(Kamgar-Parsi 92). (Karahalios 91) examines volumetric sonar visualization concepts and presents example visualizations using near-field sonar processing data. Additional images from her work appear in (Keller 93, p. 122). A summary of underwater acoustic models which includes example sonar visualizations is (Porter 93). Wireframe sonar visualization is included in simulated AUV use of mine avoidance tactics in (Hyland 93). Occupancy grid methods presented in (Elfes 86) are further considered in (Auran 95). A variety of 2D line drawings which incorporate uncertainty information appears in (Leonard 92). Scientific visualization techniques applied to the display and interpretation of very large environmental datasets appear in (Rhyne 93a, 93b).

G. ONGOING AND FUTURE PROJECTS

Directions taken in this work have also considered current and future efforts which might benefit from an underwater virtual world approach. The following projects represent many diverse and fascinating research areas which might benefit from connection to a distributed underwater virtual world architecture.

1. *JASON* ROV and the Jason Project

The *JASON* remotely operated vehicle (ROV) has been used to conduct scientific exploration on a wide range of oceanographic and historic sites of interest (Ballard 93), including investigation of benthic chemosynthetic tubeworm communities and discovery of *HMS TITANIC*. Deep ocean investigations using *JASON* are supported by a surface ship with a control van, as well as the intermediate tow sled *MEDEA* which provides lights and local decoupling from long trailing tethers. In addition to power and control signals, the use of fiber optics permits transmission of high-bandwidth sensor and video data from vehicle to support ship.

In 1989 the JASON Foundation for Education was formed to utilize scientific exploration missions best exemplified by the *JASON* ROV as a catalyst and central focus for widely distributed distance learning (Brown 93). JASON Project missions are held annually. Students first learn about science objectives in detail

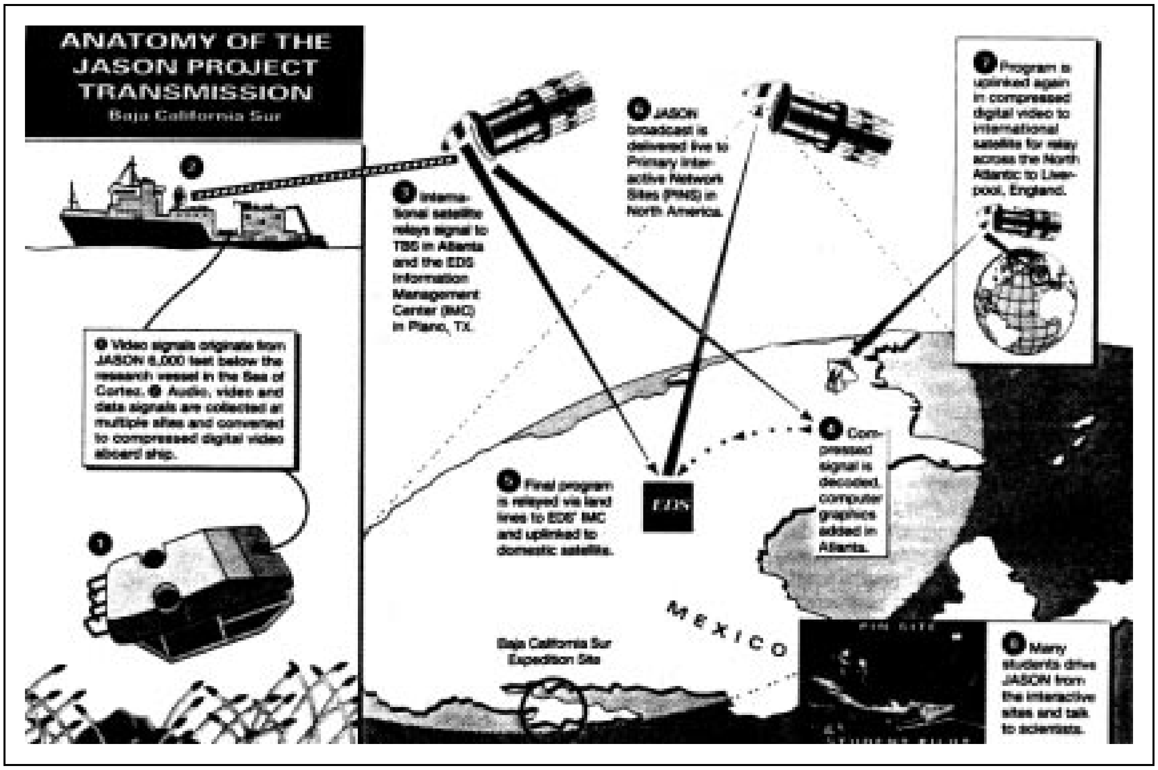

Figure 2.18. *Jason* ROV mission profile and JASON Project communications links (Brown 93).

during regular classes, and then observe and participate in the expedition as it occurs. A team of about a dozen students assists researchers on site while tens of thousands of remote students watch live video streams via satellite downlink. A small number of these remote students are also able to teleoperate the ROV via the satellite link. Months prior to each annual expedition, teachers are given a comprehensive multidisciplinary instructional guide which helps integrate subjects such as oceanography, physics, archaeology, history, biology etc. into the regular school curricula. Students are thus provided live real world examples to motivate and invigorate their studies.

Scientists also remotely participate in these missions. Scientific objectives are not diluted but rather extended to include students in the conduct of significant actual research. Live real-time multicast dissemination of *JASON* vehicle telemetry

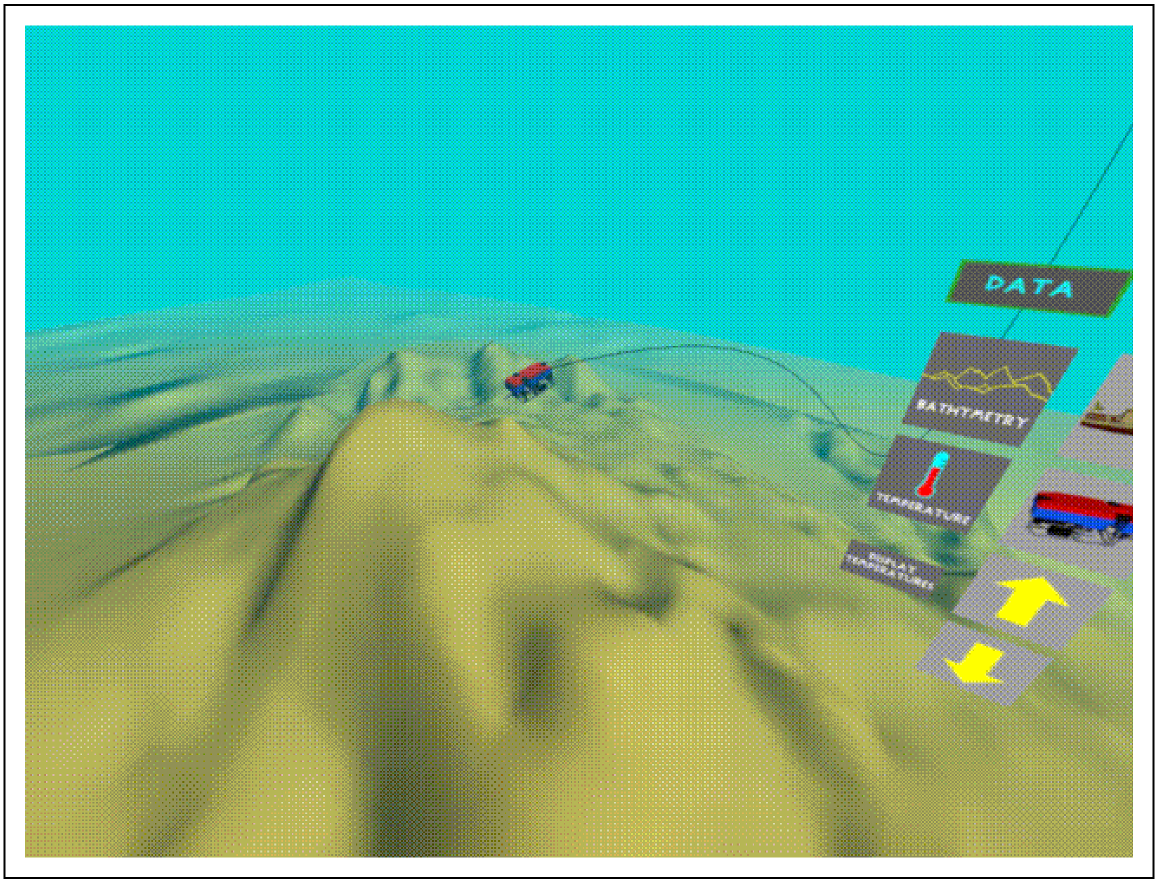

Figure 2.19. *Jason* ROV mission playback from JASON Project 94 operating in an immersive CAVE environment at SIGGRAPH 94 (Feldman 94).

and imagery over the Internet was one of the first widespread scientific collaborations that employed the MBone. Remote users have been able to download visualization software to observe the progress of each mission. Visual results are documented in (Stewart 92) (Pape 93) (Rosenblum 93), including rendering of results using a walk-in immersive display room called the CAVE Automatic Virtual Environment (CAVE) (Feldman 94) (Cruz-Neira 93). Extension of these results using a comprehensive underwater virtual world has the potential to further support distance learning and scientific research objectives. The involvement of motivated and inquisitive students can doubtless increase the realism and effectiveness of an underwater virtual world.

2. Acoustic Oceanographic Sampling Network (AOSN)

A convergence of developing technologies is enabling ambitious new approaches to oceanography. Autonomous Oceanographic Sampling Networks

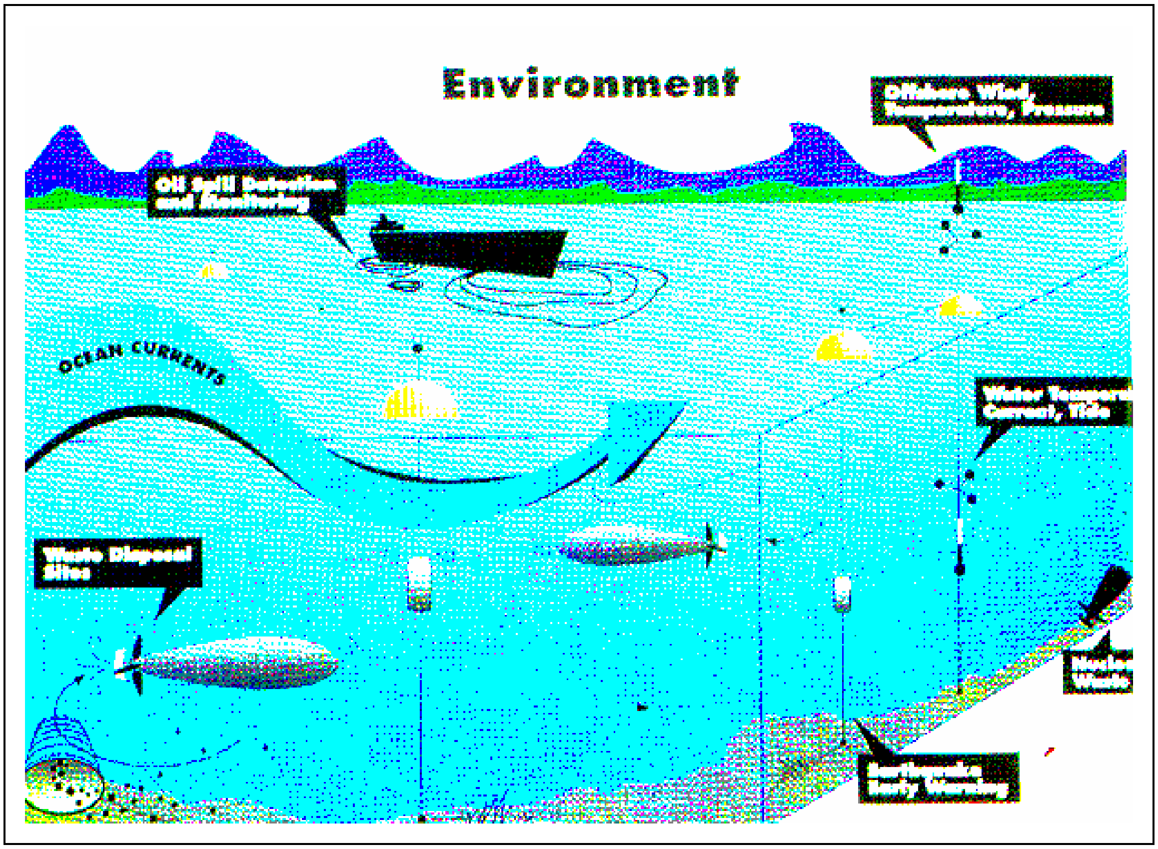

Figure 2.20. Autonomous Oceanographic Sampling Network (AOSN) environmental mission profile. Other planned mission profiles include marine operations, mineral resources and fisheries (Fricke 94) (Curtin 94).

(AOSN) are an ambitious plan for large-scale long-duration synoptic data sampling using multiple networked autonomous vehicles and sensors (Curtin 93). Untethered network connections for AUVs and underwater sensors are via acoustic modems to network nodes which relay data to shore over radio frequency (RF) links (Catipovic 93). Numerous competing design tradeoffs must be considered. AUV propulsion endurance and communications efficiency must meet energy expense per survey area criteria. The limited bandwidth and noisy acoustic channel of the water column must be effectively and reliably exploited. The physics of underwater transmission are far different than RF transmission, so packet network protocol design is not easily adapted. Currently it is not clear that multiple vehicles and sensors will effectively interconnect with the Internet. Numerous cost-effectiveness issues must be addressed simultaneously. Nevertheless it is clear that such an approach holds the promise of revolutionizing oceanographic sampling and ocean exploration. Interconnecting large numbers of information entities and diverse data products in a comprehensible fashion is an excellent application for implementation in an Internet-wide underwater virtual world.

3. MBARI-NASA Ames-Postgraduate School-Stanford Aerospace Robotics Lab (MAPS) Project

Four research institutions in the Monterey Bay region have begun a cooperative collaboration to design and build a next-generation AUV. Proposed rapid-response science missions for this AUV call for deep depth capability, single work day operating endurance between recharging, moderate cost and interchangeable mission-specific sensor suites. Use of an underwater virtual world is likely to reduce impediments to regional research collaboration, improve access to scientific data measurements, maximize utilization of shared resources and enhance a common understanding of vehicle challenges.

4. Live Worldwide Distribution of Events

Collaboration, distance learning, human interaction and communication of ideas do not magically happen when a computer is connected to the Internet. We have found that people issues and technical issues are equally important when building large open networked virtual workspaces. To improve our understanding of these issues and increase the accessibility of those worlds, we have performed an ambitious series of regional and world-wide multicast sessions using the MBone (Brutzman 94a, 94b, 94c, 94d, 94f) (Macedonia 95b) (Gambrino 94).

Regardless of whether participants are scientists, naval officers, school children or interested bystanders, it is always the same real world that we are trying to recreate virtually. Ongoing efforts to further develop the underwater virtual world will continue to narrowcast computer graphics, video, audio, hypermedia and DIS-compatible AUVs with anyone interested in participating. These events will continue to extend and strengthen the empirical basis underlying this work.

5. Monterey Bay Regional Education and the Initiative for Information Infrastructure and Linkage Applications (I^3LA)

A regional network is being planned and built which will connect researchers, educators and students throughout the tricounty Monterey Bay region via interactive multimedia, audio and video (Brutzman 94f). Named the Initiative for Information Infrastructure and Linkage Applications (I^3LA), this group project is an exciting broad-based collaboration which teams educators, scientists, business and government. We hope to fundamentally change local schools by connecting education with active ocean-related research at the individual classroom level. Our educational network design approach follows the Internet model (Gargano 94). I^3LA will give individuals at 51 different schools and research institutions interactive access to any type of live or archived media using a variety of bandwidth rates. Student ages range from kindergarten to postgraduate. I^3LA exemplars for education include daily science missions using the Monterey Bay Aquarium Research Institute (MBARI) *Ventana* ROV, Monterey Bay Aquarium (MBA) exhibits, and San Jose Technical Museum for Innovation programs. A similar regional effort which uses underwater vehicle technology as a focus to enhance science education is described in (Babb 92-93). Helping to build a regional information infrastructure with strong ties to education has benefited design of the network architecture presented in this dissertation. Current work on the underwater virtual world includes adapting the software to be suitable as

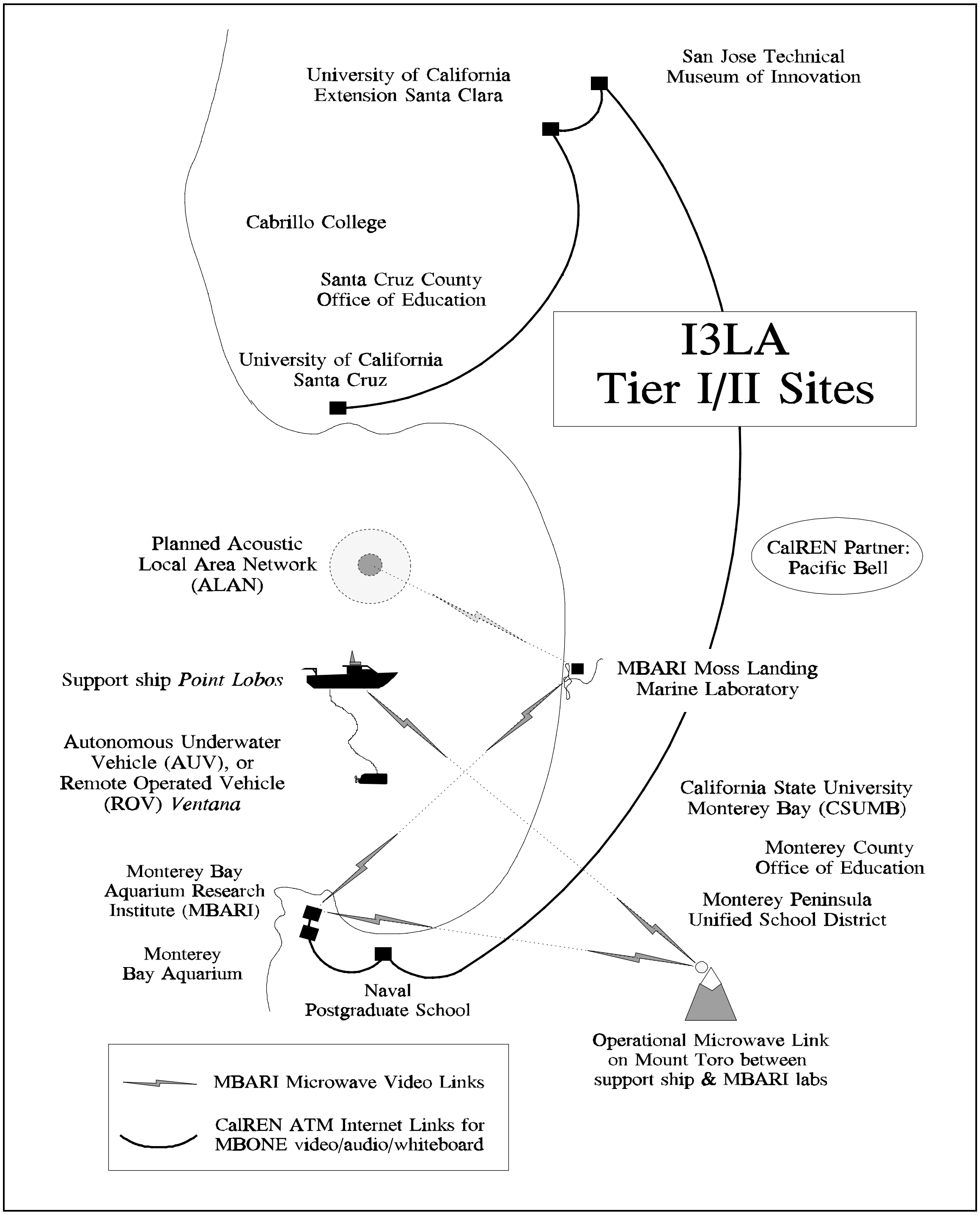

Figure 2.21. Initiative for Information Infrastructure and Linkage Applications (I^3LA) high speed communications links. Fifty one schools and research institutions are being connected.

an education application, which will further encourage extension of distributed virtual worlds as mechanisms for human interaction and information correlation.

H. SUMMARY AND CONCLUSIONS

This section presented work related to the design and construction of an underwater virtual world for an AUV. Overview summaries were provided for underwater robotics, robotics and simulation, underwater vehicle dynamics, networked communications for virtual worlds, sonar modeling and visualization, and ongoing and future projects.

Virtual reality as exemplified by immersive human-computer interface devices is a much larger albeit related field which is outside the scope of this work. Key surveys and bibliographies of virtual reality concepts, systems and trends appear in (Durlach 94) (U.S. Congress 94) (Pantelidis 94) (Emerson 94).

A number of scientific disciplines and new technological capabilities are becoming mutually compatible thanks to the multiplying effects of network connectivity. Presentation of these diverse fields under the unifying perspective of designing AUVs and virtual worlds shows that many new possibilities are becoming feasible. The review presented in this chapter shows that creation of a comprehensive networked virtual world for an autonomous robot has not been previously proposed or attempted. Following chapters will specifically show how numerous competing research objectives can be resolved and implemented to produce an underwater virtual world for an autonomous underwater vehicle.