SCHMIDT OCEAN INSTITUTE

2015 Research Planning Workshop
Summary Report and Recommendations

Transforming Seagoing Science with Robotic Platforms, Innovative Software Engineering, and Data Analytics

August 25-26, 2015

Wailea Beach Marriott Resort & Spa, Maui, HI, USA

Steering Committee

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Workshop Synopsis and Summary of Recommendations

Schmidt Ocean Institute (SOI) was founded in 2009 by Eric and Wendy Schmidt as an oceanographic facility operator charged to advance the frontiers of ocean research and exploration with innovative technologies, intelligent observation, data analysis, and open sharing of information. True to its mission, SOI is structured as a technology-focused seagoing research platform operator with no active researchers on staff. Instead, SOI invites scientists and technology developers from around the world to compete for the right to sail on R/V *Falkor* and carry out pioneering projects that advance SOI's strategic interests in five core focus areas.

The purpose of a facility operator is to maximize the success of its users. Schmidt Ocean Institute emphasizes innovation in operational, technical, and informational services that it provides to the visiting researchers in support of their projects. Resulting advancements in marine operations, robotic systems, research platforms, instrument technologies, data collection workflows, and analytical techniques are openly publicized to extend the impact of the SOI research program beyond its available ship time and otherwise limited resources.

On August 24 - 26, 2015, SOI convened 27 experts in ocean sciences, technologies, and marine operations from Australia, Canada, Germany, Japan, Portugal, Singapore, Spain, and the United States to discuss the priorities of operational oceanography enabled with accelerating technological innovations, formulate guidelines that SOI could follow to catalyze breakthrough research, and identify metrics suitable to evaluate the success of its efforts.

The 2015 SOI planning workshop produced an array of recommendations resonating with the SOI strategic interests, some of which reinforce the guidelines formulated during the 2014 SOI planning workshop. The two enduring recommendations included the following:

- Support the development of new sensors, vehicles, research platforms, data analysis tools, and other related oceanographic technologies that can help increase the spatiotemporal resolution and intelligence of ocean characterization. Success of this effort can be measured by the uptake of the resulting technologies, research methodologies, and analytical approaches by the oceanographic community.

- Make SOI research ship, robotic vehicles, and other facilities available to support oceanographic technology research and development. Provide the R&D community with access to the SOI facilities to support research, development, and testing of new marine technologies, operational practices, and analytical methodologies. Such support could be offered on a competitive proposal basis and opportunistically as logistics may permit to projects focusing on oceanographic technology R&D. Success of this measure could be evaluated by the rate of adoption of the resulting technologies by the oceanographic or other user communities.

Additionally, the planning workshop produced the following new recommendations:

- Publish the schedule of repositioning transits for R/V *Falkor* to provide ocean technology R&D teams with advance knowledge of available opportunities for shipboard technology trials at sea. This approach would facilitate more efficient utilization of ship time by allocating transits to research, development, and trials of new technologies. Success of this effort could be measured by the number of days provided to support opportunistic technology R&D during transits, as well as by the impact and adoption rate of the resulting technologies.

- Continuously refine the ship and vehicle sensor suites to improve the collection of underway data for increased situational awareness during research cruises. This includes improving the ship's communication capabilities, with both robotic assets, such as underwater vehicles, and with remote researchers via satellite link. The efficacy of this effort can be measured by increase in quality and availability of data and observations to shipboard and remote researchers in near-real-time.

- Support the development of integrated data annotation software for the ship and vehicle sensors. Data annotation software should support standard data processing workflows for key datasets, local and remote data queries, data analysis for autonomous and intelligent decision support, data visualization, as well as education, engagement, and outreach applications. It should employ open architecture to encourage its continuous improvement. Gains in data accessibility (including remote, e.g. via web-based interfaces, etc.) could be used to measure the success of this effort. Other related metrics could include the number of external users of data, data publications and/or citations, emergence of new data-driven applications, and community acceptance of the developed data annotation tools.

- Refine the proposal solicitation process to encourage technology research and development that offer transformative solutions to important scientific questions. Such successful projects would prominently validate the resulting innovations and will facilitate the new technology and methodology adoption by other scientists and operators. Calls for proposals should emphasize collaborations between technology developers and scientists. The efficacy of this measure could be evaluated by the increase in the number and quality of research applications proposing the use or development of advanced technologies to address important questions in ocean sciences.

- Support an oceanographic technology R&D facility to complement SOI's ocean-going research program. This facility would focus on developing advanced technologies to support research projects on R/V *Falkor*, including deep sea and multi-agent robotic systems, automatic vehicle recovery capabilities, intelligent control software, inter-vehicle communications, in-situ data analysis algorithms, etc. The success of this effort could be evaluated by the emergence and impact of innovative robotic and analytical tools developed at this facility, and rate of their adoption by the research community.

- Encourage standardization of instrument interfaces, survey workflows, data formats, communication protocols, and information processing tools. By adhering to standardized practices, interfaces, and formats, and by coordinating related technology R&D efforts with external experts, SOI could promote broader technology and data interoperability, and would become well positioned to benefit from standards-compliant technologies developed by others. The success of this effort could be measured by how efficiently SOI is able to incorporate the existing innovative technologies into its facility operations and how broadly the SOI-generated data and innovations become used throughout the oceanographic community.

These workshop recommendations will help inform SOI's preparation to the R/V *Falkor* 2016 field season, proposal reviews in 2017, and call for proposals in collaborative oceanographic research onboard R/V *Falkor* in 2018.

Workshop Objectives and Structure

In coordination with the Board of Directors, and with guidance of the Steering Committee, on August 24-26, 2015, Schmidt Ocean Institute convened a group of 27 top international experts in ocean sciences, technologies, and marine operations from Australia, Canada, Germany, Japan, Portugal, Singapore, Spain, and the United States, to participate in its research planning workshop. Workshop participants also included SOI colleagues from Schmidt Philanthropies, Schmidt Marine Technology Partners, Wendy Schmidt Ocean Health X Prize, as well as senior program staff from SOI and R/V *Falkor*.

Schmidt Ocean Institute’s key objective for this workshop was to ensure that its program development guidelines, priority research and technology development areas, and performance metrics continue to be well informed with the input from the global community of ocean researchers and technology developers. The workshop program was structured with close consideration to the expertise and research interests of the participating researchers. A pre-workshop participant survey was conducted to identify high priority questions and discussion topics that could contribute the most to the goals of the workshop. The resulting workshop discussions explored emerging trends and opportunities for advancing innovation in ocean sciences, related disciplines, and technologies through intelligent application, research, and development of innovative software engineering and computational algorithms, data acquisition, analysis, and interpretation methodologies, as well as robotic platforms.

The two day workshop program includes presentations and breakout sessions structured into the following three overarching half day long discussions:

1. Perceptive Systems: robotics, sensors, and hardware platforms for ocean sciences
2. Intelligent Observing: advanced autonomy, artificial intelligence, and multi-agent systems
3. Knowledge Interpretation: data platforms, interactive science and communications

Discussions on each of these three topics were introduced by 3 to 4 plenary presentations from SOI collaborators and researchers. The subsequent breakout sessions were charged with the identification of emerging research and development opportunities, program development guidelines, and success metrics in the areas of research and development relevant to the topics of the respective breakout sessions. Upon the completion of the breakout sessions, assigned Reporters presented their outcomes to all of the workshop attendees. The following sections of this report include the summaries of plenary presentations and breakout discussions that took place during the workshop.

Perceptive Systems - robotics, sensors, and hardware platforms for ocean science

This session focused on innovation in scientific systems and instruments developed to observe and characterize the ocean, such as marine robotics, sensors, and hardware platforms.

Presentations

1. Schmidt Ocean Institute Undersea Vehicle Development Program, 4500m ROV, Presentation by David Wotherspoon, HROV program manager, Schmidt Ocean Institute

   Schmidt Ocean Institute is developing a series of advanced undersea robotic research vehicles for use on R/V *Falkor*, including three remotely controlled and one autonomous robotic vehicle. These vehicles, developed sequentially, will support scientific research throughout a gradually increasing range of ocean depths, including operations at hadal depths, and will provide scientists with access to the deepest parts of the ocean.

   A 4500m depth rated remotely operated vehicle (ROV) is being developed first. The goal of the 4500m ROV is to demonstrate the ability of SOI to develop advanced technical systems internally and deliver on schedule. To maximize reliability and minimize unintended technical risks, this vehicle will employ proven technologies and operational modes, with preference for commercial off-the-shelf (COTS) subsystems and components. The project is well constrained by the requirement for the vehicle to operate from RV *Falkor* and delivery scheduled 2016.

This vehicle will support acquisition of high quality underwater video, scientific data and sample collection, object manipulation, deployment and recovery of instruments, seafloor surveying, and photomosaicing. Sea Acceptance Testing of the vehicle is planned for August 2016 on board R/V *Falkor* in Guam, Science verification cruise and the first research cruise will take place in November and December of 2016 respectively.

The vehicle will be initially delivered with a limited set of core instrument systems that has been defined in coordination with the international deep sea research community. Additional instruments and systems will be developed over time as required by the supported projects, The vehicle will not have a separately deployable tether management system and will operate in a single-body catenary supported “live boat” configuration. The vehicle’s core system sensors will include a CTD sensor, pressure / depth Sensor, and oxygen sensor. The core imaging suite will include a 4K situational video camera, HD science zoom camera on a pan/tilt unit, additional HD utility, video recording system, framegrabber, high resolution still camera, and full spectrum LED lighting. The ROV will have at least 100 kg payload capacity, and an optimized Niskin Design water sampler will be delivered as part of the core sampling suite. The core survey systems will include Forward Looking Imaging and Multibeam Mapping Sonar and a Singlebeam 360° scanning sonar. The vehicle will provide a wide array of communications and power interfaces and will be equipped with the state of the art integrated navigation system. Following exhaustive optimization, a 19.1 mm diameter cable was selected for the vehicle umbilical, and the preliminary design of the winch has also been determined.

Development for the 6000m depth rated AUV, the “companion” for the 4500m ROV is commencing by the end of the year 2015. Following the successful delivery of the 4500m depth-rated vehicle, development will begin on the subsequently planned 7500m HROV, and finally, the ultimate goal of SOI’s Vehicle Program, an 11000m – or full ocean depth rated HROV.

2. Sensing with Noise, Presentation by Prof. Mandar Chitre, head, Acoustic Research Laboratory, National University of Singapore

The oceans are filled with various sounds, for example, waves crashing, ships travelling into and out of ports, earthquakes, precipitation at the surface, biological organisms, all of which have specific frequencies associated with them. These sounds are usually a hindrance to data collection with acoustic sensing. However, these sounds carry with them valuable information about the ocean environment and can potentially be used to monitor seabed properties, using the reflective properties of the soundwaves. Prof. Chitre explored how ambient noise in the ocean can be used constructively for various sensing applications, using snapping shrimp as one example of the analysis that is possible. Snapping shrimp live in warm coastal waters and are known to emit one of the loudest organism-produced sounds on the planet. Prof. Chitre's presentation discussed a device created to measure the reflection of the snapping shrimp sound and convert that sound into an image, creating a visualization of the acoustics. Snapping shrimp are only one application of this technology; more research could be done on additional sound sources and it was hypothesized that perhaps some marine mammals use their echolocation functionality to create similar images in their brains.

3. The Evolution and Capabilities of the Saildrone: a Wind Powered, Autonomous Surface Vehicle, Presentation by Richard Jenkins, founder and CEO, Saildrone Inc.

In just three years, the Saildrone, an unmanned wind propelled vehicle, has evolved from a concept into a sophisticated autonomous vehicle carrying an array of atmospheric and oceanographic sensors. The first Saildrone vehicle was fully assembled as a working prototype in December of 2012. Following the prototype construction, the vehicle completed the first unmanned circumnavigation of the Farallon Islands in May 2013, and in October 2013, set sail for a California to Hawaii voyage. The Saildrone successfully reached Hawaii in 34 days, averaging 3 knots. Since then, the Saildrone vehicle has been improved to add sensor payloads carrying meteorological and oceanographic sensors, such as an anemometer, pyrometer, magnetometer, thermosalinograph, and fluorometer.

A small fleet of vehicles has recently undergone arduous testing to compare oceanographic data collection between the Saildrone vehicle to the data collected by the sensors onboard the *Oscar Dyson* in some of the harshest conditions on the planet in the Bering Sea, where they were deployed for 97 days. The Saildrone vehicles are 19 ft. in length, have an average speed of 3 – 5 knots, and can be deployed for 6 – 8 months. To date the fleet has sailed 10,000 NM in the open ocean. Future developments include multiple vehicle operations and building other types of environmentally powered vehicles.

4. ARTEMIS - How to Explore Europa, Presentation by Dr. Kristof Richmond, design team & software lead, Stone Aerospace, ARTEMIS Project

The ARTEMIS (Autonomous rover-airborne Radar Transects of the Environment beneath the McMurdo Ice Shelf) autonomous underwater vehicle is being developed by Stone Aerospace under the SIMPLE project funded by NASA's ASTEP program, aiming to develop technologies required for exploration of water bodies on extraterrestrial icy worlds. In October 2015, ARTEMIS will explore under the Ross Ice Shelf in Antarctica. The mission objectives are to calibrate the ice penetrating radar, test novel autonomously operated contact sensors for microbial life detection in ice, explore and map under the Ross Ice Shelf, build detailed bathymetric maps and current profiles, and to test long-range sub-ice autonomous vehicle systems for a future Europa lander.

The vehicle will be deployed through a 4 ft. diameter 30 ft. long borehole in the sea ice next to the shelf, transit under the shelf performing up - and down - look bathymetry, biogeochemical sensing, and water sampling before navigating back to a dock under the deployment hole. In addition, ARTEMIS will extend a science arm to contact and scan the interior of the ice ceiling above, looking for biological signatures in this remote, inaccessible environment. Supervised autonomy will allow the science team to observe the mission in real-time and to interact with the vehicle if something unusual is discovered. To date the ARTEMIS vehicle has been tested in a saltwater tank and in a lake prior to its mission.

Breakout Discussions

Following the plenary presentations, workshop participants split into three discussion groups, each focusing on one of the high priority questions or topics identified with the pre-workshop survey. Following the breakout sessions, assigned Reporters from every group reported the findings and recommendations of each discussion to all workshop attendees, highlighting the emerging research and development (R&D) opportunities, suggested program development guidelines, and proposed metrics of success. The summaries of three discussions on Perceptive Systems (sensor technologies, robotics platforms, communications and IT) are provided below:

1. What new horizons are emerging in ocean sensor technologies and how can they advance seagoing marine science?
    a. Emerging R&D Opportunities:
        i. The need to characterize anthropogenic impacts, biological baselines, population demography, connectivity, and distribution of high energy ocean systems and lack of research at large, hard to reach (sub-seafloor biomes) locations are driving the science.
        ii. Technologies that are still evolving include chemical sensors, optical imaging, and tools to measure sound frequency.
        iii. Gaps in current technology include communications, power systems and the cost of deployment, standardization (standardize system integration), simulation and quality assessment and quality control (QA/QC).
    b. Program Development Guidelines:
        i. Long-term operational strategies need to be identified by the “space” Schmidt Ocean Institute wants to excel in: discovery, characterization and

sustained modes are all options and the Grand Challenge the Institute is working towards also needs to be defined.

    ii. An activity that requires focused effort, yet would be important to the community, is the issue of standardization of systems.
    iii. An activity that would make a large impact is using models that drive the sensor suite development by considering protocols, communications, cost and then deployment.

  c. Metrics of Success:
    i. Measure technology and/or data uptake by the community

2. How are autonomous marine robotics transforming operational shipboard research?
  a. Emerging R&D Opportunities:
    i. Robotics can reach areas not reachable by ships, enable adaptive sampling, and measure hard - to - monitor characteristics such as internal waves, fronts, and air-sea fluxes.
    ii. The introduction of autonomous systems on ships may result in a change in operational focus, including using ships to support engineers, as an operations hub, and/or in increasing data management and communication roles. Additionally, some long range deployments of marine robotics may not require ships at all. The future of ships may include a more modular design with plug and play design, standardized interfaces and anti-roll systems.
  b. Program Development Guidelines:
    i. Access to ships should be provided for technology research and development, experimentation, and testing (including opportunistic technology testing).
    ii. Additional research and development programs could be formulated, which are not tied to specific cruises.
    iii. SOI's Request for Proposals should be revised to encourage more science-technology R&D collaborations aboard R/V *Falkor.*
  c. Metrics of Success:
    i. Technology created through support of SOI and the respective technology's uptake by the community for widespread use.
    ii. The amount and variety of audiences reached through publications resulting from supported research.

3. How can seagoing research benefit from the rapid progress in communications and information technologies?
  a. Emerging R&D Opportunities
    i. Be able to show data that is being collected in real - time via an onboard web - based tracking system. Such a system could give scientists the capability to verify the quality of the data in real - time.

    ii. Specific websites provided for citizen scientists could be used to engage large participant groups.
    iii. Give remote participants the ability to control still cameras on the ROV from shore in real - time.
    iv. Improve coordination of multiple vehicles in real-time.
    v. Improve non-satellite based high bandwidth communications.
b. Program Development Guidelines
    i. The issue of instrument and vehicle systems standardization can be solved by engaging with other teams.
    ii. Simplifying streaming systems and QA/QC of streamed data requires a focused effort to improve, but could make a large impact in the community.
    iii. The cost of communications - satellite and undersea - remain an issue.
c. Metrics of Success
    i. An improved reach to the oceanographic community through technology innovation
    ii. Amount of users accessing data collected and provided by Schmidt Ocean Institute
    iii. Uptake of the supported and development technology by others
    iv. "data per gallon" - (data collected and used per gallon of R/V fuel

Intelligent Observing - Advanced Autonomy, Artificial Intelligence, and Multi-Agent Systems

This session focused on how advanced oceanographic platforms and technologies, such as autonomous vehicles, artificial intelligence, and multi-agent systems, can intelligently work together to help accelerate the pace of ocean sciences.

Presentations

1. Making Sense of Seafloor Images Collected by Autonomous Photo-mapping Robots, Presentation by Dr. Ariell Friedman, postdoctoral research engineer, Australian Centre for Field Robotics, University of Sydney

   In March-April of 2015 R/V Falkor hosted the most diverse array of robotic research vehicles in its whole career as a research vessel. In contrast with most oceanographic sea-going projects that usually aim to answer some specific scientific questions, the *Coordinated Robotics* research cruise focused on advancing the collaborative robotic survey technologies and methodologies for efficiently coordinating operations of multiple research vehicles and robotic platforms. Wave glider, Slocum glider, photo float, SOI's 300m ROV, Iver and Sirius AUVs were deployed during this cruise to develop and test new techniques for autonomous multi-vehicle ocean surveying.

Photo-mapping AUVs are capable of collecting copious amounts of image data, but the surveys typically involve laborious, manual processing to transform seafloor images into quantitative coverage estimates that are useful for scientific purposes. As a result of this bottleneck, usually only a tiny subset of pixels in less than 1 - 2% of the collected images end up being selected for detailed analysis. Furthermore, ensuring the data is analyzed in a consistent manner across surveys and organizations, as well as managing these huge image datasets, poses significant additional challenges.

Dr. Friedman introduced Squidle, a Web-based image annotation system. Through an easy to use web portal, this image annotation system allows general public to access, review, and annotate georeferenced visual data, e.g. collected during scientific seafloor surveys with imaging AUVs. Dr. Friedman is interested in further developing the Squidle system to expand it to support additional image data platforms, types, and sources, and also incorporate the video annotation functionality.

Such interactive, near real-time access to scientific data through an intuitive web-based interface dramatically increases accessibility of scientific data throughout the scientific community and for the general public as well. Ease of access promotes more active data annotation by the volunteering external users. The resulting image annotations can then be used to train machine learning algorithms to enable automatic image pattern classification for more comprehensive data analysis, including that beyond the subset of image data that may have already been tagged by human experts.

Dr. Friedman presented the results of his research where supervised machine learning was used to assist in analyzing benthic image data. He also demonstrated how online tools can be effectively used for managing, analyzing and querying large visual datasets. The presented underwater optical imaging and habitat characterization techniques can in principle be applied at different spatial scales, and thereby can help resolve different habitat types. The recent applications of the visual data annotation system included characterizing the presence of sea urchins during the day and at night based on AUV photosurvey data, inspecting healthy vs. dead corals, imaging artificial hydrothermal vents, and mapping the submerged city of Pavlopetri in Greece and 1st Century Shipwrecks in Antikithera, Greece.

2. Multi-vehicle Systems for Ocean Observation: Are we Missing Something?
Presentation by Dr. Joao Sousa, head, Underwater Systems and Technologies Lab (LSTS), University of Porto

Dr. Sousa presented a unique vision for the role of networked vehicle systems in future ocean observation systems, contrasted to the current practices in deployments of unmanned ocean vehicles. In LSTS's vision, networked vehicle systems are composed of physical and computational entities with coupled physical and computational dynamics in a dynamic expandable structure. This approach delivers new system level properties, particularly related to the multi-agent robotic system observability and reliability, which cannot be found in the constituent physical and computational entities. The multi-agent robotic system typically includes a portable/scalable collection of interacting autonomous vehicles, operators, and satellites. In this vision, the key system properties are a function of the system variables – vehicles, networks, and interactions.

The LSTS develops low cost vehicles supporting multi-vehicle inter-operability frameworks. For reliable operation of low-cost ocean vehicles, common software/hardware platforms and inter-operability frameworks are important. The LSTS control architecture for networked vehicle systems has off-board and on-board components (LSTS Neptus - IMC - Dune software tool chain) for mixed-initiative control of unmanned ocean and air vehicles operating in communications-challenged environments with support for Disruptive Tolerant Networking protocols. LSTS recently released all of its related software code to the public as open source.

During planning and execution, the user can specify tasks to be performed by a set of vehicles. The Neptus is the decision management node that feeds tasks to the planning engine. In return, the planning engine feeds back the plans and locations to the Neptus software component and to the vehicles. Neptus is a distributed command, control, communications, and intelligence framework for operations with networked vehicles, systems, and human operators. IMC is a communications protocol that defines a common control message set understood by all types of LSTS nodes (vehicles, consoles or sensors) in networked environments. IMC enables standard data exchange support for heterogeneous software components. Dune is the vehicle on-board software. Dune has also been integrated with the deliberative onboard planning system TREX.

LSTS also investigates the use of its fleet of Aerial vehicles to develop innovative and alternative way for coordinating technical systems to survey the ocean. The fleet has logged more than 1400 autonomous flights for applications such as maritime surveillance, aerial mapping/photography, search and rescue, inspection of power lines, and fisheries and other biological studies. The LSTS has also completed work with multi-vehicle systems, including multi-vehicle command and control.

LSTS has been organizing, in cooperation with the Portuguese Navy, the international Rapid Environmental Picture annual exercise to test and evaluate new systems and technologies, to develop new concepts of operation, and to promote inter - operability and long term cooperation. In 2014, simultaneous operations took place in the Pacific, Atlantic and Adriatic Sea, testing the inter-operability of systems and communication networks, with a variety of international partners and topic focus areas. The July 2015 exercise took place in the Atlantic Ocean with partners from Portugal and the United States focusing on a various interdisciplinary research areas, such as mine warfare, mapping of thermal vents, UAV/AUV interaction, and whale tracking.

3. Advanced AUV Capabilities for Inspection and Intervention,
   Presentation by Dr. Marc Carreras, associate professor, University of Girona

   Dr. Carreras summarized the key R&D activities of his laboratory at the University of Girona in advanced AUV R&D for applications in inspection, mapping, classification, and intervention. Girona Underwater Vision and Robotics lab developed hovering AUVs to perform R&D in autonomous robotic manipulations, such as recovering a target, turning a valve, or plugging a connector. These multi-purpose hovering AUVs are designed to be neutrally buoyant, stable in Roll and Pitch, have low weight, small in size, and be easy to operate. Their hovering capabilities make them ideal for tasks requiring precise positioning and attitude control for inspection, mapping, and intervention applications. Real-time sensor data processing is used for mapping, target identification, and motion planning, enabling close autonomous inspections of underwater structures. Such AUVs can be used for chain inspection, e.g. by conducting horizontal chain search and pattern matching for link detection, acoustic mosaicking of the seabed and chain lying on it. These AUVs also support 3D mapping and inspection of underwater seamounts. In the future, the goal for these new AUV capabilities is to become more broadly available for scientific and industrial applications, including oceanographic applications.

Breakout Sessions

Participants were assigned to participate in one of three breakout sessions related to the topic of Intelligent Observing. They reported back on their discussion, including emerging research and development (R&D) opportunities, program development guidelines, and metrics of success.

1. How can research ships support data collection at sea in more intelligent ways?
   a. Emerging R&D Opportunities
      i. Before a cruise sails, there needs to be thorough pre - cruise information on the ship and science party capabilities, as well as knowledge shared of any pre - existing data and/or metadata for the area the cruise is taking place in beforehand. Having a cruise backup plan is also important.
      ii. There is also an opportunity to collect data in between scheduled data collection deployments. Data that could be collected in between deployments are continuous multibeam, deploying other standard instrumentation, and ADCP data. Plug and play AUV operations could also be used for on - station operations between deployments.
      iii. Other effective techniques for multi - platform operations include piggybacking with other programs that would use AUVs when not in primary operations.

        iv. Data bottlenecks that slow down the smooth collection of data are QA/QC'ing of data, processing data in real - time, lack of shore support, and lack of more automated/turnkey data visualization and analysis tools.
    b. Program Development Guidelines
        i. Achievable outcomes for SOI include publishing their planned transits so that users know where/when there is a potential for extra data collection, enlisting more collaborators, improving the sensor suite aboard R/V *Falkor*, improving pre-cruise communications, and increasing the awareness of the various data collected while underway.
    c. Metrics of Success
        i. How SOI data is used and the quantity and quality of the data collection (improved).
        ii. Increased uptake of SOI data logging software systems, if implemented.

2. What emerging oceanographic applications can benefit from the advancement in robotic autonomous vehicles?
    a. Emerging R&D Opportunities
        i. Benefits from the advancement in robotic autonomous vehicles include use of robots in sensitive/unreachable areas, the capability for long term and long range persistent surveillance and monitoring, the ability to complement other operations, real - time data (shipboard) analysis and visualization capabilities, and the general reduction of cost of marine data collection.
    b. Program Guidelines
        i. Attainable goals are to provide existing vehicles for technology research and development and support research and development in autonomous vehicle technologies.
        ii. More focused effort would be required by SOI to develop vehicle designs that others can learn from.
        iii. SOI would make a large impact if it developed standardized workflows and tools and aimed to support research and development not supported by other funding mechanisms.
    c. Metrics of Success
        i. SOI could measure its success in the amount of data resulting per dollar invested in research, carbon dioxide emission reductions, or savings in ship time
        ii. SOI could also count the sustainability of data for a large number of users and established oceanographic models as a success.

3. What new technology R&D opportunities emerge with the introduction of multi-agent autonomous and remotely controlled robots?
    a. Emerging R&D Technologies

i. Applications for multi-agent autonomous robots include exploration at areas of rapid change, spatially distributed phenomena (fronts, earthquakes), sensitive phenomena, and/or where multidisciplinary targets or model forecast coordination is needed
ii. Additional applications include conducting synoptic surveys, multi-statis sensing, and phased arrays
iii. Technical areas of emerging research and development opportunities include inter - vehicle communication, inter - agent communication and energy saving advances
iv. Concerns when conducting operations including public relations, developing regular operations, and valuing practical communications
v. The introduction of multi - agent autonomous and remotely controlled robots could allow for researchers to be moved to shore, with less personnel on the ship, using the ship for more R&D opportunities, such as testing and utilizing the ship mainly for complex science applications.
vi. If using multi - agent robots, launch and recovery need to be automatic, a data escape capsule should be used so that in the event the vehicle is damaged or unreturnable to the surface, the data collected can survive. Tools for operators (such as tools that increase situational awareness on the bridge) are also important to have.

b. Program Development Guidelines
   i. It will require focused effort to development software for multi - agent communications, inter - vehicle communications and automated recovery.
   ii. SOI could make an impact in the community if it was able to provide a multi - agent facility with operations and automated recovery systems.
c. Metrics of Success
   i. SOI could measure its success by measuring the multi - agent operations: number of agents, vehicles lost, spin - off technologies, data collected, data denial impact and uptake of data by others.

Knowledge Interpretation - Data Platforms, Interactive Science, and Communications

This session focused on innovative methods for interpreting data into knowledge through data visualization, on-line platforms, interactive science, and communications.

Presentations

1. Data Stewardship for Mobile Platforms at Ocean Networks Canada,

Presentation by Reyna Jenkyns, data stewardship and operations support lead, Ocean Networks Canada

Ocean Networks Canada (ONC) is responsible for the maintenance and operation of the digital and marine infrastructure across the VENUS, NEPTUNE, and Cambridge Bay facilities off the coast of British Columbia, Canada. ONC collaborated with SOI on board R/V *Falkor* in 2013, collecting data via shipboard systems, ROPOS ROV, and profiling platforms. While shipboard and autonomous data have been collected at ONC since VENUS launched 2006, increased emphasis has recently been applied to developing digital infrastructure and data stewardship practices to support the wealth of data acquired from mobile platforms, such as those employed during the *Falkor* expedition.

SeaScribe is annotation software for ROV dive data logging which records maintenance, survey, and sampling activities. It logs the Cruises (Cruise Name, Ship Name, Duration of Cruise and Description of Cruise activities), followed by the ROV Dives (Description, Location, Duration, Dive Chief, and given Dive Reference ID). Following this log of information, observations can be annotated, including comments, timestamp, logger and tags can be given. These tags and annotation allow for increased searchability and usability of dive video and support derivative applications such as comparison or training of automated data classifiers and generation of geodatabase layers.

ONC has expanded its suite of web-based tools and back-end infrastructure for Oceans 2.0 to enable more generalized data acquisition and distribution. A ship-based server solution can support live acquisition for supported instruments, data streams to shore shown live on the cruise website and recorded for future viewing in Oceans 2.0, and seamless archiving into ONC's central repository. The ability for remote scientist participation to direct ROV dives and classroom participation has also been enabled. Data stewards have developed workflows and best practices for handling data sets from mobile and third party platforms. For the 2013 cruise aboard R/V *Falkor*, data from *Falkor*'s shipboard systems (multibeam sonars, ADCP, and flow-through sensors), ROPOS ROV data (video, digital stills, navigation, CTD/O2, and physical samples), and data from profiling platforms (CTD, MVP) were uploaded into the system and made available to the general public.

Despite these advances, additional work remains related to improving data management processes, particularly for video and physical samples. This is a common issue throughout the oceanographic community, and not specific to ONC. Video management and distribution options are subject to rapidly changing technology and high volume challenges. Physical samples require an alternative solution that considers the entire lifecycle of a sample, and incorporates interoperability and community standards for data discovery and exchange. As a member of the ICSU World Data System and contributor to working groups such as the EarthCube iSamples Research Coordination Network for digital curation of physical samples, ONC is striving to maintain high standards for data stewardship and repositories. Ongoing related efforts at ONC include establishing better guidelines, vocabularies, syntax and training available for data logging; streamlining transcodes for video and creating a repeatable, recordable process; increasing use of the ship-to-shore data acquisition system and better documenting data ingestion processes and tools; and improving systems for digital still capture, archiving, and distribution.

2. Latest Developments in Oceanographic Applications of GIS, Including Near-real-time Interactive Map Exemplars and Scientific Empowerment through Storytelling, Presentation by Dr. Dawn Wright, chief scientist, Environmental Systems Research Institute

   Dr. Wright presented an overview of how intuitive data analytics and visualization tools in geographic information systems (GIS), such as interactive maps and storyboards, can inform both shipboard and shore based science. In the brave new world of science communication, scientists can be powerful storytellers if they can effectively use GIS dashboards to visualize their data and stories. People, in general may get the idea from maps, perhaps occasionally from graphs, but are all hardwired to understand stories. GIS tools can be used to provide helpful and unique view of data, including, e.g. specific georeferenced data extractions or aggregated polygons or cells summarizing what is nearby or within a field of study, etc. Every single scientific success is perfect fodder for a narrative structure. In that vein, an introduction to "cool maps" and story boards as fast and simple platforms for telling compelling stories and communicating science with shipboard data, including photos, videos, sounds, and sensor dashboards was given.

3. Virtual Fieldwork on the Seafloor: How to get there, What to take home? Presentation by Dr. Tom Kwasnitschka, researcher, GEOMAR Helmholtz Centre for Ocean Research

   Immersive visualization can be used to extend long standing geological field exploration methods applicable on the dry land to the seafloor, and with aims of matching the expectations of terrestrial field geologists. In 2016, the *Virtual Vents* cruise onboard R/V *Falkor*, will photogrammetrically survey an entire hydrothermal vent complex in order to provide a quantitative visualization of the site.

   A traditional workflow may look like this: scientific idea – expedition – post-processing – interpretation – and finally dissemination. Implementing a more virtual approach, as the 2016 *Virtual Vents* cruise plans to do, poses challenges in determining a survey strategy, real-time data processing, situational awareness through telepresence, inclusion of onshore colleagues through remote interaction, and the onshore exploration of the final data product using immersive visualization technology. As development of the Artificial Research Environment for Networked Analysis continues at GEOMAR, the program's goals are to provide the users with an immersive collaborative 3D simulated high precision and resolution geological (and oceanographic) virtual survey and research environment, while remaining user-friendly, enabling data annodation, collecting metadata, improving interactivity, and catalyzing scientific dialogue.

4. Collaborative Scientific Visualization Using Commodity Virtual Reality Systems, Presentation by Dr. Oliver Kreylos, associate researcher, W.M. Keck Center for Active Visualization in the Earth Sciences, Department of Earth and Planetary Sciences, University of California Davis

   The difficulty of analyzing large and complex three- or four-dimensional datasets is a roadblock for scientific progress in many disciplines, specifically the Earth and physical sciences, including oceanography.

   Virtual reality (VR) is a human-computer interface technology that can present three-dimensional (3D) pseudo-holographic virtual objects, and support natural 3D interaction with those objects in a collaborative multi-user 3D virtual environment. For data analysis, this means 3D datasets can be presented in their natural state, without the distortions incurred from projecting them onto two - dimensional display screens.

   Dr. Kreylos showed how software developed at the University of California Davis W.M. Keck Center for Active Visualization in the Earth Sciences (KeckCAVES, http://www.keckcaves.org) supports interactive data analysis across a wide range of VR display systems, and how a VR tele-collaboration system integrated into that software allows multiple researchers from different locations to jointly analyze their 3D datasets as if they were in the same physical space.

Breakout Sessions

Participants were assigned to participate in one of three breakout sessions related to the topic of Knowledge Interpretation. They reported back on their discussion, including emerging research and development (R&D) opportunities, program development guidelines, and metrics of success.

1. What analytical, software, and data tools can help make seagoing research with robotic platforms more interactive and effective?
   a. Emerging R&D Opportunities
      i. An important aspect of robotic collection of data is trusting the data. QA/QC for the data need to be defined and software should be able to do this in real - time. The same is true of samples being collected - generalized workflows, as well as the software, should be developed to implement the workflows and product suites
      ii. Standard processing workflows for key datasets should be developed.
      iii. Access tools for querying and viewing data by all users should be developed.
      iv. Standardization is key for data processing, but tools need to remain flexible as well.
   b. Program Development Guidelines

    i. Standardization and frameworks for QA/QC are achievable actions to undertake.
    ii. It will require a focused effort to develop systems with open architecture, filtering logs and/or query tools.
    iii. Taskings that would make a large impact within the community are improving user interfaces, communications, data visualizations tools, methodologies for video archiving, and improving interactive remote science.
    iv. SOI has the opportunity to make an impact because it can carry a more agile mindset than some other organizations and the incentive structure for achieving these goals is correct.
  c. Metrics of Success
    i. SOI will be successful if the community has accepted and uses the developed tools and if the resulting data is accessible.
    ii. SOI could measure the number of external users of the data, and how many data and publications and citations result.

2. How can we effectively communicate data-rich knowledge between ship and shore (and other ships) and enhance shipboard science with interactive remote input and participation?
  a. Emerging R&D Opportunities
    i. Communication of data-rich knowledge needs to include live storytelling and real - time engagement (maps, data, video, sound streaming, virtual reality engagement in real-time, and post cruise exhibits).
    ii. To tell a good story, you must give science a personality, rather than just a dot on a map.
    iii. The tools for successful citizen science are engagement + data analysis via crowdsourcing.
    iv. It is important to have face to face engagement with communities that don't have access to cyber technologies
  b. Program Development Guidelines
    i. It is easy to start to focus on tools for science, with outreach as a by - product, but in order to make science data appealing to the public, it needs to be visualized.
    ii. Key challenges to good outreach efforts are improving bandwidth constraints and real - time post - production of video and media products.
    iii. SOI may be poised to make an impact by providing science and student training, cluster computing for data processing, and make science 'cool'.
  c. Metrics of Success
    i. Like most organizations, SOI should be keeping track of its social analytics, such as visits to website, likes, tweets, retweets, etc.

   ii. Pre - and post - outreach experience evaluations and long term tracking of students to see if opinions or careers are influenced could be useful
   iii. Artist program exhibitions could also take place on board R/V *Falkor*.

3. How can innovative computational algorithms onboard research vessels inform seagoing research and facilitate real-time information sharing?
   a. Emerging R&D opportunities
      i. Modeling and prediction to guide observations and mapping of environmental variables are common uses for computation at sea. Other uses of computation at sea are use of VR, creating rich acoustic datasets, and multi-vehicle inputs while onboard to feed models. Spatial analytical processing can aid in understanding of data collected only a few hours earlier and fast on board sample processing can remove concerns about sample preservation.
      ii. Additionally, bandwidth constraints can be ameliorated with real-time processing.
      iii. Community standards for video storage and analysis should be developed as a key advance related to data analysis, storage, and management. Another consideration is can machine learning be used for pattern recognition?
   b. Program Development Guidelines
      i. Focused effort will be required to ameliorate bandwidth constraints for rapid data and sample analysis processing.
      ii. SOI could make an impact by providing increased bandwidth and attempt to shift the culture to rely more on real - time data analysis than post - cruise data analysis.
      iii. Standardization of data interfaces/ processing and analysis is still a key issue.
   c. Metrics of Success
      i. Success of developing new shipboard intelligent research practices can be measured by their adoption rate throughout the community.

Discussion

The field of ocean sciences is on the verge of a large-scale transition - from ship-based to robot-based observation and research. Coordinated, simultaneous, spatially distributed data collection using multi - agent autonomous systems far surpasses conventional observations from methods that are inherently single-point-in-space-and-time, such as research ships (in coverage, persistence, endurance, and cost efficiency). Robots can collect data in seas that are too rough, too shallow, or otherwise unsafe for ships, in habitats that are too sensitive to ship noise and emissions, and, in the case of autonomously powered vehicles, for periods of time that are not constrained by resource availability onboard a research vessel.

As more ocean observing and data collection is taken over by robots, the role of research ships will be shifting from direct sample collection to operational support of these scientific vehicles, platforms, and instruments. Research ships will more intently support oceanographic technology research and development, engineering testing, prototyping, sensor calibration, high-throughput data QA/QC, and data integration, interpretation, and visualization for interactive use.

Each of these emerging uses for research vessels offer interesting programmatic opportunities for SOI in the fields of ocean science and marine technology development. For example, due to the structural inertia of typical, large (e.g. government-supported) research vessel operations, these vessels are not likely to have the ability to undertake the risk of developing and operating a non - standard, robot - centric seagoing R&D platform. Such operators often do not have the liberty or agility to step outside of established funding and operational models.

However, a more agile, philanthropic, operating organization, such as SOI, is well positioned to innovate in methods and technologies for comprehensive and cost - efficient ocean characterization. For example, SOI may be well - poised to offer a research facility focused on the operations and research and development of hardware, software, communications, and data integration for multi - agent intelligently coordinating marine robotics, including underwater, surface, and aerial systems. This new model of a seagoing technology R&D and test platform would be different from conventional research ships, as it could be optimized for ease of overboarding operations, could have a more modular design to accommodate easy mobilization and demobilization of various types of robotic vehicles and scientific platforms, data ingestion, data integration, and near - real - time processing and visualization capabilities, vehicle maintenance, repair, and also facilitate technology research and development at sea.

The amount of fuel required to be exhausted by ships while transiting and operating is often not mentioned when considering which methods to use to support traditional observation and data collection models. The advancement of multi-agent robotic observers will boost the metric of fuel burnt (or dollars spent) per terabyte of data collected. In the future, this could provide a new metric for the efficiency and success of a research facility operating at sea.

Additionally, the latest innovations in sensor technologies greatly increase the volume and quality of fine - grain data to characterize (micro)biological, chemical, and physical ocean processes. However, many ocean scientists still operate on seasonal cycles (one data collection and one interpretation cycle per year), leaving various ocean characteristics unobserved for most of the year, including during poor weather seasons. Utilizing the newest sensor and/or robotic capabilities to collect data in all seasons, could result in a more seasonal view, better informing research at sea.

During SOI's recent cruises where new data were processed in near - real - time with the use of a shipboard high performance computing system, the power and efficiency of at - sea data integration and post - processing was clearly demonstrated. Access to this system enabled scientists to have the capability to respond to the newly observed phenomena while the cruise was still in progress and inform their day - to - day research at sea with insights from the new incoming data and data processing. More shipboard data processing capabilities will be needed to address new and growing streams of instrument data and help address the shortage of satellite bandwidth. New critical uses seem to emerge with every increase in bandwidth capacity. For example, a GPU array could be used to support high bandwidth acoustic and visual data interpretation in real - time while at sea.

Rapidly growing volumes of diverse collected data require focused effort on assimilated data QA/QC and integration, post - processing, and visualization to inform day - to - day research at sea. This quality assurance requirement places emphasis on the standardization of instrument interfaces, sensor calibration techniques, streaming / communications, data logging protocols, data QA/QC, and data post - processing practices.

The community of ocean researchers who could leverage these advances is continuously growing, and the ocean sciences overall could greatly benefit from focused support of R&D in these areas. During the workshop, participants highlighted the impact SOIs agile, purpose - defined mindset and ability to drive broad cultural change in global ocean science community could make. For example, in the growing acceptance of data sharing, by SOI requiring that the data collected onboard R/V *Falkor* is shared openly and rapidly, and by the organization providing the necessary technological and operational support to our collaborating scientists, the organization would set a leading example within the ocean sciences community.

List of Workshop Participants (in alphabetic order)

Dr. Jim Bellingham – Director, Center for Marine Robotics, Woods Hole Oceanographic Institution

Dr. Marc Carreras – *Associate Professor*, University of Girona, Guest Speaker

Dr. Mandar Chitre – *Head*, Acoustic Research Laboratory, National University of Singapore, Guest Speaker

Prof. Mike Coffin – Professor, Institute for Marine and Antarctic Studies, University of Tasmania

Dr. Stuart Feldman – *retired*, former Director of Engineering, Google; VP Research, IBM

Dr. Vicki Ferrini – *Research Scientist*, Lamont Doherty Earth Observatory – Columbia University

Prof. Chuck Fisher – *Professor* & *Associate Dean for Graduate Education*, Pennsylvania State University

Dr. Ariell Friedman – *Post Doctoral Research Engineer*, Australian Centre for Field Robotics, Univ. of Sydney, Guest Speaker

Mr. David Fries – *Systems Architect and Scientist*, University of South Florida

Mr. Richard Jenkins – *CEO*, Saildrone, Guest Speaker

Ms. Reyna Jenkyns – *Data Stewardship & Operations Support Team Lead*, Ocean Networks Canada, Guest Speaker

Mr. Oliver Kreylos – University of California Davis, Guest Speaker

Dr. Tom Kwasnitschka – *Researcher*, GEOMAR Helmholtz Centre for Ocean Research Kiel, Guest Speaker

Mr. Trent Lukaczyk – *PhD Candidate*, Stanford University

Dr. Phil McGillivary – *US Coast Guard Pacific Area and Icebreaker Science Liaison*, US Coast Guard

Dr. Russ Moll – retired, former Director of California Sea Grant

Mr. Webb Pinner – *Owner/Operator*, Capable Solutions Inc.

Dr. Joe Resing – *Research Scientist*, University of Washington

Dr. Kristof Richmond – *Design Team Lead and Software Lead*, Stone Aerospace, ARTEMIS Project, Guest Speaker

Mr. Scott Ross – *Director*, Schmidt Marine Technology Partners

Prof. João Sousa – *Head*, Underwater Systems and Technologies Laboratory, Porto University, Guest Speaker

Prof. Oscar Schofield – *Professor*, Rutgers University

Dr. Blair Thornton – *Associate Professor*, University of Tokyo

Dr. Jyotika Virmani – *Senior Director*, Wendy Schmidt Ocean Health X Prize

Prof. Stefan Williams – *Professor*, Australian Centre for Field Robotics, Univ. of Sydney

Dr. Dawn Wright – *Chief Scientist*, Esri, Guest Speaker

Dr. Christopher Zappa – *Associate Research Professor*, Lamont-Doherty Earth Observatory, Columbia University

Schmidt Ocean Institute Team

Mr. Eric King – *Director of Marine Operations*

Mr. Stian Alesandrini – *Science Services Manager*

Mr. Adrian Tramallino – *Information Technology Manager*

Mr. Reuben Mills – *HROV Technical Manager*

Mr. David Wotherspoon - *HROV Program Manager*

Captain Heiko Volz – *Senior Captain R/V Falkor*

Mr. Leighton Rolley – *Lead Marine Technician R/V Falkor*

Dr. Victor Zykov – *Director of Research*

Ms. Lisa Pereira – *Program Coordinator*

Ms. Carlie Wiener – *Communications Manager*

Mr. Leonard Pace – *Science Program Manager*

Mrs. Allison Miller – *Research Program Manager*

Mr. Logan Mock-Bunting – *Outreach Communication Specialist*