2010 Sixth IEEE International Conference on e–Science

COVE: A Visual Environment for Multidisciplinary Ocean Science Collaboration

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Abstract—**Advances in cyberinfrastructure for virtual observatories are poised to allow scientists from disparate fields to conduct experiments together, monitor large collections of instruments, and explore extensive archives of observed and simulated data. Such systems, however, focus on the 'plumbing' and frequently ignore the critical importance of rich, 3D interactive visualization, asset management, and collaboration necessary for interdisciplinary communication. The NSF Ocean Observatories Initiative (OOI) is typical of modern observatory-oriented projects–its goal is to transform ocean science from an expeditionary science to an observatory science. This paper explores the design of an interactive tool to support this new way of conducting ocean science. Working directly with teams of scientists, we designed and deployed the Collaborative Ocean Visualization Environment (COVE). We then carried out three field evaluations of COVE: a multi-month deployment with the scientists and engineers of an observatory design team and two deployments at sea as the primary planning and collaboration platform on expeditionary cruises to map observatory sites and study geothermal vents.**

Keywords - Collaboration, Visualization, e-Science

I. INTRODUCTION

Oceanography has traditionally been an expeditionary science: small crews of oceanographers periodically going to sea to collect data and conduct observations. Now, new ways of collecting and analyzing data offer to increase our understanding of complex ocean processes. For example, multidisciplinary teams share instruments and data to carry out research in Monterey Bay and to gather information about typhoons in the Pacific Ocean. Ocean observatories that continuously collect and analyze diverse oceanic data propose an even more extensive use of this approach. The goal of this endeavor is to provide a flexible platform allowing hundreds of scientists from disparate fields to conduct experiments together, manage assets in real-time, and create a vast archive of observed and simulated data.

These environments pose new challenges for cyberinfrastructure. To better understand these new environments, we employed participatory design techniques with scientists at two oceanographic institutions. In our close collaboration we observed teams with several specialized tools to support specific tasks or disciplines, but none that provided an effective collaborative interface. Powerful desktop science data viewing tools allow visualization of bathymetry and science data [1-3], but are difficult to use and lack necessary layout capabilities for instruments and data sharing support. Geo-referencing browsers (geo-browsers), such as Google Earth [4] and Microsoft Live Earth [5], provide a familiar physical metaphor for viewing the large geographic layouts of these projects, but do not support high resolution 3D bathymetry (sea floor terrain) required by ocean scientists or viewing of rich multi-dimensional science data. Scientists therefore must move between multiple systems to plan experiments, analyze data and share results.

To address these needs, we worked closely with the scientists to implement and deploy the Collaborative Ocean Visualization Environment (COVE) shown in Figure 1. COVE offers the ease of use of a geo-browser along with a set of key enhancements in the areas of data visualization, asset management, and team collaboration. Refined through iterative prototyping with the scientists, the final system provides a powerful interactive workplace for the team.

To evaluate our design, we deployed COVE in two very different environments. The first was extensive use by an observatory design team to create the core cabling and instrumentation layout for a deep water ocean observatory. Here it provided a common ground to quickly examine new layout options, discuss trade-offs, and present these options to experts from various fields of oceanography, earth science, and engineering. We then carried out an *in situ* design evaluation with multidisciplinary science teams as part of two ocean expeditions. The first expedition assessed two research sites for the observatory where COVE supported the creation of high resolution bathymetry and integrated diverse datasets to carry out daily planning, execution, and review of missions. In the second expedition, we visualized and supported mission planning for manned submarine dives to study volcanic vents on the seafloor. The results of these deployments show that by providing an intuitive common interface for the team, visual environments like COVE can play a pivotal role in large-scale multidisciplinary scientific collaborations.

The primary contributions of this work are a description of the elements we found crucial to a successful geo-browser collaborative ocean science interface and a deployment and evaluation of COVE's approach in three different collaborative science environments. The software and COVE examples can be found at http://cove.ocean.washington.edu.

978-0-7695-4290-4/10 $26.00 © 2010 IEEE
DOI 10.1109/eScience.2010.13

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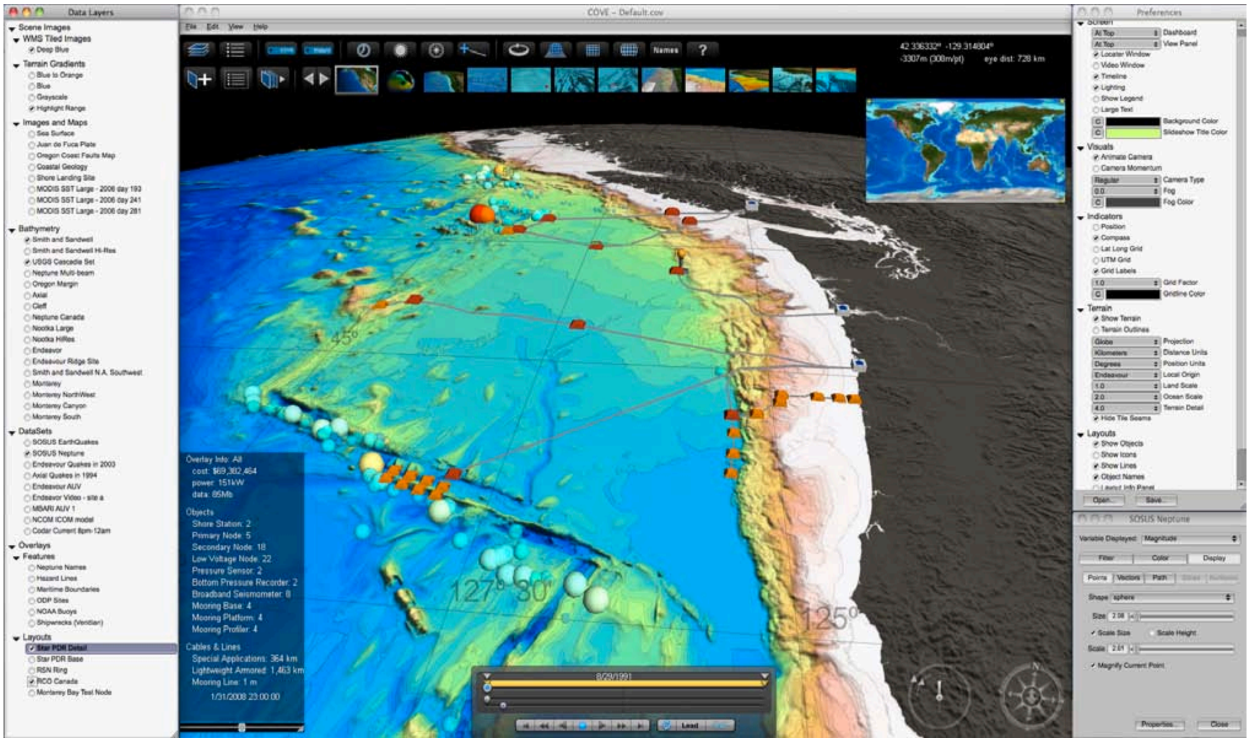

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▼ Scene Images
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☑ Deep Blue
▼ Terrain Gradients
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○ Grayscale
☑ Highlight Range
▼ Images and Maps
○ Sea Surface
○ Juan de Fuca Plate
○ Oregon Coast Faults Map
○ Coastal Geology
○ Shore Landing Site
○ MODIS SST Large - 2006 day 193
○ MODIS SST Large - 2006 day 241
○ MODIS SST Large - 2006 day 281
▼ Bathymetry
☑ Smith and Sandwell
○ Smith and Sandwell Hi-Res
☑ USGS Cascadia Set
○ Neptune Multi-beam
○ Oregon Margin
○ Axial
○ Cleft
○ Neptune Canada
○ Nootka Large
○ Nootka HiRes
○ Endeavor
○ Endeavour Ridge Site
○ Smith and Sandwell N.A. Southwest
○ Monterey
○ Monterey NorthWest
○ Monterey Canyon
○ Monterey South
▼ DataSets
○ SOSUS EarthQuakes
☑ SOSUS Neptune
○ Endeavour Quakes in 2003
○ Axial Quakes in 1994
○ Endeavour AUV
○ Endeavor Video - site a
○ MBARI AUV 1
○ NCOM ICOM model
○ Codar Current 8pm-12am
▼ Overlays
▼ Features
○ Neptune Names
○ Hazard Lines
○ Maritime Boundaries
○ ODP Sites
○ NOAA Buoys
○ Shipwrecks (Veridian)
▼ Layouts
☑ Star PDR Detail
○ Star PDR Base
○ RSN Ring
☑ RCO Canada
○ Monterey Bay Test Node

Overlay Info: All
cost: $69,382,464
power: 151kW
data: 85Mb
Objects
Shore Station: 2
Primary Node: 5
Secondary Node: 18
Low Voltage Node: 22
Pressure Sensor: 2
Bottom Pressure Recorder: 2
Broadband Seismometer: 8
Mooring Base: 4
Mooring Platform: 4
Mooring Profiler: 4
Cables & Lines
Special Applications: 364 km
Lightweight Armored: 1,463 km
Mooring Line: 1 m
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▼ Screen
At Top Dashboard
At Top View Panel
☑ Locator Window
○ Video Window
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☑ Lighting
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Background Color
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☑ Animate Camera
○ Camera Momentum
Regular Camera Type
0.0 Fog
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▼ Indicators
○ Position
☑ Compass
○ Lat Long Grid
○ UTM Grid
☑ Grid Labels
1.0 Grid Factor
Gridline Color
▼ Terrain
☑ Show Terrain
○ Terrain Outlines
Globe Projection
Kilometers Distance Units
Degrees Position Units
Endeavour Local Origin
1.0 Land Scale
2.0 Ocean Scale
4.0 Terrain Detail
☑ Hide Tile Seams
▼ Layouts
☑ Show Objects
○ Show Icons
☑ Show Lines
☑ Object Names
○ Layout Info Panel

Variable Displayed: Magnitude
Shape: sphere
Size: 2.08
✓ Scale Size
○ Scale Height
Scale: 2.01
✓ Magnify Current Point

Figure 1: COVE displays geo-positioned scientific data, seafloor terrain, terrain specific color gradients, and instrument layout. Instrument layout information is available in the heads up display on the screen, selectable layers on the left and rich visualization controls on the right.

II. MULTIDISCIPLINARY OCEAN SCIENCE

The oceans are an important focus of scientific study: they cover over 70% of the earth's surface, moderate its climate as a stabilizing force for the environment and are a significant source of food for much of the planet. Due to the impact of global warming, understanding ocean processes is increasingly central to predicting how our climate will evolve during the next century and the impact of those changes on ocean and human health. To date, our ability to collect data about the oceans has been extremely limited relative to this need, as oceanography has traditionally been an expeditionary science: small crews of oceanographers periodically go to sea to collect data and make observations.

New projects in the ocean sciences are taking a different approach. They are combining their resources to create virtual observatories, which look at sections of the ocean and inter-related problems, and require large scale scientific efforts. The hope is that by making vast amounts of collected and simulated data available to many different types of scientists we will greatly increase knowledge of the studied systems. While some of these missions are intentionally temporary and focus on a single scientific issue, ocean observatories are projects intended to be in place for decades to answer a range of scientific questions by providing constant intensive monitoring of a location. Over the next few years, the National Science Foundation (NSF) Ocean Observatories Initiative (OOI) will create an ocean observatory of unprecedented scale [6]. The Regional Scale Nodes (RSN) portion of the OOI, installed off the Washington and Oregon coasts, is a long term research platform that will support sensors from the ocean surface to deep in the seafloor, connected to cables delivering power and bandwidth.

This new approach to ocean science requires looking at the software tools necessary to support these efforts. To determine user needs for these type of projects, we carried out research at two different ocean science institutions: the Monterey Bay Aquarium Institute (MBARI) [7], and the University of Washington College of Ocean and Fisheries Science [8]. MBARI is the largest privately funded oceanographic organization in the world and acquires data through fixed and mobile instruments, ship based cruises, and occasional large-scale multi-institute projects. We worked with MBARI on two such projects. The Autonomous Ocean Sampling Network (AOSN) is a program to create an adaptive, coupled observation/modeling system through a series of multi-month activities to measure the effectiveness of adaptive sampling in Monterey Bay. A second MBARI effort involves the preparation for a multi-organization program to study the interaction of typhoons with the ocean surface. At the University of Washington College of Ocean and Fisheries Sciences, we worked with one group building the Regional Scale Nodes (RSN) portion of the NSF-funded Ocean Observatories Initiative, and another group generating regional-scale simulations of Puget Sound.

As with other design investigations involving science teams [9-12], we employed a user-centered, iterative, rapid prototyping strategy with the scientists at these institutions. Our approach involved reviewing existing visualizations and documents used by the teams, observing group meetings and individuals, discussing current processes with the primary participants on the team, and interviewing 2-3 members from each team in depth.

III. COVE

The Collaborative Ocean Visualization Environment (COVE) (Figure 1) is new type of science tool produced from our long term collaboration with these scientists. The design of COVE is in response to the three primary needs voiced by the teams we worked with:

- Make all data available in a common environment, so that it can be viewed concurrently.
- Enable monitoring and positioning of instruments and assets in the context of experiment sites and data.
- Provide an intuitive visual way to communicate across the team and with external groups.

To enable easy concurrent viewing of data the user interface is modeled on a geo-browser paradigm much like that of Google Earth, Microsoft Virtual Earth, and similar systems [4, 5, 13]. It provides an intuitive multi-scale interface, a familiar geographic context, and a simple layering metaphor to help organize different data. It also allows scientists to interact with layouts and datasets ranging from the hundreds of square miles covered by these projects down to a few meters around a sensor in an experiment.

Previous researchers have explored using geo-browsers interface for science data, but had based their work on existing interface features or presented limited enhancements [14-16]. Based on user research and feedback, we found that a more extensive set of additions was necessary for an effective collaborative science environment. Below we describe the three areas of user needs–*Visualizing Data Concurrently*, *Managing Assets*, and *Sharing with the Team*– in more depth and detail the specific enhancements to the standard geo-browser interface necessary to address them.

A. Visualizing Data

Virtual observatories encompass several different types of data. Contextual data includes high resolution bathymetry (sea floor terrain), geological maps, and site features such as telecommunication cables and navigation hazards (e.g., ship wrecks). Large amounts of observed data are often collected. Most is relatively small (less than a megabyte) as sensors often collect only a few data points at a time, but terrain and sonar data may be many megabytes in size and the availability of cheap, durable camera technology has created multi-gigabyte repositories of video and image data. Finally, high resolution simulated ocean models are becoming more common for all areas of the ocean. These are sometimes terabytes in size and only limited by the systems that generate and store them. Geo-browsers support concurrent viewing of many of these datasets, but required extensions to support all the necessary types used by the team.

Geo-located 3D scientific visualization is provided to view multidimensional scientific datasets. The goal is not to deliver the exhaustive capabilities of specialized scientific visualization packages, but rather a set of interactive visual techniques commonly used by the scientists. Datasets can be viewed as points, paths, vectors, surfaces, and volumes over time using customized color gradients. In Figure 2, COVE displays variables from several data sets layered in the context of regional geography. We natively read geo-referenced NetCDF files [17] and other formats used by the scientists. We also provide data exploration tools such as filtering, scaling and resampling, as well as specialized tasks such as vertical ocean sections and particle advection.

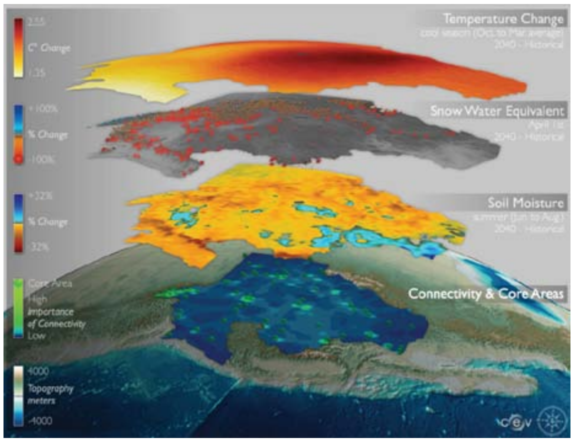

Figure 2: This view created in COVE shows several types of collected data layered above its geo-location to provide context.

High resolution bathymetry support is particularly challenging since it is constantly updated as better versions become available and there are few existing image collections to aid visualization. COVE allows arbitrary combinations of bathymetry sets to be assembled in real-time, showing the highest resolution terrain available for any point. To provide visual cues for the terrain, scientists can apply maps and images, customized depth-based gradients, contour lines or binned color values to highlight depth ranges, as well as shading, fog, and scaling.

A web-based workflow solution allows use of external resources to address the size, arbitrary formatting, and extensive manipulation often required to visualize key attributes. COVE can initiate, monitor, and download workflow results through a web service. A rich workflow library can be built up to allow re-use of valuable processes or sub-processes. As these processes are run, attributes can be automatically captured to create a complete provenance trail for processes and data used by the observatory. By combining workflow and direct manipulation capabilities, interactive exploration of large datasets becomes possible.

B. Managing Assets

Many of the instrument sensors and delivery vehicles are expensive and scarce resources. Optimizing their use can often greatly increase the amount of data collected on a mission. Observatories require the management and monitoring of hundreds to thousands of heterogeneous sensors collecting data at any given time, independently changing state based on detected events, and possibly being completely re-tasked to focus on major ocean occurrences such as earthquakes, volcanic eruptions, or storms. COVE enhances user interaction, on screen feedback, and customization to enable monitoring and positioning of instruments in the context of the data and sites.

A drag and drop instrument management interface is available to add and position objects represented by icons or 3D models (Figure 3). Information summaries for any instrument can quickly be viewed as text in a popup window or as a detailed web page in a web browser. Cables can be added following the bathymetry and displayed in a cross section view to detect extreme drop-offs and other hazards. Positioning handles are available for maneuvering cables around obstacles in the terrain. Objects and cables can be collected into instrument templates to allow easy insertion of complex packages, such as geodetic arrays containing several connected components.

Heads-up displays that are automatically updated on the screen during editing sessions provide instant status on characteristics of assets and instruments, e.g., budget, current cost, and length of cable. By having budgets and installation timing readily visible and costs automatically updated with changes, layouts can be quickly refined to meet specific goals.

Experiment specific instrument libraries enable a team to define its own visual vocabulary of icons and 3D models. Switching between libraries allows each experiment to have individualized visual metaphors.

C. Sharing with the Team

These projects usually bring together scientists that have not previously worked together, and in the case of some projects may bring together sciences that have not worked together before. Observatories are creating an infrastructure that is designed to make it easier for non-oceanographers to participate in, or completely manage ocean experiments. And all the sciences are finding it more and more important to reach out to policy makers and citizen scientists to effect change, create awareness or raise funds. Geo-browsers allow sending of XML based files to share collections of data, but we required capabilities for richer sharing across a team.

Interactive views can easily be created and stored to save a specific set of camera, layer, and visual settings in COVE. These views can then be invoked locally for examining and discussion work from various perspectives or posted to a website. Once posted, other team members can investigate and click on the view to activate it in COVE, and be able to quickly start exploring the data themselves (Figure 4). A set of views can also be automated, like a slide show, to provide a guided tour through different aspects of the site and data. For communication outside the team, COVE can create high-resolution images, movies, and Google Earth KML files of various views.

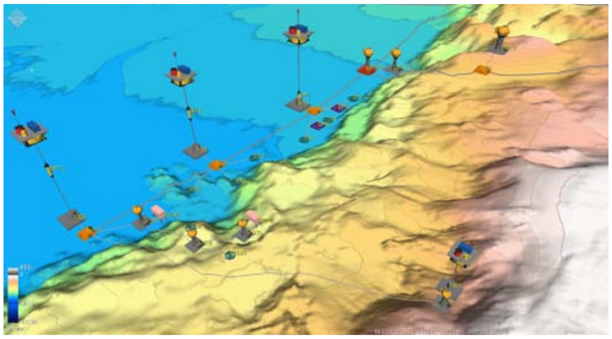

Figure 3: Sophisticated instrument layout can be easily created, modified, and shared with collaborators to ensure the best use of assets.

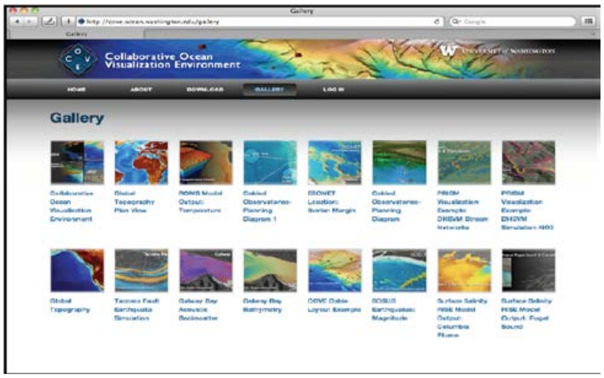

Figure 4: Views are easily created in COVE and can then be uploaded to a website to make it easy to share visualizations of experiments and data.

A web-based data repository makes it easy to upload and share new datasets with the rest of the team. These files can then be automatically downloaded when needed. To be kept apace of changes in the repository, scientists can register to receive messages in COVE, much like an RSS feed, when someone makes changes to data or locations of interest.

View integrated search enables searching for data that can replace a dataset in a saved view, or to find views created by team members that may help in exploring a given data set. As the collection of views and data sets grows, search capability becomes more important to find data. Search is also available on keywords, as well as location and time stored with views and data.

IV. EVALUATION

We took a two-pronged approach to evaluating COVE. We first observed its use on land in the design of the core infrastructure of an observatory over several months. Then we joined two, two-week expeditions at sea with multidisciplinary science teams. The first evaluated two primary observatory sites and the second carried out manned submersible missions to study geothermal vents.

A. RSN Design

The goal of RSN design team is to determine the layout of primary cables, connection hubs, and instruments that form the infrastructure for future science experiments. Bathymetry, maps, and datasets for the sites are analyzed to understand possible issues at each location. Various layout options are created and analyzed to determine optimal designs within budgetary and technical constraints. The layout must then be presented to scientists, engineers, and funding agencies to discuss feasibility.

The design process used by this team before COVE included utilization of paper and digital maps, geographical surveys, and multiple software applications. When new layouts were created by the project team, they were recorded in word processing or spreadsheet documents, and visualized by a graphics team for presentation. Changes were time-consuming and expensive as there was no automated way to update costing or cabling, comparisons of different models required several documents and spreadsheets, and it was hard to examine designs from different angles or scales.

Our methodology was to take a long-term, embedded approach. The main participants were the RSN's lead scientists, engineers, and graphics staff who were involved in the daily design process. Based on observations of participant interaction with COVE and their feedback, new prototypes were created on a weekly basis.

1) Results

We observed many interactions highlighting the value of COVE in this environment. Scientists created new layouts in minutes rather than hours or days. They saved multiple views to evaluate the results from various angles, particularly between 2D top-down and 3D perspective views. Maps of fault lines and surface geology were displayed together to help with interactive cable layout while using the heads-up display to ensure budgets were met. The scientists found the layering model for datasets intuitive and integration with Google Earth formats beneficial for distribution outside the group. One participant explained how her work was improved by COVE. *"For me, since I don't have the tools that our graphic artists have, it meant that I can respond much quicker. There was a period of several months where we were getting crisis level, 'you need to respond to this in the next month' to deal with contingencies or inflation or budget changes, and COVE made that possible."*

Once COVE was adopted it became the primary collaboration tool in the creation of the RSN primary infrastructure. *"As soon as we got access to COVE and had some useable knowledge; from that time on we stopped using anything else. It really was a transformation. From that day on it became the base map for what we do."* COVE was used extensively in preparation for NSF design reviews where the team was required to present and defend their design to the funding agencies. It allowed different core cabling alternatives to be explored quickly, and helped convince the team of the necessity to adopt a significant change from a ring-based to a star-based cabling configuration. It was also the key tool for creating visuals to explain the layout at design reviews, as it quickly created production level visuals in sync with the most recent designs. The reviews were deemed highly successful and the RSN team has been vocal in praising COVE as a key contributor to their achievements.

We also learned much from the team to improve our initial COVE design. We saw that it was necessary to support existing techniques for the scientists to comfortably switch to COVE. Although paper maps and rulers had many drawbacks, they were also familiar and dependable. We found we needed to add simple 2D top down views and map views that could be printed. Similarly, it was necessary to provide ways to double check results within COVE with overlay grids and measuring tools to reconfirm distances and locations. We also initially considered presentation-quality visuals a minor aspect of COVE, but found that since the RSN team had to present and defend their work regularly, providing high-resolution output formats, text and image overlays and visual highlights were important additions to the collaborative environment.

B. Expedition to Map RSN Sites

After working with the design team for several months and refining our system based on their feedback, we were presented with the opportunity to test COVE in the field. The next stage of the RSN design process was a two-week ocean expedition to collect extensive data from two major seafloor research sites for the observatory.

The chief goal of the expedition was to verify that the multi-million dollar primary connection hubs were being placed at safe and durable locations. Mapping the seafloor was the most important part of this effort. In this task, sonar is used to collect 3D point sets by bouncing acoustic reflections off the seafloor to create a map of the terrain (Figure 5). The ship or sub carrying the sonar travels back and forth over an area covering new terrain on each pass. Since the beam is fixed angle width, the closer the sonar is to the bottom, the thinner the area covered, but the more detail collected. These detailed maps of the bottom would determine if it was flat, solid, and free of landslide danger.

The cruise took place on a research vessel 100 meters in length with 25 fulltime crew and 32 research staff. Hull-mounted sonar was used for lower resolution mapping from the sea surface. For high resolution mapping, the SENTRY autonomous submarine [23] provided by Woods Hole Oceanographic Institution followed a programmed route 50 to 100 meters above the seafloor for up to 10 hours. The previous technique for determining routes involved the team gathering around a map and placing markers (usually coins) to designate possible waypoints (turn locations) for the ship. The SENTRY sub was programmed by printing a high-resolution map of the location and using a ruler to determine lengths of runs. Although this approach had been used on many cruises to carry out missions, it suffered from the same drawbacks as those noted with instrument layout for the RSN: routes were hard to create and modify, it was hard to compare alternatives, and different views of the route were difficult to create.

Our goal was to replace this approach by using COVE to

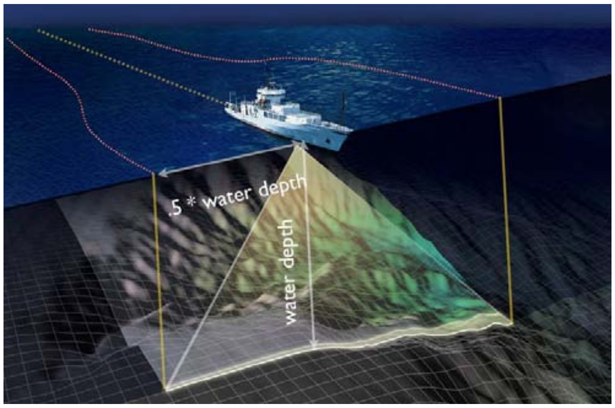

Figure 5: EM 300 Side Scan Sonar from the Research Vessel.

plan the dive, track progress, and then view and analyze the final bathymetry. Since all the observatory data was already available in COVE, planning with potential layouts was possible and new layout plans could be created if necessary. The primary participants still included scientists, but there were also research assistants, ship's engineers, and students. Whereas the methodology in the preceding section was long-term, this evaluation context was short-term and time-sensitive and new prototypes were created at least daily.

1) *Results*

In the time-sensitive environment on the ship our interactive mechanisms for route layout were effective in many ways. *"On the cruise where we used COVE for the first time, I would say that it increased efficiency several orders of magnitude for laying track lines. And it's much more iterative since it's so easy to move things around and see the swath width of the sonar. Since we fly over such steep topography, we'd often have holes in the data doing it by hand. With COVE we increased the efficiency, the quality, and the communication between people."*

The 3D bathymetry visualization tools were all used extensively to explore collected terrain and discuss site tradeoffs. Since it was cheap to make new routes, several possible plans could be created, compared and discussed to determine effectiveness. It also allowed the team to take advantage of unexpected opportunities. *"The nice part was that because of bad weather or instruments breaking, the normal things that go on out there; sometimes we'd have two more hours of ship time, so we'd plan out a track line to fill in a hole and use the ship efficiently. We could have done it before by hand, but the ability to respond in a timely manner - I can't tell you how much easier it was."*

The interactive visualization interface of COVE was used by all levels of the science staff, from students to the chief scientist. COVE became the forum to showcase collected datasets for the expedition at daily science meetings. The slideshow mechanism enabled everyone to become presenters and story tellers for their aspect of the trip. We saw not only great interest from the science staff, but also from the ship's engineering staff. By the end of the cruise, the expectation was that COVE would become part of the future process for all mapping expeditions. This is particularly impressive considering that the research vessel costs $25K per day to operate and may take months to reschedule if a mission is unsuccessful.

We learned much in the transition from lab to the expedition environment. We had little time to test COVE in this setting before we shipped out and soon noted several stability issues due to a variable network in this environment. We eventually had to use portable drives to share data, which was acceptable on this occasion but must be resolved for future expeditions. One insight arising from our work on this issue is that the science staff is forgiving of software crashes in their research environment, but data loss is never acceptable. As a result, changes were made in COVE to support local data servers and provide a fault tolerant data system.

C. *Exploring Geothermal Vents with ALVIN*

After our success mapping observatory sites, we were invited to evaluate COVE in a second ocean-based science environment with a team of scientists on a two week cruise investigating geothermal vents in the northeast Pacific. This would take place with a vessel and crew size similar to the previous mission and be centered around twelve manned missions in the ALVIN underwater sub [18] to collect data on the seafloor. The crew for each mission consisted of one pilot and two scientists and lasted 6-8 hours with 4-6 hours of bottom time based on the depth of the site.

Since it was difficult to communicate with the sub once it was on the bottom, careful planning was necessary before each mission. This required collaboration among the scientists to determine experiments that were to be carried out, data collected, and samples brought up for further study. Once the science goals were agreed upon, the crew of the sub and the ALVIN support team met to map the goals against constraints and create the dive plan. This process involved a large collection of paper maps and the expertise of previous crews to sites. On the bottom, it was often hard to navigate due to the lack of light and unique landmarks, and the surface team was often unable to provide help due to their limited ability to track the sub position. It was not uncommon for the sub to lose up to an hour of its bottom time finding locations in the dive plan, and the sub crew would often need to modify the plan mid-dive. When the ship was not on site waiting for the sub to surface, the science crew deployed other instruments and examined data to find new vent fields. All these tasks were documented at the end of the cruise for submission to the funding agencies.

Our goal was to determine usefulness of COVE in supporting the collaboration, mission planning, execution, and data presentation on the ALVIN missions. As with the previous ocean expedition, this evaluation context was short-term and time-sensitive. The primary participants included scientists, research assistants, and ship's engineers, as well as the ALVIN support crew and pilots.

1) *Results*

Given the established routine on the ship for handling missions, integrating COVE into the process was an incremental process with much more impact on later missions. By the end of the cruise, COVE was being used to visually scout each site before the mission. This involved looking at high resolution terrain and previous dive tracks to determine new dive locations. Proposed dive tracks were laid out and compared against the subs power supply, which could then be interactively changed to make trade-offs against the science plan. Different views of the track were available to help point out issues and a set of key views were printed for collaboration with the pilot when tuning the mission plan on the bottom. When the team returned they could compare the actual dive track with the planned one, as well as mash up the track with photos, gradients, data visualizations to present to other scientists (Figure 6).

As well as planned ALVIN missions, COVE played a key role in investigating a possible new vent field.

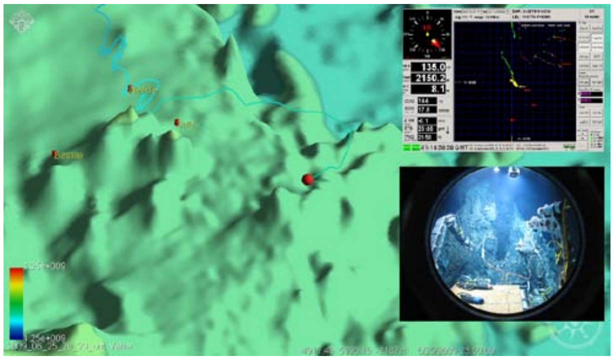

Figure 6: Here we see the track of the ALVIN sub in COVE alongside the original ship-side navigation screen in the upper right and the external view.

Anomalous heat readings were noted while steaming between sites and COVE was used to quickly mash up the temperature data with the terrain in the area. The scientists were able to compare different views, zoom in to possible candidate locations on the sea bottom, and then plan a series of new data collection tracks to test the hypothesis. The ability to move from detection to a research plan so quickly in COVE was praised by all the parties involved. By the end of the cruise, we were unable to determine the new vent field's location, but did amass extensive data for future research.

Lastly, we were able to participate in one of the ALVIN dives to test the usefulness of COVE's interactive 3D visuals in the sub itself. This was enabled in COVE by connecting to the real-time Doppler location feed from the sub and combining it with visualizations of high resolution terrain. This allowed the track of the sub to drive the viewer location in COVE and give a real-time view of underwater terrain for the area relative to sub location; a view the ALVIN crews had never had before. This proved very useful to the pilot and at one point showed that the course from the surface were 180 degrees off from our required path. This mistake could have easily taken up more than ten minutes of precious bottom time. As it was, we were back on track in one.

As in the other two evaluations, COVE was well received by the scientists and engineers, who offered many comments about how the system improved their work processes, enabled them to test more mission options than previously possible, and demonstrate them to fellow scientists. Based on their feedback it was also clear that work remained to be more useful on future cruises. With the support of the head of the ALVIN team and the chief scientists, we plan on submitting a proposal for participation in an upcoming cruise to more tightly integrate COVE into future ALVIN missions.

V. RELATED WORK

Zooming user interfaces were initially presented by Bederson and Hollan in Pad++ as a multi-scale navigation method to allow users to easily zoom in to reveal more detail and zoom out to provide more context [19]. Other authors have since proposed improvements to the original design by: providing cues based on interesting elements in the data to regain user context [20], making it easy for the user to temporarily jump to a home or bookmarked location [21], providing a context layer for the user in the form of a tree hierarchy [22], and providing an overview window for the user to indicate current location when exploring maps [23].

This interface paradigm used with global data is the basis for earth visualizing systems such as Google Earth [4], Microsoft Virtual Earth [5], and World Wind [13]. These systems provide an intuitive, multi-scale interface to geographic data. They facilitate labeling of locations, geo-referencing maps and images, and sharing with other users through XML-based documents. Google Oceans [15], released by Google in early 2009, provides an example of using a geo-browser for displaying oceanographic data and also shows the limitations of current systems: ocean terrain is limited to the low resolution data in the Google servers or to 2D images overlaid on the ocean bottom, there are no scientific data display or analysis tools and there are limited interactive layout capabilities.

Geo-browsers have also been used to display earth observatory data, as demonstrated by the EarthScope project which displays seismometer locations and provides sensor detail by clicking on a geo-located object [24]. A World Wind based project added data visualization through their software plugin interface [14]. Google Earth is also used as a front end to allow quick mash-ups of geo-visualizations [16] to study interactive visualization with a large spatio-temporal dataset. They found this approach successful for exploration and sharing of visualizations, but their system was constrained to a static data set and focused on casual users. Spyglass is an observatory-specific non-geo-browser system that supports viewing of instruments, their connections, and node details via collections of 2D layers where geospatial context is available as an optional map layer [25]. The Starlight system [26] provides an example of collaborative system using rich visualization as a central focus for data exploration, but does not include science asset management capabilities.

Several non-geo-browser based visualization tools are available for visualizing and exploring ocean science data. GeoZUI3D [27] (and its commercial version Fledermaus™) integrates multiple 3D bathymetry sets, geo-located 2D and 3D objects for oceanographic visualization, and has investigated the ability to playback time varying 3D point data [28]. The Interactive Data Viewer (IDV) [1] was built for the atmospheric community and supports sophisticated 3D model visualization, terrain maps, and data animation, but has no inherent support for oceanographic data. IDV is based on the VisAD visualization toolkit [29]. Paraview [2], provides analogous capabilities based on the Visualization Toolkit [30]. These tools use the filter-map-render dataflow pipeline, which has been the model for several similar visualization systems including AVS, IRIS Explorer, and the IBM Data Explorer [31]. These are powerful visualization tools, but are often difficult for scientists to use and may require extensive data manipulation to create visualizations.

Several human-computer interaction projects have provided insight into successful software design methodologies with the science community. Work on Collaboratories [11] and Labscape [10] found integration with the daily work patterns of the research teams crucial for determining software requirements. Schraefel's research on understanding chemist lab books used a mixed approach, including both user-centered interviews and ethnographic observational studies [12]. Akers created CINCH, an interface for 3D neural pathway selection, by capturing automated event logs, carrying out interviews, and involving the neurologists in participatory design [9].

VI. CONCLUSIONS AND FUTURE WORK

The ocean sciences are taking new approaches to better understand the complex inter-related processes in the ocean. We carried out a long term study of multiple science teams to determine the special software needs of these projects. We observed the teams utilizing several specialized tools to support specific tasks, but there was no single tool that provided an effective collaborative interface across the team.

By closely working with these teams to understand their needs, and by prototyping solutions to test possible systems, we developed the Collaborative Ocean Visualization Environment. COVE provides a geo-browser environment along with a set of specific enhancements that we found crucial for an effective collaborative interface. We evaluated COVE in three different settings: in extensive use by the RSN team on land as well as two scientific expeditions at sea. The results of these deployments show that by providing an intuitive common visual environment for the team, tools like COVE can play a pivotal role in these types of large-scale multidisciplinary scientific collaborations.

Future plans for our work include expanding our data presentation capabilities. Presentation of scientific work at conferences and to peers is still primarily done with presentation tools designed for business users and COVE could provide an effective alternative to this page based view of presenting scientific results. We also want to focus on making the collaborative features of COVE available on a broader basis as a public web service. This will enable sharing data and perspectives beyond a science team to reach across science teams throughout the world.

ACKNOWLEDGMENT

The authors wish to thank Microsoft's Technical Computing Initiative, University of Washington School of Oceanography, and Monterey Bay Aquarium Research Institute for data and technical advice. This work was supported in part by grants from Microsoft Corporation and the National Science Foundation.

REFERENCES

[1] D. Murray, J. McWhirter, S. Wier, and S. Emmerson: 'The Integrated Data Viewer—a web-enabled application for scientific analysis and visualization'. Proc. IIPS for Meteorology, Oceanography and Hydrology, 2003, pp. 8-13.

[2] A. Henderson: 'ParaView Guide, A Parallel Visualization Application' (Kitware, 2007)

[3] W. Colin, P. Matthew, M. Stephen, L.W. Louis, W. David, et al.: 'GeoZui3D: Data Fusion for Interpreting Oceanographic Data'. Proc. MTS/IEEE, 2001, pp. 1960–1964.

[4] Google Earth, http://earth.google.com

[5] Virtual Earth, http://www.viawindowslive.com/VirtualEarth.aspx

[6] ORION's Ocean Observatories Initiative Conceptual Network Design: A Revised Infrastructure Plan, http://www.ooi.washington.edu/

[7] Monterey Bay Aquarium Research Institute, http://www.mbari.org

[8] College of Ocean and Fishery Sciences, University of Washington, http://www.cofs.washington.edu/

[9] D. Akers: 'CINCH: A Cooperatively Designed Marking Interface for 3D Pathway Selection'. Proc. ACM Symposium on User Interface Software and Technology, 2006, pp. 33-42.

[10] L. Arnstein, C.Y. Hung, R. Franza, Q.H. Zhou, G. Borriello, et al.: 'Labscape: A Smart Environment for the Cell Biology Laboratory', IEEE Pervasive Computing Magazine, 2002, 1, pp. 13-21.

[11] G.M. Olson, D.E. Atkins, R. Clauer, T.A. Finholt, F. Jahanian, et al.: 'The Upper Atmospheric Research Collaboratory (UARC)', Interactions, 1998, 5, (3), pp. 48-55.

[12] M.C. Schraefel, G.V. Hughes, H.R. Mills, G. Smith, T.R. Payne, et al.: 'Breaking the book: translating the chemistry lab book into a pervasive computing lab environment'. Proc. ACM Conference on Human Factors in Computing Systems, 2004, pp. 25-32.

[13] World Wind, http://worldwind.arc.nasa.gov/manual.html

[14] J.C. Coughlan, and P. Hogan: 'Connecting Virtual Observatories with Visualization and Display Tools, Lessons Learned with NASA Worldwind', AGU Fall Meeting Abstracts, 2006, pp. A811+.

[15] Google Oceans, http://earth.google.com/oceans

[16] J. Wood, J. Dykes, A. Slingsby, and K. Clarke: 'Interactive Visual Exploration of a Large Spatio-temporal Dataset: Reflections on a Geovisualization Mashup', IEEE Transactions on Visualization and Computer Graphics, 2007, 13, pp. 1176-1183.

[17] H. Jenter, and R. Signell: 'NetCDF: A public-domain software solution to data-access problems for numerical modelers', Preprints of the American Society of Civil Engineers Conference on Estuarine and Coastal Modeling, 1992, pp. 72.

[18] Alvin, http://oceanexplorer.noaa.gov/technology/subs/alvin/alvin.html

[19] B.B. Bederson, and J.D. Hollan: 'Pad++: a zoomable graphical interface system'. Proc. Conference Companion on Human Factors in Computing Systems, 1995, pp. 23-24.

[20] S. Jul, and G.W. Furnas: 'Critical zones in desert fog: aids to multiscale navigation'. Proc. ACM Symposium on User Interface Software and Technology, 1998, pp. 97-106.

[21] C. Plaisant, D. Heller, J. Li, B. Shneiderman, R. Mushlin, et al.: 'Visualizing medical records with LifeLines'. Proc. ACM Conference on Human Factors in Computing, 1998, pp. 28-29.

[22] S. Pook, E. Lecolinet, G. Vaysseix, and E. Barillot: 'Context and interaction in zoomable user interfaces'. Proc. Working Conference on Advanced Visual Interfaces, 2000, pp. 227-231.

[23] K. Hornbæk, B.B. Bederson, and C. Plaisant: 'Navigation patterns and usability of zoomable user interfaces with and without an overview', ACM Transactions on Computer Human Interaction, 2002, 9, (4), pp. 362-389.

[24] H.B. Newman, M.H. Ellisman, and J.A. Orcutt: 'Data-intensive e-science frontier research', Communications of the ACM, 2003, 46, (11), pp. 68-77.

[25] C. Buschmann, D. Pfisterer, S. Fischer, S.P. Fekete, and A. Kröller: 'SpyGlass: A Wireless Sensor Network Visualizer', SIGBED Review, 2005, 2, (1), pp. 1-6.

[26] J. Risch, D. Rex, S. Dowson, T. Walters, R. May, et al.: 'The STARLIGHT information visualization system'. Proc. IEEE Symposium on Information Visualization, 1997, pp. 42-50.

[27] C. Ware, M. Plumlee, R. Arsenault, L. Mayer, and S. Smith: 'GeoZui3D: Data Fusion for Interpreting Oceanographic Data'. Proc. MTS/IEEE, 2001, pp. 1960-1964.

[28] R. Arsenault, C. Ware, M. Plumlee, S. Martin, L. Whitcomb, et al.: 'A System for Visualizing Time Varying Oceanographic 3D Data'. Proc. IEEE OCEANS, 2004, pp. 743-747.

[29] B. Hibbard: 'VisAD: connecting people to computations and people to people', SIGGRAPH, 1998, 32, (3), pp. 10-12.

[30] W. Schroeder, K. Martin, and B. Lorensen: 'The Visualization Toolkit' (Kitware, 2003, 3rd edn.)

[31] G. Cameron: 'Modular visualization environments: past, present, and future', SIGGRAPH, 1995, 29, (2), pp. 3-4.