to another manager if necessary. Protocol extension implementation, experimentation and analysis is in progress. The capability to use multicast protocols will be required for future DIS compliance (IEEE 94a), underscoring the importance of these concepts. These ideas are explained within the larger context of state-of-the-art trends in virtual reality networking and communications in (Durlach 94).

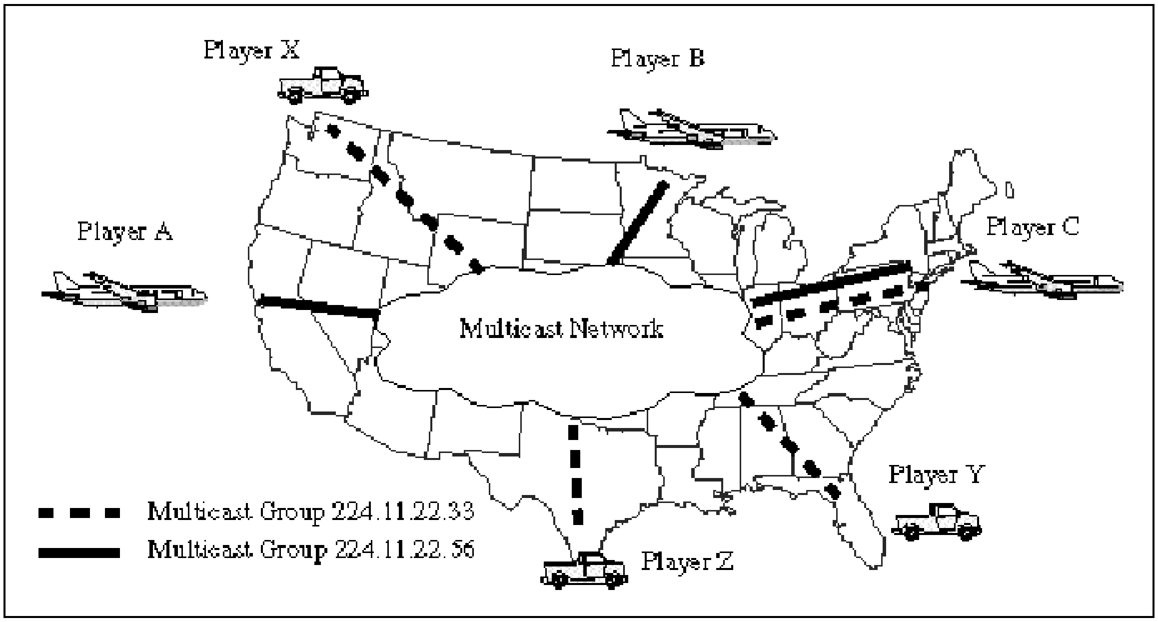

Figure 2.14. "Exploiting Reality with Multicast" - multiple DIS channels for geographic sectors, functional classes (e.g. communications) and temporal classes (e.g. highly dynamic aircraft) (Macedonia 95a).

5. Gelernter: *Mirror Worlds* and Linda

(Gelernter 92a, 92b) describes a powerful set of abstractions for networked virtual world communications. He extends and simplifies the message-passing paradigm used by communicating software objects through creation of a "tuple space." Tuples are persistent messages without a specific addressee. Tuples are ordered lists that begin with some keyword and contain any number of additional elements. Processes have three operations to use with tuples: jettison, grab and read (alternatively publish, consume and nondestructive read). Processes can access tuples by pattern matching against any or all potential tuple elements, thus retrieving individual tuples or groups of tuples. Tuple space consists of these persistent tuples being read and generated by information machines (i.e. processes), somewhat similar to a blackboard architecture. Since tuple elements might be further tuples, and because tuples can themselves be programs, recursive hierarchies and distributed processing are natural possibilities without explicit specification by the original programmer. This communication methodology has also been shown to be identically portable to massively parallel processors, permitting programmers to concentrate on developing parallel algorithms for problem solving rather than tuning the idiosyncracies of the underlying hardware (Gelernter 92b).

These concepts define the characteristics of coordination languages, which extend computational programming languages in a general and orthogonal way (Gelernter 92b). Arguably coordination languages provide the ability to scale up the number of interacting computational processes to a degree that can reflect real world functionality; hence "mirror worlds" (Gelernter 92a). Initial implementation of these ideas is demonstrated by the Linda communication system (Carriero 91) (Gelernter 92a, 92b). As virtual worlds continue to grow and network bottlenecks permit much larger numbers of entities to interact, implementing the functionality of nonhierarchical nonimperative distributed communication schemes as described in *Mirror Worlds* will be essential.

6. Distributed Interactive Virtual Environment (DIVE)

Distributed Interactive Virtual Environment (DIVE) is a heterogeneous distributed world representation that shares copies of a world database to permit multiple users and applications to simultaneously interact in a single virtual 3D space (Carlsson 93). The world database serves as a global memory shared over the network using a reliable ordered multicast scheme. Maintaining global database consistency is an important problem in large-scale virtual worlds. Multicast protocol packet delivery is ordinarily "best effort" and not guaranteed. Including sequential numbers to each message can achieve reliability for multicast through retransmission, but the cost of that error recovery is expensive and such approaches (as exemplified by DIVE) currently do not scale past several dozen peers (Macedonia 95c). Static and dynamic distributed databases are another key bottleneck that must be addressed for arbitrarily scalable virtual worlds.

7. Other Network Communication Systems for Virtual Worlds

Many other active research projects are working on eliminating the barriers which prevent arbitrarily scaling up distributed virtual world communications. Recommended references are (Zyda 95) (Singh 94) (Bricken 94) (Shaw 93) (Morrison 95) (Codella 93) (Kazman 93). Overlapping and interdependent areas of investigation include:

- peer-to-peer versus client-server models
- network bandwidth reduction
- network processing reduction for participating hosts
- reliable versus best-effort delivery
- object-oriented functional partitioning
- parallelization to improve performance
- decoupling user interfaces (input devices and output graphics)
- persistent and coherent distributed global database management
- open toolkit construction
- compatibility over heterogenous platforms, peripheral hardware independence
- operating system modifications for improved performance
- defining temporal relations, establishing synchronization
- application interaction protocols

Aside from the common denominator of Internet Protocol (IP) use and occasional compliance with the Distributed Interactive Simulation (DIS) application protocol, there is little direct compatibility among any of the aforementioned approaches. Even if a "silver bullet" solution were to emerge from these many efforts, current virtual worlds are likely to remain isolated as closed, incommunicado islands of functionality. General requirements for open interoperability between virtual worlds are examined in (Bréant 94). Specification and development of a specific open communications model as an extension of World-Wide Web (WWW) is a goal of the Virtual Reality Modeling Language (VRML) working group (Bell 94) (Pesce 94). A commonly accepted baseline interaction model for virtual world communications is needed.

F. SONAR MODELING AND VISUALIZATION

Sonar modeling attempts quantify and predict the highly variable behavior of sound waves underwater. A large number of sonar models have been in use since sonar was first widely employed in the 1940s, and development of effective sonar models is the subject of ongoing research. Sonar visualization is the application of scientific visualization techniques for rendering sonar information, in an attempt to better understand the temporal, spatial and physical behavior of underwater acoustics. It is a relatively new area of study. This section identifies prominent related work in sonar modeling and sonar visualization.

1. Etter: Acoustic Modeling

(Etter 91) presents a comprehensive treatment of underwater acoustic modeling, defined as "the translation of our physical understanding of sound in the sea into mathematical formulas solvable by computers." He first treats the physics of underwater sound and acoustical oceanography, synopsizing another key reference on sonar behavior (Urick 83). Sound speed in the ocean is identified as the single most important acoustic variable. Etter then identifies three broad classes of sonar models and organizes the wide variety of existing sonar models into a conceptual hierarchy, shown in Figure 2.15. Each model type is examined in depth. There is no "perfect" sonar model suitable to all situations, and users must carefully choose models (or combinations of models) based on problem requirements. Typically models become less general and more specific to individual sonar systems as one proceeds up the hierarchy.

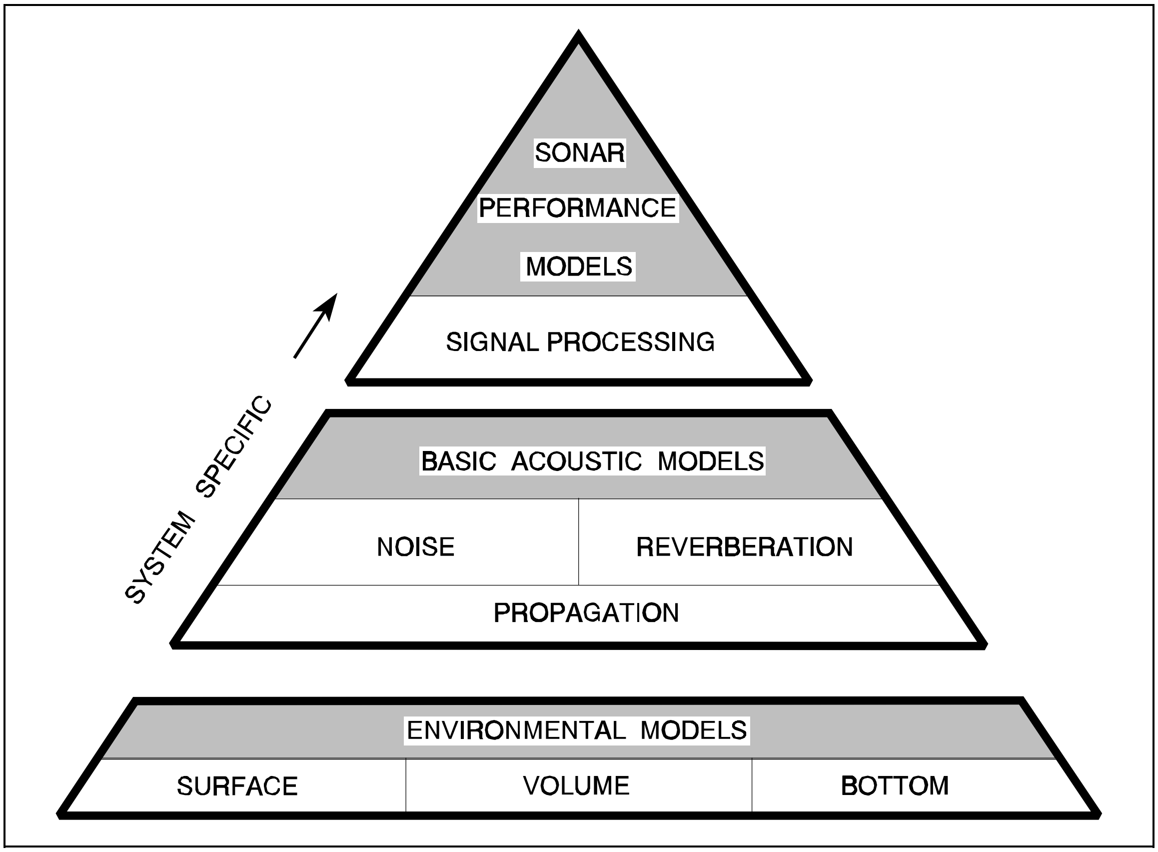

Figure 2.15 Generalized relationships among Environmental Models, Basic Acoustic Models and Sonar Performance Models (Etter 91, p. 3).

The three types of models identified are Environmental Models, Basic Acoustic Models and Sonar Performance Models. Environmental Models examine ocean surface and bottom boundary conditions as well as volumetric effects. Basic Acoustic Models represent the physics or empirical behavior of noise, reverberation and propagation (transmission loss). Sonar Performance Models combine signal processing theory with the preceding Environmental Models and Basic Acoustic Models to enable end-to-end solution of typical sonar detection problems particular to specific types of sonar equipment.

The field of sonar modeling is characterized by tremendous variety. Most models have very narrow domains of applicability and may need to be used in combination with others for the solution of specific problems. Management of this complexity has even led to the development of model operating systems (MOSs) which attempt to assist users by managing the selection of multiple models and appropriately connecting their various input/output requirements. Initial examination of the subject of sonar modeling from the perspective of underwater virtual world construction identified this plethora of models as a key obstacle to scalability and generality. This difficulty is compounded by the fact that many models are reported to be classified (Etter 91) and unavailable for use in an open, arbitrarily scalable virtual world.

2. Stewart: Stochastic Backprojection and Sonar Visualization

(Stewart 88) presents a novel approach to modeling underwater objects. Sonar data are typically high-bandwidth high-noise information streams that include

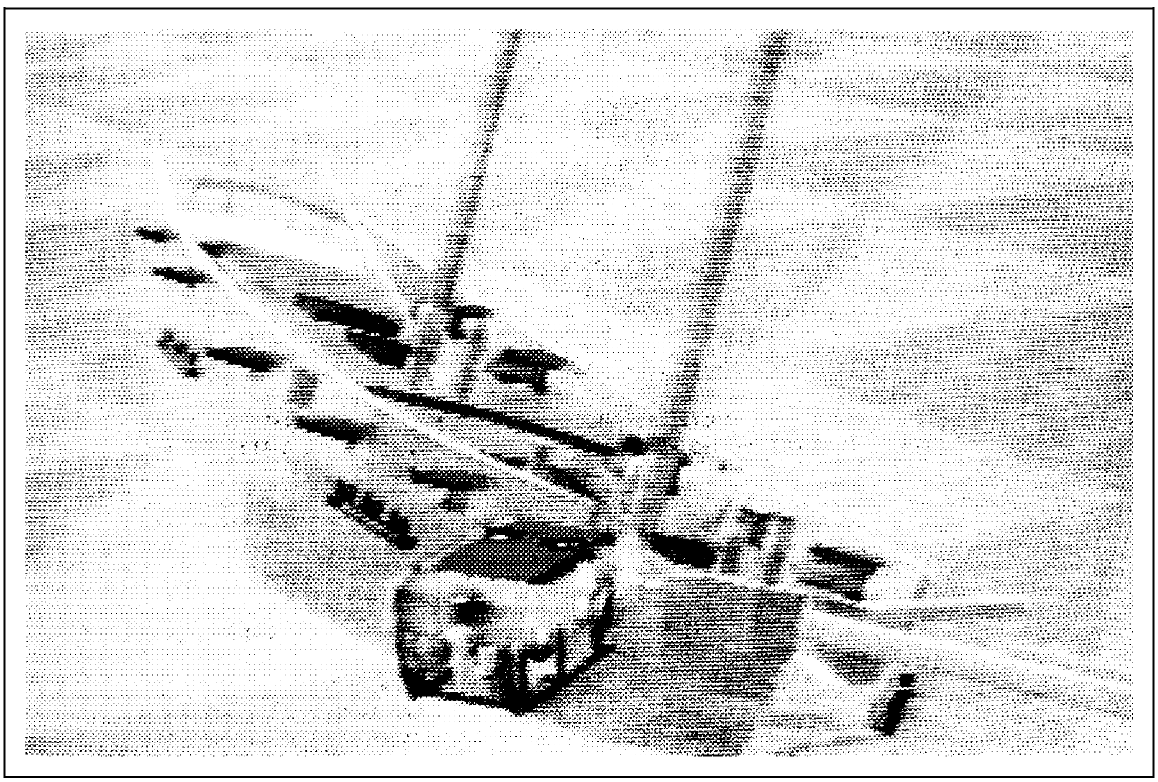

Figure 2.16. Graphics visualization of *JASON* ROV approaching submerged wreck *HMS SCOURGE* (Stewart 92).

redundant returns from target of interest, as well as a large proportion of signal corresponding to false returns or objects of little interest. Key characteristics of underwater sensing applications include "real-time constraints; unstructured, three-dimensional terrain; high-bandwidth sensors providing overlapping, redundant coverage; lack of prior knowledge about the environment; and inherent inaccuracy in sensing and interpretation." Sonar and other sensor returns are treated as probability distributions which are adaptively combined to create 3D maps of terrain and object surfaces using a new statistical technique, *stochastic backprojection*. Model representation accuracy and certainty improve as redundant data accumulates. Intermediate results are available and steadily improve in real time, permitting "anytime" use by operators or robots. Reduction of bandwidth and extraction of useful information are also significant benefits. Stochastic backprojection is appropriate for use in bathymetric mapping, ROV piloting control, and world modeling for AUVs.

Sonar visualization techniques were essential to the successful development of stochastic backprojection methods, since qualitative visual inspection of results were used to evaluate model effectiveness. In addition to the sonar visualization techniques presented in (Stewart 88), an illustrated survey of underwater visualization in (Stewart 92) supplemented by (Stewart 89, 91) and (Rosenblum 93) presents a thorough state-of-the-art summary of sonar visualization and underwater sensor visual representations.

3. Ziomek: Recursive Ray Acoustics (RRA) Algorithm

As previously noted, a key difficulty in sonar modeling as applied to underwater virtual world use is the very large numbers of models that are available for different ocean conditions and different sonars. The Recursive Ray Acoustics (RRA) algorithm (Ziomek 93, 94) provides an approach which appears to be general and well-suited for real-time graphics rendering. A ray tracing algorithm, RRA derives the fundamental wave equations describing sound propagation from a differential equation form to a difference equation form. Three-dimensional models for sound speed profile (SSP) and terrain bathymetry are retained as independent inputs. The algorithm is fast

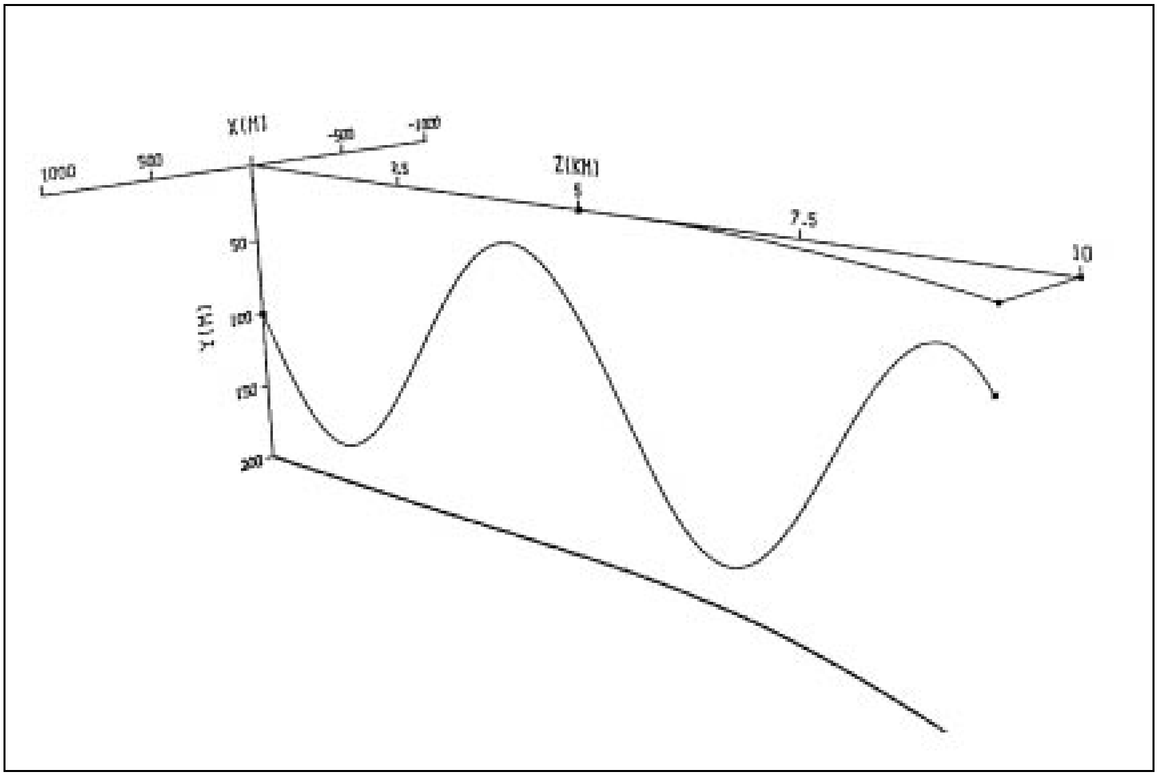

Figure 2.17. Example Recursive Ray Acoustics (RRA) algorithm plot showing sound ray bending due to vertical and down-range sound speed profile (SSP) variations (Ziomek 93).

since each short ray segment in a long ray path is calculated recursively based on the ray segment preceding. RRA can be used to calculate position, propagation angles, sound pressure level (SPL) and travel time along a ray path. Most significantly it appears to be applicable over a wide range of frequencies since approximations and empirical simplifications are avoided in the original RRA derivation. Comparison of RRA results with different models validated in a variety of problem domains has been excellent. RRA appears to be a general, precise and rapid algorithm suitable for real-time sonar modeling and visualization.

4. Additional Work in Sonar Visualization

(Rosenblum 93) presents an overview of current work relating to sonar visualization. Additional images and explanation appear in (Rosenblum 92)