worlds 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 Ref. [22]. 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 Ref. [23].

## 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. 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. Ocean Fertilization

One particularly important application for ATOEM would be the monitoring of deliberate ocean fertilization experiments Ref. [24] 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 Ref. [25]. 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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