OOI – Cyberinfrastructure

Planning and Prosecution and Analysis and Synthesis Subsystem Pilot Period Report

Version 1-00
Final

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in Cooperation with

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OOI - CyberInfrastructure
Planning and Prosecution, Analysis and Synthesis
Subsystems Pilot Period Outcome Report
(OSSE Report)

1 Introduction

The Planning and Prosecution (PP) subsystem of the OOI Cyberinfrastructure provides the services together with the standard models for the management of stateful and taskable resources. It provides controller processes with the semantics to monitor and control the operating state of an active resource as well as to initiate, monitor and amend tasks being carried out by a taskable resource. Central applications of the Planning and Prosecution services network are to provide observatory and observation mission planning and prosecution. Such activities include carrying out simultaneous coordinated multi-objective observations across the resources of the observatory. Further activities include event-response behaviors and the interface with autonomous vehicle resources.

The Planning and Prosecution subsystem provides the following capabilities:

- Command, control and monitor semantics to operate and manage a (stateful and taskable) resource,
- Time-structured, concurrent coordination and prioritization of shared resources that are distributed and constrained,
- Provisioning of a behavior-based architecture for rapidly reconfigurable autonomous task execution,
- Unique multi-objective optimization of behavior coordination, allowing for effective compromise to be attained between periodically competing task objectives for a collection of resources,
- Provisioning of a behavior calculus, allowing sequences of task states to be structured for long-term, persistent plans while remaining highly reactive to events and in situ control requests,
- Autonomous robust execution of observation plans on fixed and mobile intermittently connected instrument platforms,
- Defining, storing and managing observation plans and event response behaviors

The Analysis and Synthesis (A&S) subsystem provides capabilities and user/application interfaces to support advanced and systematic data analysis and output synthesis applications. This includes the life cycle and operational management of community numerical ocean models, ensembles of models and the virtual ocean simulator framework as well as modeling activities (i.e., assimilation, analysis, evaluation) using observed and derived data products. Analysis and Synthesis provides a flexible scientific stream based workflow execution capability. Analysis and Synthesis services support event detection, data analysis and visualization by utilizing the workflow mechanism and providing specialized advanced support services for these activities. A&S also provides the virtual collaboration services used to create virtual observatories and classrooms that may provide interactive collaboration, analysis and synthesis workspaces.

The Analysis and Synthesis Subsystem will provide the following capabilities:

- A scientific workflow definition, execution and control framework based on data streams,
- A data stream processing capability, including stream subscription, stream process scheduling, and stream process execution,
• Support for and execution of advanced measurement processing services, including a measurement calculus and measurement semantic model,
• Support for and execution of data assimilation processes,
• Support for and execution of data analysis processes, such as event detection,
• Support for and execution of output synthesis processes, such as data visualization, transformation,
• Generation of derived data products from analysis and synthesis stream workflows,
• Numerical ocean model integration services, including on-demand modeling, data assimilation, assimilative modeling, ensemble model execution,
• Virtual collaboration services, enabling virtual observatories, laboratories and classrooms,
• User and application interfaces for interactive analysis and synthesis workspaces.

The highest risks associated with the advanced, transformative and over-arching nature of P&P and A&S and the need for new services and user applications are addressed in the OOI pilot period that followed the OOI Final Design Review in November 2008 and will be ongoing until the end of December 2009. The pilot period’s goals are to prepare for OOI construction and to mitigate significant risks through prototyping.

This report documents the risk mitigation efforts since January 2009 that were relevant for the P&P and A&S subsystems. Most development related to these subsystems does not start before Release 3, but drives and influences the development of other more fundamental subsystems.

The Observing System Simulation Experiment (OSSE) was a high profile prototype project with multiple collaborating and sub-contracting partner organizations, coordinated by the OOI CI team. The OSSE effort consisted of a development and preparation phase leading up to a two week field deployment in November 2009 off the New Jersey coast. The OSSE constituted the efforts related to advancing the CI Planning&Prosecution and Analysis&Synthesis subsystems and to perform risk mitigation.

2 OSSE Overview

The OOI CI OSSE (Observing System Simulation Experiment) prototype project was conducted to test designed Planning and Prosecution capabilities of the OOI CI together with some Analysis and Synthesis capabilities. The prototype software was developed in mid 2009 and tested virtually in September 2009 followed with a full field deployment in the first two weeks of November. The goal was to provide “real-world tests” of the software not possible in a simulated environment. The effort, which leveraged off several other federal agencies, the National Ocean and Atmospheric Administration (NOAA) and the Department of Defense (DoD) allowed outside team oceanographic experts provide critical feedback on the software. A review of the effort is provided below and highlights the experimental strategy, the results of the field efforts, and the next steps in accelerating the ongoing development of the OOI planning and prosecution software. The OSSE prototype system as initially designed includes: a) CI Common Infrastructure with Message-Based Network Infrastructure and Data Distribution Network, b) True Ocean Model Environment (Ocean Model), c) Ocean Forecasting Model Environment (Forecast), d) Shore-side observation operation center, and e) Glider simulator environment.

Note that component (a), the CI common infrastructure was prototyped independently within two other CI pilot prototype projects: the Common Operating Infrastructure's (COI) Messaging Service prototype (see [13]) and the Data Management (DM) subsystem's Data Exchange prototype (see [14]). Due to descoping caused by the early OOI construction start, these prototypes have not been integrated according to the full OSSE design; nonetheless, compatible science data interoperability technologies.

2.1 The OSSE Experiment Strategy, Work Breakdown and Team

OOI CI conducted the Observing System Simulation Experiment (OSSE) pilot prototype project to test the capabilities of the OOI CI to support field efforts in a distributed ocean observatory in the Mid-Atlantic Bight. The goal was to provide a real oceanographic test bed in which the CI will support field
operations of ships and mobile platforms, aggregate data from fixed platforms, shore-based radars, and satellites and offer these data streams to data assimilative forecast models. The MAB region is selected because of the existing communities and the presence of NOAA and ONR coordinated by Rutgers University. The NOAA contribution was associated with the Mid-Atlantic ocean observing system (MarCOOS) that is part of NOAA’s the Integrated Ocean Observing System. The IOOS system provided a nested array of HF radar systems, several Slocum Gliders, and several numerical ocean models. This network was complemented by a DoD Major University Research Initiative conducting an Experimental Shelf Predictive Shelf-Slope Optics (ESPreSSO) program, which contributed satellite imagery and optically-outfitted Slocum gliders. It allowed a suite of propeller Autonomous Underwater Vehicles to be deployed during the OSSE. The field and numerical modeling efforts provided the test-bed for several CI software packages to be deployed as part of the OOI program.

This overall effort was split between several of the OSSE team members: University of California, San Diego, Rutgers University, Jet Propulsion Laboratory, and the Massachusetts Institute of Technology. The specific goals for the team members were:

*The UCSD team coordinated by Michael Meisinger was in charge of:*

1. Provide architectural guidance in compliance with OOI CI Planning and Prosecution and Analysis and Synthesis subsystem architecture and design.
2. Provide cross prototype fertilization and integration
3. Document OSSE architecture, operational procedures and integration steps
4. Operate and manage the collaboration tool environment and OSSE web presence
5. Project management
6. Status and result reporting

*The Rutgers University team coordinated by Oscar Schofield was in charge of:*

1. Coordinate the integration with physical current models and mission plan outputs as originally planned for data throughput testing by accessing the wider ocean.
2. Provide the feedback to develop the baseline glider planning models including path planning for “use case” testing and feedback.
3. Collect a range of data to feed path planning software and deploy several gliders to be controlled by plan planning tools.
4. Host MARCOOS scientists to provide “outside” user input to path planning tools.
5. Demonstrate path planning results in real-time at the OOI Science planning meeting in Baltimore to provide a forum for community outreach.

*The Jet Propulsion Laboratory team coordinated by Yi Chao was in charge of:*

1. Developing a single stop web portal where users can access the following data products that include oceanographic data (bathymetry, satellites, HF Radar), atmospheric forcing, and a range of ocean numerical models being run by the IOOS community. The models included three high-resolution models being run by Rutgers University, Stevens Institute of Technology, and Massachusetts Institute of Technology. These models were complemented with a coarse resolution model being run by the University of Massachusetts at Dartmouth.
2. Provide event detection based on data assimilation and model computation as needed for event-triggered observations in the OSSE experiment, communicated via the messaging system.
3. Provide numerical model making use of adaptive observations collected by gliders in real-time and after bulk-download of data. This required development of a control and management interface for the numerical models, an integrated data assimilation and numerical model input with the CI provided messaging system, and an integrated numerical model and event detection output with the CI provided messaging system.
The Jet Propulsion Laboratory team coordinated by Steve Chien was in charge of:
1. Demonstrate automated shore planning in the OSSE field effort in Fall 2009 which requires completing baseline integration with physical current models and mission plan outputs as originally planned for data throughput testing.
2. Development of baseline glider planning models including path planning for “use case” testing and feedback
3. Integration of CASPER with MOOS-IvP simulation environment for Linux based simulation of glider control based on ASPEN shore-based plans. This is the closest proxy to CASPER actually onboard the gliders until we can get a glider with a Linux card.
4. Operate the CASPER and ASPEN mission planning suite during the November field effort.

The Massachusetts Institute of Technology team coordinated by Arjuna Balasuriya was in charge of:
1. Integration of the MOOS-IvP with the current ocean models.
2. Development of an autonomy architecture along with the JPL shore side planner.
3. Develop a mathematical model for glider simulation on shore side planner.

The specific breakdown of the individual components that were developed are listed below.

Table 1. Components for integration and development for the November OSSE

<table>
<thead>
<tr>
<th>Name</th>
<th>Segment</th>
<th>State</th>
<th>Group</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROMS Regional Ocean Nowcast Model</td>
<td>Ocean Model</td>
<td>Existing</td>
<td>Yi</td>
<td>Numerical model for ocean region of interest (Mid Atlantic Bight). Needs configuration.</td>
</tr>
<tr>
<td>Data assimilation for ocean nowcast model</td>
<td>Ocean Model</td>
<td>Existing</td>
<td>Yi</td>
<td>Retrieve input data for initial and boundary conditions from various data sources and assimilate for model runs.</td>
</tr>
<tr>
<td>Ocean model output presentation</td>
<td>Ocean Model</td>
<td>Existing</td>
<td>Yi</td>
<td>Provide network access to NetCDF files generated by numerical model</td>
</tr>
<tr>
<td>HOPS/ROMS Regional Ocean Forecast Model</td>
<td>Forecast</td>
<td>Existing</td>
<td>Yi</td>
<td>Numerical forecast model for specific region of interest based on observations made by the Glider.</td>
</tr>
<tr>
<td>Data assimilation for forecast model</td>
<td>Forecast</td>
<td>Existing</td>
<td>Yi</td>
<td>Data assimilation including data provided by Glider observations</td>
</tr>
<tr>
<td>Forecast model output presentation</td>
<td>Forecast</td>
<td>Existing</td>
<td>Yi</td>
<td>Access to forecast model output (LAS Server, user interface, etc.)</td>
</tr>
<tr>
<td>Data Distribution Network</td>
<td>Common Infrastructure</td>
<td>Separate Prototype (DM)</td>
<td>CI</td>
<td>Access to science data in NetCDF and distribution as requested via DAP to recipients.</td>
</tr>
<tr>
<td>Message-Based Network</td>
<td>Common Infrastructure</td>
<td>Separate Prototype (COI)</td>
<td>CI</td>
<td>Messaging infrastructure with standard access protocol and management. All information will be exchanged between components using messages.</td>
</tr>
<tr>
<td>ASPEN</td>
<td>Shore-side Operations</td>
<td>Existing</td>
<td>Steve</td>
<td>Stand-alone mission planning tool</td>
</tr>
<tr>
<td>ASPEN connector to message-based network</td>
<td>Shore-side Operations</td>
<td>Dropped</td>
<td>Steve with CI</td>
<td>Receive numerical model analysis results as provided and needed via the messaging system and make them available to ASPEN. Make ASPEN mission plans available via the messaging system.</td>
</tr>
<tr>
<td>Observation plan</td>
<td>Shore-side</td>
<td>To De-</td>
<td>Steve</td>
<td>Transformation of numerical model analysis</td>
</tr>
<tr>
<td>Component</td>
<td>Type</td>
<td>Status</td>
<td>Inquiry</td>
<td>Description</td>
</tr>
<tr>
<td>-----------</td>
<td>------</td>
<td>--------</td>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>Operations</td>
<td>Shore-side Operations</td>
<td>Existing</td>
<td>Yi</td>
<td>Formal constraint model as input for ASPEN that encodes knowledge of the environment and capabilities of mobile assets (the glider), such that observation requests and environmental observations (events, etc) can be solved into adaptive observation plans.</td>
</tr>
<tr>
<td>MOOSDB</td>
<td>Shore-side Operations</td>
<td>Existing</td>
<td>Arjuna</td>
<td>Shore-side installation of MOOSDB interfacing with communication simulator processes and with the messaging infrastructure.</td>
</tr>
<tr>
<td>MOOSDB to messaging bridge</td>
<td>Shore-side Operations</td>
<td>Dropped</td>
<td>Arjuna with CI</td>
<td>Bidirectional bridge MOOSDB to CI message-based network.</td>
</tr>
<tr>
<td>Communication simulator processes</td>
<td>Existing</td>
<td>Arjuna</td>
<td>Acoustic modem, satellite communications and wireless communication simulator driver MOOSDB processes. Acoustic for underwater use, satellite/surface for surface use.</td>
<td></td>
</tr>
<tr>
<td>Glider Simulator</td>
<td>Existing</td>
<td>Oscar</td>
<td>Rutgers glider simulator software environment.</td>
<td></td>
</tr>
<tr>
<td>CASPER</td>
<td>Glider</td>
<td>Existing</td>
<td>Steve</td>
<td>Mission execution of observation plans received from ASPEN via message interface. Also receives environment and onboard system monitoring events. Controls MOOS-IvP behaviors via control commands sent via the onboard messaging system.</td>
</tr>
<tr>
<td>MOOSDB to messaging bridge</td>
<td>Dropped</td>
<td>Arjuna with CI</td>
<td>Bidirectional bridge MOOSDB to onboard message-based network. This messaging system is very light-weight and has different properties than the shore-based messaging system. The bridge needs knowledge of the originator and recipient MOOSDB processes and their expected data exchange formats.</td>
<td></td>
</tr>
<tr>
<td>MOOSDB</td>
<td>Glider</td>
<td>Existing</td>
<td>Arjuna</td>
<td>Onboard installation of MOOSDB interfacing with communication simulator processes and with the onboard messaging infrastructure.</td>
</tr>
<tr>
<td>MOOS-IvP</td>
<td>Glider</td>
<td>Existing</td>
<td>Arjuna</td>
<td>Helm process for glider navigation.</td>
</tr>
<tr>
<td>MOOS-IvP Behaviors</td>
<td>Glider</td>
<td>Existing</td>
<td>Arjuna</td>
<td>Selected library of configurable and controllable behaviors suitable for adaptive observations in OSSE scenario.</td>
</tr>
<tr>
<td>Onboard messaging system</td>
<td>Glider</td>
<td>Dropped</td>
<td>CI</td>
<td>Lightweight messaging system for embedded resource limited platforms.</td>
</tr>
<tr>
<td>Instrument simulator processes</td>
<td>Glider</td>
<td>Existing</td>
<td>Arjuna</td>
<td>MOOSDB processes that simulate sensor observations.</td>
</tr>
<tr>
<td>Onboard system control processes</td>
<td>Glider</td>
<td>Existing</td>
<td>Arjuna</td>
<td>MOOSDB processes that monitor and control glider onboard systems.</td>
</tr>
</tbody>
</table>

The components listed in rows with italics were not realized within the final scope of the OSSE due to the shortening of the pilot period for an earlier OOI construction start. The CI Messaging Service was prototype independently within the scope of the COI subsystem. The Data Distribution Network was prototyped as Data Exchange within the scope of the DM subsystem. Consistent data interoperability technologies, namely as DAP servers have been applied within the OSSE Data Distribution system.
2.2 OSSE Field Deployment

The OOI Cyberinfrastructure (OOI-CI) together with various IOOS partners primarily from MaRCOOS, performed a field deployment experiment, aka an Observing System Simulation Experiment (OSSE) on Nov 2-13, 2009. The objective was to provide a real oceanographic test bed in which to test the designed OOI-CI technologies which will support field operations of ships and mobile platforms, aggregate data from fixed platforms, shore-based radars, and satellites and offer these data streams to data assimilative forecast models. Some specific goals were to use multi-model forecasts to guide glider deployment and coordinate satellite observing, and to demonstrate the ability to do two-way interactions between the sensor web and predictive models.
The actual experiment consisted of 5 models modeling, 4 Slocum gliders gliding, 3 Autonomous Underwater Vehicles (AUVs) flying, 2 types of ensembles modeling and 1 satellite pass. The 5 real-time forecasting models were from U. Mass-Dartmouth, Stevens Institute of Technology, USGS/WHOI, Rutgers University, MIT. The 4 gliders consisted of three from Rutgers and one from University of Dartmouth. The AUVs consisted of an IVOR from Cal Poly and from MIT/Naval Underwater Warfare Center and a REMUS from Rutgers. The OSSE allowed for comparisons of observations (HF Radar) vs. multi-model ensembles, glider data (ru05) vs. model, equal vs. objective weighted ensembles, and multi-model ensemble and its uncertainty.

During the experiment, the group used the Jet Propulsion Laboratories (JPL) ‘OurOcean data and model integration portal’ to integrate and view all the data. This was possible because of the use of OpenDAP and the njTBX toolbox, introduced by Rich Signell (USGS) to the OSSE data producers. These tools allowed for the easy transmission and conversion of data sets. To experiment with mission planning, the OSSE used the CASPER/ASPEN mission planning and control tool being developed by JPL for planning the glider flights. Finally they experimented with the MOOSDB/MOOS-IvP autonomous vehicle control system on the AUV’s to see how it performed.

The main accomplishment of the OSSE was to close the loop from modeling to observations and back. During the experiment, scientists integrated in-situ sensors with space-based Earth observation system. Scientists also gathered data locally by a fleet of gliders and fed it into a real-time assimilative ocean forecasting system. Finally scientists used model forecasts to command the gliders and space craft to optimize the spatial coverage over the areas of interests. In addition, both observation data and model forecasts were available in real-time and could be provided to aid decision making.

Further scientific evaluations of the OSSE results and data collected will be published as reports and papers in journals of relevant scientific communities, such as EOS, the American Meteorological Society and the Journal for Field Robotics. These analysis will target, for instance, how well the models performed compared against the data and what improvements were made to the models, and how close the glider simulations were to the actual glider paths.
For more information about the OSSE field deployment, see the blog: [http://www.i-cool.org/?cat=5](http://www.i-cool.org/?cat=5), the Data/Model Integration Portal: [http://ourocean.jpl.nasa.gov/CI](http://ourocean.jpl.nasa.gov/CI), and the wiki site: [http://www.oceanobservatories.org/spaces/display/CIDev/OSSE+Rocks](http://www.oceanobservatories.org/spaces/display/CIDev/OSSE+Rocks)

### 2.3 OSSE Deployment Data and Command Flow

The idealized data and command flow for the OSSE field deployment, in particular the tasking of gliders is described and illustrated below.

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**Fig. 3. Data and command flow for shore-side glider operations**

Steps (see also [http://www.oceanobservatories.org/spaces/display/CIDev/OSSE+Integration](http://www.oceanobservatories.org/spaces/display/CIDev/OSSE+Integration)):

- 1A Acquire observational data (for each data source)
- 1B Forecast modeling (for each operational model and team)
- 2 Shore planning: Situational Awareness
- 3A Shore planning: Set Coarse Waypoints
- 3B Shore planning: Interpolate Waypoints with Current-Sensitive Path Planner
- 3C Automatic Conversion to Detailed Plan
- 3D Detailed Planning in ASPEN Timeline Interface
- 4A Shore planning: Dynamic simulation
- 4B Shore planning: Plan Correction
- 5A Glider operations
- 5B Virtual Glider Deployment
2.4 The OSSE experimental results

Glider Operations and Planning and Prosecution strategy. In a test of the OSSE Aspen and Casper planning and prosecution software, we coordinated a fleet of four Slocum gliders in a series of tests of coordinating behavior. Combined the different behaviors provided a suite of tests for the software. These behaviors were chosen to simulate many of the behaviors likely to be used by the science user community when the OOI is deployed. A brief description and the results of the different behaviors are provided below. The distributed science team successfully coordinated the goals with a daily teleconference and WebEx. Preplanning prior to call was enabled with a full data description of a dat blog which uploaded each day prior to the Telex. The ASPER/CASPEX planning and prosecution successfully developed a flight plan proposed by the science user community which then successfully remotely uploaded the mission to the glider operations center where it was uploaded to the glider upon subsequent call in. Proposed way-points were inspected by glider technicians prior to be uploaded to the gliders. This was effectively a machine-to-machine operation. The planning for the glider operations was organized through a data portal (Fig. 5), which not only provided real-time data and model forecasts but also provided the community the ability to examine real-time metrics between the observations and the models. Data was served via an OpenDap allowing any user to access both observation and modeling data that was stored at individual institutions that collected the data. This was enabled with the Thredds server. The OSSE successfully demonstrated the ability of CI to coordinate a diverse set of field assets and support the science need of a diverse range of science users simultaneously. This represents a critical significant advance to enable sustained operation of exceedingly complex ocean observing networks which would not be possible given the traditional mode of operation.

Test 1. Fan gliders out to collect spatial data after deployment. Three gliders were deployed nearshore on a single day while a fourth glider that had been deployed weeks earlier was transecting towards the shore. This is typical as often the high costs associated with ships require glider deployments to be as short as possible in terms of time. Therefore often multiple assets are deployed in a single location and the they need to spread out as efficiently as possible to maximize the available spatial data for the scientist. The CI software directed the gliders to fan out across the shelf. The progress of the gliders was monitored by the distributed science/engineering team (Fig. 4). The gliders were successfully navigated to fan out across the local study area by the shore side planning software.

Test 2. Fly glider parallel to each other in a cross-shore sampling mode to collect spatially coordinated data. Here the goal was to coordinate the glider fleet to conduct sampling of the mid-shelf. The hope is that gliders could maintain coordinated sampling despite the spatially variable currents. This is a key need for these Lagrangian platforms which often collect data that is spatially aliased in both and space.
and time. By coordinating the multiple glider to collect data in a regular grid mode can help minimize the spatial aliasing of the data. Gliders collected regularly spaced data over the mission, however the gliders during the mission “over-shot” the way-points and the gliders quickly reversed course the missed target. The glider heading to the shore was directed to head to the ship rendezvous location for pick-up. (Fig. 6). Building in the logic to deal with waypoint a glider “over shoot” is a something that should be addressed in the next iteration of the shore side planner.

Test 3. Swarm the glider to a common location. The shore side planner was used to direct the gliders to fly together in order to simulate the need to aggregate spatially distributed field assets. This is often required an individual glider might locate a feature of high scientific interest and field assets might be used to map the feature of interest. A glider from of the University Delaware (denoted by school mascot logo) was added to the glider fleet. The gliders began to move to central location successfully despite variable currents along the shelf. (Fig. 7).

Test 4. Distribute gliders to satisfy several science missions. The OSSE team came up with several different science missions. Two gliders were directed to span and move into the directed swath of a Hyperion satellite over-flight. This was a difficult mission as the Hyperion path was very small and often OOI assets will be used to calibrate remote sensing algorithms however often lack in situ data during the overflights. This over-flight was adaptively chosen by the OSSE team based on the real-time data accessed though the web portal. The other two gliders were directed conduct inner and outer shelf surveys to map the phytoplankton winter bloom. The gliders made good progress and collected calibration data for the Hyperion satellite (Fig. 8).

Test 5. Direct gliders based on variability in numerical ocean model forecasts. The team benefitted from having several different ocean forecasts. The models provided a range of forecasts some with significant differences. Therefore the OSSE team directed the gliders to collect data in the regions of greatest variability between the models. This was possible given the ability of the CI to visualize the uncertainty between the models using the ASPER/CASPEN software. This experiment was conducted for several days (Fig. 9) and demonstrated that modelers could 1) coordinate field assets and 2) their input could lower the variance in the model comparisons. This is being analyzed by the modeling team after experiment.
Test 6. Allow community participation at the science community workshop in Baltimore. During the OOI community workshop, the community was asked to redirect the gliders. The community decided for several different goals, which was to fan two glider away from each other and then move two gliders to meet at a common position. The communities input was emailed to the OSSE team from the meeting room which then directed the ASPER/CASPEN software and commanded the gliders to move to the positions chosen by the community.

Fig. 10. Gliders sampling regions of uncertainty between the ocean models. The yellow halo around the glider represent the “reachability” space for the different gliders over a 24-hour period. The “reachability” region varied with the specific numerical model used.
3 OSSE Planning and Prosecution Components

3.1 Shore side observation planning
The mission planning software interpolates high-level goal locations with current-optimal paths, validating the plan to ensure that the glider can reach a desired end-of-day location given the current predictions provided by the ocean forecast models. The end results is a set of data products, including: a mission plan for execution onboard the Rutgers stock gliders, an ASPEN/CASPER plan for execution by the advanced MOOS-IvP prototype for onboard autonomous execution, and various high-level visualizations for display during planning and from a web archive.

The planning procedure averaged 20 minutes during the OSSE. Scheduled vehicle surfacings provided the planning software updates (via the Rutgers network) about the latest positions of the gliders. These seed a planning procedure in which the user manipulates waypoints and interpolates them. “Reachability polygons” provide a visual summary of current predictions by showing the area that the glider could reach at each hour into the future. The operator controls the planning session from a map-based interface where high-level goals can be manipulated against overlay imagery. The user can activate planning functions through a MATLAB command window with a handful of simple commands. Figure 2 shows a typical planning session with two basic interfaces to the plan. The first is a map-based view in which the operator manipulates the glider position in space and time, setting high-level waypoints and verifying compatibility with current forecasts. The second option is a timeline view through the ASPEN planner-scheduler, which tracks resources at a high resolution and permits fine-grained modifications to glider activities. The ASPEN planner scheduler exports an alternative plan format which can be used by the CASPER real-time planner onboard a future AUV.

The novel technologies of the shore planner, including the path planning methodology, are documented in the following publications:


3.2 Dynamic simulation
The dynamic simulation validates glider mission plans in a dedicated high-fidelity “dynamic” simulation of the glider performance. The simulation takes advantage of a behavior-based control system, MOOS-IvP, that moderates between different behaviors attempting to control the vehicle. MOOS-IvP uses an integer programming approach to produce an optimal control signal to the AUV. Unlike the coarse model of vehicle/current interactions used by the planner, MOOS-IvP offers a fully dynamic simulation with high time resolution. The two goals of the dynamic simulation were to validate plans on shore in the most faithful representation possible, and to test the interfaces between planning and vehicle control to ensure that future AUVs could benefit from the MOOS-IvP control system.
Fig. 11. Typical mission planning workstation. (A) Waypoints are adjusted in a visual map interface. The white line shows glider ru23 traveling toward the coast; if extra time is available it will perform a “runout activity, traveling toward the footprint of the next day’s satellite overpass (green rectangle). Yellow polygons show areas reachable by the glider by the end of the forecast period. (B) The Cartographic planning terminal provides utilities for rough manipulation of the plan. It draws on real-time glider position information from Rutgers University and five OpenDAP ocean simulation models. Its current-sensitive path planner computes optimal trajectories through the time-varying currents; these are visible in the vector field animation (C). Finally, ASPEN command terminal and GUI appear in window (D) and (E). Here ASPEN shows a timeline view of the ru23 plan, tracking resources and state.

The OSSE testing regimen tested the full ASPEN plan in a simulation using the MOOS-IvP control mechanism [11]. This evaluated the interface between the shoreside ASPEN planner and the onboard behavior-based control system. Onboard, a parallel planning and execution module (pCASPER) could execute the full plan autonomously on a future AUV. Tests during and after the OSSE fed real glider plans to the pCASPER module, a subcomponent of the MOOS-IvP system which interpreted ASPEN plans and adjusted behaviors accordingly. Real-time simulations demonstrated pCASPER executing the entire seventh day of OSSE operations. Here pCasper controlled a simulated glider, scheduling waypoint-following activities and interpreting the plan dynamically to modify actions in response to unforeseen errors and positioning inaccuracy. This provides an additional layer of robustness to plan execution, and could be used to trigger adaptive science-driven behaviors between communications cycles.

The Moos-IvP helm runs as a single MOOS process and uses a behavior-based architecture for implementing the on-board autonomy. A state space configuration determines which behaviors are active under what situation. A Slocum glider dynamic model was developed for testing each behavior and to test the overall performance of a glider in executing the commands sent by the ASPEN/CASPER planner.

### 3.2.1 Slocum Glider Dynamic Model

By considering the forces acting on the glider, a mathematical 3D model is derived for the 6 degrees of freedom. The state changes in the vertical and horizontal planes are represented as pitch, heading, roll,
and depth. This dynamic glider simulator is written as a MOOS process called uSlocumSim which has a direct interface to the environmental model. In the simulations MIT MSEAS model is used as the environmental model. Interfaces called iMseas and iMseasBathy were developed to read the current speeds, bathymetry, conductivity and temperature from the MSEAS environmental model. Similar to the real Slocum glider, the simulated glider changes its state according to the gravitational, buoyancy and current forces. So the Moos-IvP multi-objective optimizer will generate the desired depth, desired heading and desired speed for the glider based on the way-point determined by the CASPER planner. A separate MOOS process called pHelmToSlocum derives the desired pitch, which is the controllable parameter on a glider, using the three parameters published by the Moos-IvP process.

![Fig. 12. The MOOS-Scope shows all the variables published and active processes including pCasper and uSlocum-Sim on the MOOS-DB](image)

### 3.3 Autonomous Mission Execution

AUV autonomy tests spanned two days of operations in a shallow area near the coast. Remote scientists determined the AUV “operating box” by examining satellite data products and directing mission planners to a local biological anomaly. They identified a promising area and described the mission to planners at JPL who forwarded the intended deployment location to the boat-side field team. Three AUVs were deployed: MIT/NUWC IVER, CAL. POLY IVER & RUTGERS REMUS\(^1\).

\(^1\) Iver2 and Remus are models of Autonomous Underwater Vehicles (AUV). Iver2 vehicles are produced by OceanServer Technology Inc. Remus vehicles are produced by Hydroid LLC.
Each AUV was equipped with an acoustic modem enabling underwater communications between each vehicle as well as with the topside command and control station on-board R/V Arabella through a gateway buoy, as shown in Fig. 13. Using this communication network AUVs reported their status information such as position (Lat, Long and depth), speed, heading, and some sensor readings such as CTD². Topside published this information on Google Earth which was then shared with scientists at different locations through the internet in real-time. A snap shot of the topside view can be seen in Fig. 14.

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² A CTD sensor measures conductivity, temperature and depth, the essential physical properties of sea water. Salinity and density can be computed based on these measurements.
Adaptive behaviors were running on the IVER vehicles adapting to the environmental features such as temperature. The communication infra-structure enabled collaborative behaviors. Both IVER vehicles were running MOOS-IVP backseat driver missions. Using the topside command and control station AUVs were commanded acoustically to deploy at the locations determined by the JPL planner. Back-seat driver carried out these tasks autonomously using the behaviors on-board the AUV.

4 OSSE Analysis and Synthesis Component

4.1 Data Portal

A major feature of the OSSE was the web portal (http://ourocean.jpl.nasa.hgov/CI) developed to provide a single access point for the observational and model predictions. During the field experiment, a high-level summary was posted daily describing both the atmospheric and oceanographic conditions. The following is the example posted on the first day of the field experiment:

“Executive Summary of 11/01/2009: Southerly winds are observed during the weekend with a speed around 10. NAM forecasts indicate that the wind will switch to northerly winds by Monday and last for about two days with about the same magnitude. Because of the improved weather conditions, there is therefore excellent satellite coverage for SST. We continue to receive four ocean model forecasts on the daily basis. A multi-model ensemble forecast is constructed based on the equal weighting method. The variance of the ensemble forecast is also estimated and will be used to guide the glider deployment in the coming days. Four model forecasts are also compared with observed SST and surface current. A Google Earth (GE) based web interface is also developed to track the four gliders being deployed.”

4.2 Data Integration

During the field experiment, there was excellent coverage for the sea surface temperature (SST). The web portal provided daily SST map from multiple sensors/platforms including Advanced Very High
Resolution Radiometer (AVHRR), Moderate Resolution Imaging Spectroradiometer (MODIS), Advanced Along-Track Scanning Radiometer (AATSR), the Geostationary Environmental Satellites (GOES, SEVIRI), Advanced Microwave Scanning Radiometer Earth Observing System (AMSR-E), Tropical Rainfall Measuring Mission Microwave Imager (TMI) as well as in situ measurements. Using a multi-scale two-dimensional variational (MS-2DVAR) algorithm [12], a blended SST product at 1-km resolution is also provided (Fig. 15). This blended SST data was provided to the participating investigators in the netCDF format through the OpenDAP (http://www.opendap.org/) and THREDDS (http://www.unidata.ucar.edu/projects/THREDDS/) server.

Fig. 15. A sample snapshot of sea surface temperature on November 8, 2009 blending multi-satellite and in situ measurements

Surface currents are obtained from high-frequency (HF) radar or CODAR. Both the long-range and short-range systems are used to derive the surface current shown here at 6-km spatial resolutions (Fig. 16a).
Fig. 16. Snapshot of surface current as measured by the HF radar network (a: top-left) and predicted by the equal-weighted (b: top-right) and objective-weighted (c: bottom) ensemble mean.

4.3 Numerical Model Operation and Integration

We were accessing four numerical model nowcast/forecast products (i.e., HOPS, NYHOPS, ROMS-COAWSST, ROMS-Expresso) on the daily basis. During the first week of the field experiment, we are constructing the multi-model ensemble mean using the Equal Weighting Method: the ensemble forecast is the mean of available individual model forecasts, with equal weights for each individual model (Fig. 16b). The variance of the ensemble forecast is therefore the average square difference between individual forecast and ensemble forecast.

Starting from the week 2 of the field experiment, we started to produce the ensemble forecast using an objective weighting method (Fig. 16c). The weighting for each individual model is based on the performance of the model during a training period. The probability density function of any quantity to be predicted is a weighted average of probability density functions centered on the individual bias-corrected forecasts, where the weights are equal to posterior probabilities of the models generating the forecasts. A linear regression between model forecasts and observations is used to remove any possible biases for each individual model. The weighting is estimated by maximum likelihood through iteration. The probability density functions for each individual model are assumed to be Gaussian. The training period for the CI OSSE field experiment is Oct. 10 to Oct. 20, 2009. The verifying observations are daily 1-km blended sea surface temperatures and hourly 6-km high-frequency coastal radar surface currents. Clearly, the objective weighted ensemble mean performs significantly better than the equal weighted mean.
The model performance is also evaluated in real-time against the four glider measurements (Fig. 17). Users can select each of the four gliders as well as four individual models and ensemble means using either equal weighting or objective weighting.

![Diagram](image)

**Fig. 17.** Vertical profiles of temperature (top-left) and salinity (bottom-left) as measured by gliders (green) and predicted by models (red). Right panels show the differences of temperature and salinity between the observation and model forecast (blue).

During the field experiment, gliders are tasked on 24-hour cycles. Each daily glider planning session produces a 24-48 hour trajectory that is designed to optimize travel time toward the operators’ chosen destination. The planned trajectory accounts for time-varying 3-dimensional current forecasts produced by the "ensemble" numerical model. The trajectory appears in the Google Earth view as a grey path, with circles at the beginning and end containing additional information about the glider, time schedule, and locations (Fig. 18). As a byproduct the planning session also computes paths using forecasts from each of the independent numerical models taken individually. These are represented as colored lines and circles. Occasionally, an individual model will not find a path to the goal due to missing data or anticipation of strong countervailing currents. In this case the line trajectory is omitted.
Fig. 18. Spatial locations and trajectories for the four gliders being deployed during the field experiment.

The highlight of the field experiment was the formation flight between underwater gliders and the Hyperion (http://eo1.usgs.gov/hyperion.php) imager flying on the Earth Observing One (http://eo1.gsfc.nasa.gov) spacecraft. The Hyperion images are typically 7.5 km (across track) by over 100km (along track) and resolve 220 spectral bands from 0.4 to 2.5 microns with a spatial resolution of 30m (Fig. 19). During the field experiment, both observational data and multi-model forecasts are analyzed to determine a tasking location. These coordinates are then used by the EO-1 sensor web capability (http://sensorweb.jpl.nasa.gov) that enables autonomous operations and tasking of the EO-1 spacecraft. With several days’ planning, we were able to co-locate two gliders within the EO-1 Hyperion swath, a major technology breakthrough in simultaneously coordinating satellite and underwater assets guided by multi-model forecasts.
5 OSSE Conclusions and Lessons Learned

The OSSE experiment successfully demonstrated the potential for the OOI CI Planning & Prosecution software. The CI successfully allowed a distributed group of scientists to coordinate a range of models and a diverse suite of field assets. The distributed scientists who partook in the effort spanned from Rutgers University, University of Massachusetts at Dartmouth, University of Maryland, Woods Hole Oceanographic Institute, California Polytechnic State University, United States Geological Survey, Massachusetts Institute of Technology, University of Delaware, University of Miami, Stevens Institute of Technology, Jet Propulsion Laboratory, and Scripps. The experiment also included an observer from NOAA’s Integrated Ocean Observing System’s office. The two-week experiment resulted in a series of ongoing discussions on how to sustain the CI capabilities to coordinate the ocean observing assets in the Mid-Atlantic Bight. Many of the scientists, who were not part of the immediate OOI team partook in the OSSE and were extremely impressed about the potential of OOI. Given this, these field demonstrations offer great potential to maximize community buy-in of the OOI and can serve as a powerful ambassador for the program.

The primary goal of the OSSE was to assess the strengths and weaknesses of the planning prosecution software, however the experiment was also designed to support science simultaneously. The OSSE was conducted during the end of autumn when continental shelf stratification was breaking down which replenishes the nutrients to the upper euphotic zone that stimulates the winter phytoplankton bloom on the inner shelf of the MAB. The winter phytoplankton bloom is the largest and most significant planktonic event on the shelf; however very little data has been collected on the winter bloom. The fleet of gliders coordinated using the OOI CI software successfully mapped out the initiation and corresponding increase in the phytoplankton biomass. The bloom was increasing in biomass but the passage of Nor’Easter resulted in the intense mixing which dissipated the bloom. The OSSE also documented complex frontal
features associated with the Hudson Canyon. Gliders and satellites were adaptively adjusted using the OSSE software to study the physical optical dynamics in the Hudson canyon.

There were lessons learned during the OSSE. The lessons listed below are based on the input from the external community. The lessons are split between those scientists operating the observatory and those scientists using the observatory.

**Operator needs**

1) For glider planning prosecution 24-48 forecasts are useful time frames however hourly waypoints are too frequent for the shore side operators. For most coastal applications surfacing intervals are usually minimized (3 to 6 hours) to maximize the time for the glider “flight” time and minimize surface exposure to waves and ships.

2) In contrast, the hourly waypoints are a bit too long for AUVs, which ideally would have access to updates whenever required.

2) The ability to upload waypoints based on forecasts show great promise, however there is sensitivity to the forecast model being used. Ensembles of models showed the greatest success in predicting the actual glider trajectories.

3) For glider operations, synchronizing the commands to glider call-in times are crucial to glider experimental planning and allowing operators to coordinate sustained operations of multiple vehicles.

4) On the fly data/model metrics is critical to optimizing mission planning based on potentially many available forecasts.

5) Data assimilation models require robust data streams, however most of the numerical model grid scales are relatively large in space and time, and data is most averaged in both space and time.

6) Shore-side planning is enabled by dynamic simulations in both space and time. This tool was critical to allow for the science

**Science needs**

1) Large distributed groups of scientists require the visualization tools to allow for some frame of reference. These tools are required to provide a common frame-work of reference to coordinate science efforts.

2) Utilizing community standard data formats and model frameworks lower the barrier to allow distributed scientists to join distributed science teams.

3) Social networking tools must be simple to join and needs to be easy to find to enable the wider community involvement with low barriers to join the effort. Teleconferencing was a critical tool to enable a sense of community.

4) Blogging tools are critical to providing a historical narrative to coordinate field science. These blogging efforts will likely need to be community initiated.

5) Given OOI will support many multiple simultaneous experiments the ability to easily search ongoing often independent activities will be important to allowing wider community involvement.
6) The maps of variance of between the models were extremely informative.

7) Easy to navigate data portals are critical and with basic visualization tools to see the data in both and space in time.

6 Summary

The OSSE prototype and experiment was the central effort in advancing the Planning & Prosecution and Analysis & Synthesis subsystems and mitigating risks related to their construction. The results and lessons learned from the OSSE effort have been summarized in the previous section.

The particular risks targeted and reduced were

- #2223 Virtualized Collaboration Services. The OSSE portal and the mission planning procedures and tools demonstrated how ocean observing mission planning can be conducted remotely by leveraging advanced virtual collaboration tools.
- #2225 Observation Planning & Coordination Services. The OSSE shore side and embedded mission planning procedures and tools demonstrated initial feasibility for observation planning at an observatory scale, both technically and operationally.
- #2239 User Involvement. The OSSE experiment directly involved collaboration ocean observing, observatory management and data analysis users and had substantial visibility to the related scientific communities. The success as the OSSE as cyberinfrastructure oriented scientific collaboration experiment contributed to a reduced likelihood of the risk of lack of user involvement.
- #2233 Model Integration Strategy. The OSSE demonstrated how to integrate numerical forecast models successfully into an ocean observatory system, both as input for observing mission planning and as target for improved numerical model output products, in a closed loop scenario. This was based on common interoperability standards and technologies (DAP servers, NetCDF files, CF conventions).
- #2224 Event Detection Services. The OSSE demonstrated feasibility of event detection services in a closed loop observing mission planning and prosecution scenario. Event detection, whether automatic and manual, can lead to improved and modified observation mission plans for available stationary, mobile and satellite assets, which can be interactively retasked accordingly with short turn-around.
- #2230 IOOS Interoperability. The OSSE experiment showed interoperability with operational data products from IOOS regional observatories (MaRCOOS) in both directions. A joint effort between IOOS and OOI was made towards data interoperability by establishing standards and technologies. The successful OSSE integration demonstrated the value of a close IOOS-OOI partnership and its technical and operational feasibility.

Next steps for the OSSE will be to perform further reanalysis by the participating science teams and publication of scientific results and data in suitable journals. The intent of all OSSE participants is to continue this collaboration beyond the OOI CI pilot prototype phase through collaboration with IOOS and other funding sources. In the near future, further integration of available CI components such as COI messaging and data distribution that was not feasible for this OSSE experiment will lead to even more advanced and automated ocean observing and mission planning.

The Planning & Prosecution and Analysis & Synthesis subsystems will enter construction for the most part with releases 3 and 4. Technology is expected to improve within this time. Beyond demonstrating fundamental feasibility, the results of the OSSE prototype refined the architecture for these subsystems and will provide valuable technical requirements for more fundamental subsystems, such as COI, S&A that enter construction in release 1.
7 References