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Towards an Autonomous Space In-situ Marine Sensorweb

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We describe ongoing efforts to integrate and coordinate space and marine assets to enable autonomous response to dynamic ocean phenomena such as algal blooms, eddies, and currents. Thus far we have focused on the use of remote sensing assets (e.g. satellites) but future plans include expansions to use a range of in-situ sensors such as gliders, autonomous underwater vehicles, and buoys/moorings.

I. Introduction

THE study of physical and biological phenomena in our oceans is vital to our understanding of the Earth's climate and environment. The oceans encompass the majority of the Earth's surface and biomass. Ocean dynamics play a major role in every aspect of our planet's climate.

Oceans present a number of challenges to scientific study. First, many ocean events are dynamic and require rapid response to measure the phenomena. Algal blooms may appear and spread within a few days. Eddies and other ocean currents may appear and change in a matter of hours or days. Second, the ocean environment requires study of subtle signatures that challenge both remote sensing and in-situ instrumentation to accurately distinguish between event types. Third, the ocean presents a hostile environment. Designing, building, and deploying autonomous underwater vehicles (AUV's), gliders (less powerful but long endurance submersibles), and drifters. present a range of engineering and technological challenges. Fourth, many of the assets must be able to operate for extended periods autonomously due to underwater travel or power constraints that hinder communication with centralized control.

II. Existing Space Sensorweb

Our previous studies demonstrate the value of autonomous sensor networks that combine diverse platforms and modalities. We have been operating an Earth Observing Sensorweb intermittently since 2003 using several space assets including EO-1, MODIS, QUikSCAT together with in-situ sensors [Chien 2005a]. This sensorweb has been used to track volcanic activity [Davies EOS], flooding, and cryosphere events. Science tracking systems process space and in-situ data - indicating alerts for science events such as volcanic activity, floods, and lake or sea ice formation or breakup. When such alerts are received, campaign management software compares the event notices to response criteria. It triggers appropriate actions whenever criteria are met for responses such as acquisition of spaceborne imagery, reconfiguration of in-situ networks, or notifications to authorities (See Figure 1).

For example, the MODVOLC and GOESVOLC [Harris et al. 2000a] systems use the MODIS and GOES space-based sensor systems respectively. These systems track volcanic activity and report the results to the internet via web posting systems. The international Volcanic Ash Advisory Center (VAAC) [VAAC] does the same for mostly manually generated reports of aviation hazard volcanic ash plumes worldwide. Using these and in-situ sensor networks as inputs we have built an early warning system that can deliver alerts to interested volcanologists and also automatically request followup data. In our case the principal asset used to acquire followup data is the Earth Observing One [EO-1] spacecraft. Its ground and flight autonomy systems enable rapid response to events.

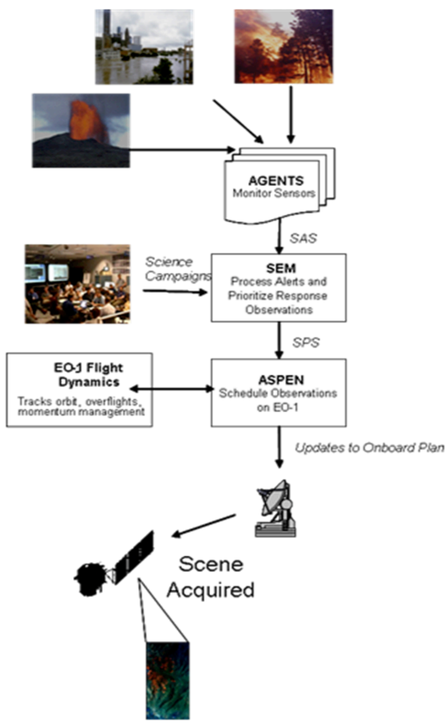


Figure 1: Space Sensorweb

In the more general case, scientist campaigns can identify specific science alerts to generate custom requests. A scientist campaign specifies a combination of events that should produce one or more observation requests. For example, two or more MODVOLC alerts over a given thermal signature threshold within 3 days for a specified volcano might trigger a high priority request to image with ASTER and EO-1 for the next 3 days.

At periodic intervals new observations are considered for insertion into the EO-1 schedule. An EO-1 observation request can only be accommodated if the insertion respects priority, scene overlap, downlink overlap, maneuver, onboard storage, and thermal constraints. Priority means that no scene will be taken if it prevents acquisition of a higher priority scene. Scene overlap means that the spacecraft can only acquire scenes with a certain temporal separation between overflights. Downlink overlap means that the spacecraft cannot acquire a scene while it is performing high data rate science downlink. Maneuver means that the spacecraft must be able to change pointing from the prior scene to the current scene within the time between overflights while accounting for spacecraft stabilization and settling. Onboard storage means that the scene must fit within the data volume and file count supportable by the EO-1 storage until the next science data downlink. Thermal constraints mean that powering the instruments to acquire the requested image must not overheat any of the spacecraft imaging instruments.

The EO-1 ground system incorporates the spacecraft operations constraints in constructing and modifying observation plans. It first incorporates priority, overlap, and maneuver constraints by constructing blocks of observations combining scenes. These scene combinations, called "tuples" are then modeled within the ASPEN automated planning system which tracks all constraints except maneuver (already incorporated in tuple construction). ASPEN then constructs or modifies plans based on candidate tuples, searching the combinations of compatible tuples to ensure that the remaining constraints are respected.

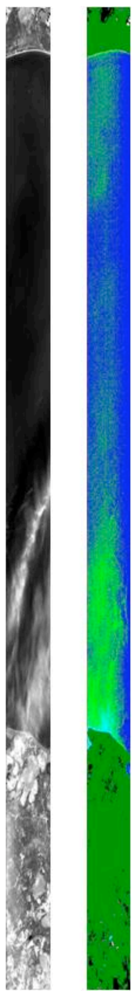
After scenes are acquired and downlinked they can be automatically processed to derive science products and analyses that are then delivered to scientists. Thus, the scientists automatically receive customized science products based on detected events. The existing sensorweb demonstrates a comprehensive architecture combining automatic event detection, replanning under resource constraints, dynamic followup observations and automatic delivery of data to scientists. It suggests that a similar approach could be used to study dynamic phenomena in the oceanographic domain.

III. An Oceanographic Sensorweb

Ocean phenomena are ideally studied at multiple scales and by a range of assets. Space assets are useful for surface and atmospheric observations and can provide coverage of large areas. In-situ assets can provide measurements at depth and follow dynamic phenomena such as currents, eddies, and algal blooms. Autonomous underwater vehicles and gliders are useful in that they can be deployed to the study locations and can travel to observe phenomena. Buoys and moorings can supplement these assets when their fixed locations are appropriate.

A sensorweb is a network of sensors that dynamically, autonomously reconfigures itself to best study and track a phenomena with dynamic temporal and physical extent. For an oceanographic sensorweb this reconfiguration might include deployment and direction of autonomous underwater vehicles and gliders, activation of sensors and data acquisition, acquisition of in-situ samples, and deployment of surface vessels. While we are far from autonomous operations, we are developing the concepts, technologies, and software to someday enable this end vision (for prior work in this area see [Bellingham 2007a, Fiorelli 2006a, Leonard 2007a]).

IV. Automated Algal Bloom Detection—Initial Efforts



Figures 2: true image and decision tree classification for 2008 Lake Peipsi scene

Decision tree legend:
dark green = land,
black = shadow,
white = cloud,
dark blue = water,
red = dense/surface algae,
bright blue = visible algae,
bright green = mostly indiscernible algae

Recent efforts include feasibility pilot tests to track oceanographic events using sensorweb technologies. Wide coverage assets such as MODIS and MERIS have ocean color products useful in studying algal blooms [Ryan et al. 2008]. However these wide coverage sensors have lower spatial resolution. Ideally these datasets would be combined with point and shoot satellite data with less spatial coverage but higher spatial (and possibly spectral) resolution.

In August 2008 using the EO-1 spacecraft we acquired a number of scenes of algal bloom activity in the Baltic Sea and also nearby large lakes. Together with historical scenes of algal blooms in the same region [Kutser 2004] we have been developing automatic classification algorithms to identify these blooms. These efforts are complicated by the difficulty of accurate atmospheric correction. Figure 2 shows an example from the prototype system. The image at left shows processed Hyperion imagery. The image at right is a classification result produced by a manually-derived ENVI decision tree.

The end goal is to eventually develop automated processing flows that deliver alerts and science classification products to interested scientists and authorities. These automated alerts could then be used to deliver data to interested authorities and also request subsequent data to track the evolving phenomena.

V. Tests in Monterey Bay October 2008

Recently the EO-1 sensorweb participated in an oceanographic deployment to Monterey Bay in October 2008 called MB08. This deployment involved a wide range of participants and assets including MBARI (hosts, buoys, gliders, auv, ships, drifters), Rutgers (gliders), NASA/JPL/GSFC (space assets imaging using EO-1/ALI/Hyperion, ASTER, MODIS), JPL/UCLA/JIFRESSE (Ocean simulations), UC Santa Cruz (in-situ, aerial imaging), and Naval Postgraduate School (radar and radar processing), and Rutgers/California Polytechnic Institute (gliders). Monterey Bay was chosen as the site for this deployment because: (1) its frequency and intensity for algal blooms [Ryan et al. 2008] and (2) its location facilitates use of in-situ assets due to its proximity to relevant oceanographic institutions.

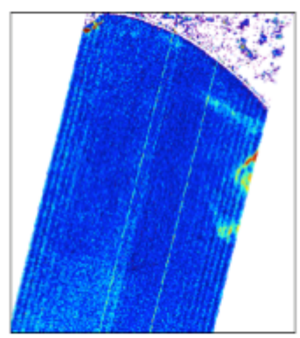


Figure 3: Maximum Chlorophyll Index derived from Hyperion imagery acquired 21 October 2008.

As part of the Monterey Bay deployment the EO-1 satellite was tasked and automatically delivered oceanographic science data products for scientist evaluation. Specifically, EO-1 Hyperion acquisitions were made in coordination with the EO-1 Sensorweb team on 10 days in September and October 2008 with 5 scenes during the MB08 deployment. EO-1 used automated workflows to process and deliver the data to the MB08 science and operations team along with two derivative science products Fluorescence Line Height (FLH) and Maximum Chlorophyll Index (MCI) linear baseline data products [Gower and Borstad 2004, Gower et al. 2005]. Figure 3 shows the MCI product for Day Of Year 294 (October 21st) processed into false color by MBARI for subsequent use.

These automated sensorweb workflows were triggered by the campaign tag associated with the acquired scenes and invoked perl/IDL processing to produce the desired science products. The resultant science products were automatically delivered to the scientists through a collaboration web portal. The system updated the web portal with links to files downloadable from EO-1 servers. This capability was later generalized to enable sftp and email delivery of products as well. These efforts demonstrated the utility of automated science processing and delivery of EO-1 products to support science operations and also provided guidance on areas of improvement needed before operationally useful products could be delivered. Key operational areas identified for future work include improved instrument and atmospheric correction.

The MB08 team also discussed future demonstrations of the EO-1 sensorweb to automatically trigger observations from remote sensing ocean systems such as MERIS and MODIS. Other potential demonstrations could use permanent in-situ sensors in Monterey Bay to trigger EO-1. Such sensors include nutrient sensors for point of entry to Monterey Bay as well as moorings within the bay. These automated sensorweb triggers would represent another application of automated response to enhance science - automatic acquisition of remote sensing data during periods of intense algal activity could significantly enhance the study of biological activity in Monterey Bay.

VI. Future directions – deployment of autonomy software for shore planning and gliders

As part of the Ocean Observatories Initiative (OOI) [OOI] we are planning to deploy the ASPEN batch planning system [Chien et al. 2000a] to perform shore planning for ocean assets and the CASPER onboard planner [Chien et al. 2000b] and the MOOS-IvP behavior-based control software [Benjamin] to gliders for in-situ oceanographic science. The OOI project envisions an oceanographic sensorweb in which events are detected by assets including space, fixed, in-situ, or shore sensors. A shore planning system coordinates a response that may also include space, in-situ, shore, and other platforms. Figure 4 depicts this scenario. Coordinating these assets throughout the long-duration missions will require autonomy at multiple levels. Communications blackouts require significant autonomy from the sensing nodes. Individual gliders must manage vehicle health and respond to deviations from expected environmental conditions. They must adapt their paths, recognizing and tracking dynamic phenomena that change on timescales too short to capture by sporadic communications with shore. Autonomy also exists at the level of shore planning, where the ASPEN planner coordinates glider resources to maximize the utility of their observations with respect to real-time oceanographic models. Finally, the extreme volume of incoming data requires automation in data processing and publication of resultant products. The OOI Cyberinfrastructure [OOI-CI], currently in early prototyping, will support these capabilities through its high available and scalable Data Distribution Network (DDN) based on a high performance message broker infrastructure. This effort is still in a very early stage with demonstration of automated shore planning and onboard sea asset replanning planned in the next several years.

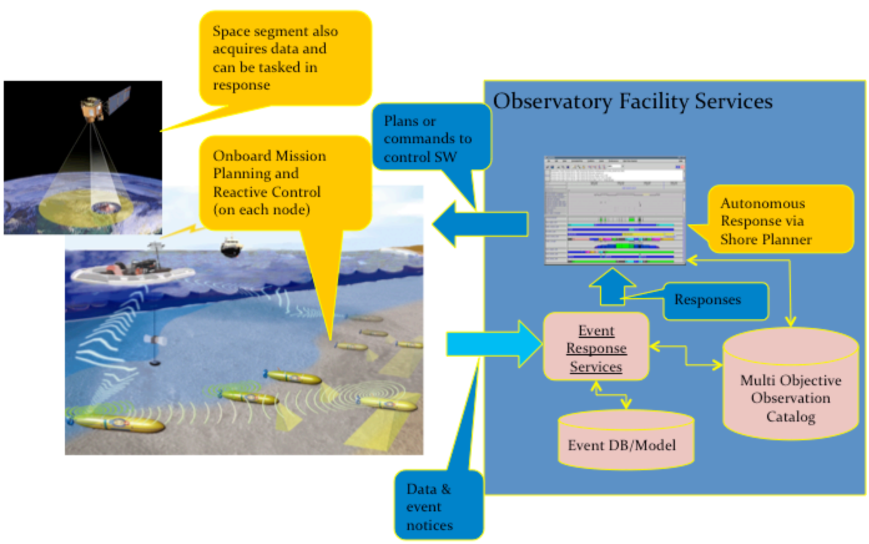


Figure 4: Ocean Observatory Sensorweb

VII. Conclusion

We have described preliminary efforts to develop sensorweb technologies and early results of utilizing space assets in a demonstration in Monterey Bay in October 2008. This deployment included space, shore, fixed ocean, and mobile ocean assets with autonomous tasking of space assets and data delivery from the space data acquisition. We also described future plans to more tightly integrate space and marine assets.

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