VIII. SONAR MODELING AND VISUALIZATION

A.   INTRODUCTION

This chapter describes the role of sonar modeling and sonar visualization in an underwater virtual world. The potentially significant effects of sound speed profile (SSP) on sound ray paths in the ocean are briefly examined, and example SSP plots are presented showing component measurements and possible ray path variations. Differences in sensor modalities and difficulties in forming mental models provide motivation for utilizing scientific visualization techniques to graphically render sonar. The necessity for a real-time sonar model makes the RRA algorithm (Ziomek 93, 94) appear to be a desirable choice based on offline results. Since short-range models are the most time-critical sonar application, an example geometric sonar model is presented for the NPS AUV test tank. A discussion of sonar parameter and graphics rendering considerations for sonar visualization is presented along with preliminary rendering examples. A great deal of important future work is possible in this area.

B.   SOUND SPEED PROFILE (SSP)

The behavior of sound waves in the ocean is highly variable. Sound waves "bend" as they travel, away from the direction of higher sound speed and toward the direction of lower sound speed. This is an example of Snell's Law within a continuously varying medium. Since this bending may cause significant sound wave path changes, and since it does not occur uniformly over a wave front, the travel of sound through the ocean is highly nonlinear.

The primary factor influencing sound path is the sound speed profile (SSP). Water depth and bottom type can also have significant effects. Descriptions of SSP, water depth and bottom type effects on sound propagation are described in detail in (Etter 91) (Urick 83). Sound may be bent towards the bottom or surface, reflect off

bottom or surface, be masked at certain depths by "shadow zones," travel for long ranges via convergence zones, or remain trapped in a deep sound channel.

The many ways that sound can travel in the ocean is highly variable. Assuming knowledge of local bathymetry, the primary information needed for sonar prediction is the SSP. Three factors control local sound speed: salinity, temperature and pressure. These parameters can be determined by measuring conductivity, temperature and density (each versus depth) directly in the water column. Empirical formulas have been determined which utilize conductivity, temperature and density to calculate sound speed. Typical SSP datasets are noisy and highly redundant, and large SSPs may be subsampled, smoothed or represented by polynomial approximations for computational tractability. Figure 8.1 shows a typical SSP plot taken from deep water in Monterey Bay in September 1990 along with component conductivity, temperature and density contributions (Rosenfeld 94). Figure Figure 8.2 shows the large possible variations in effects of an example SSP on ray paths, calculated by the RRA algorithm for a set of rays initially separated by only 0.4°.
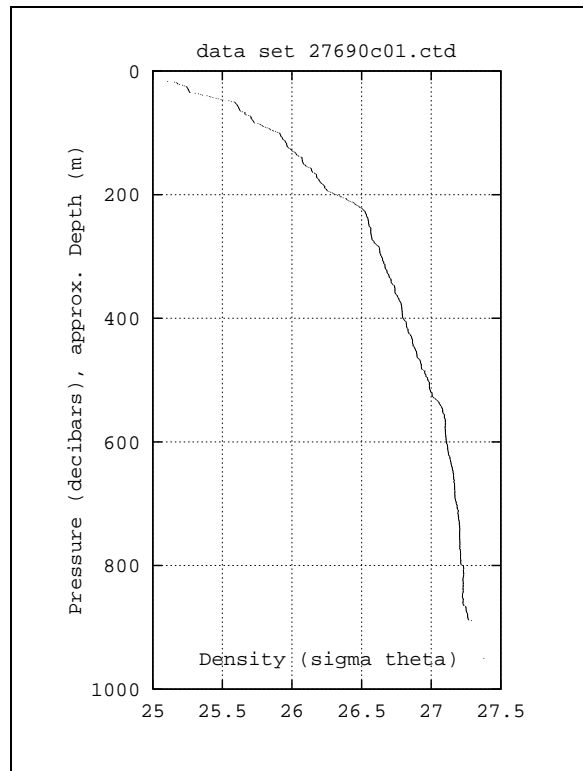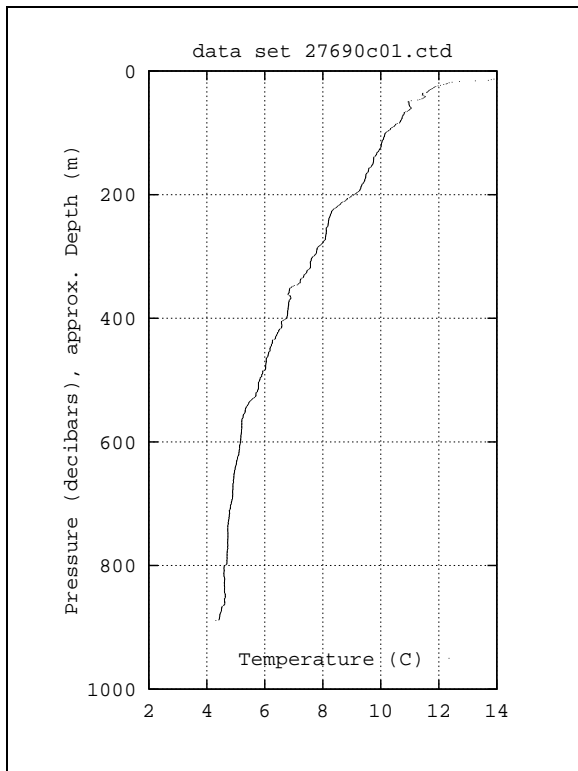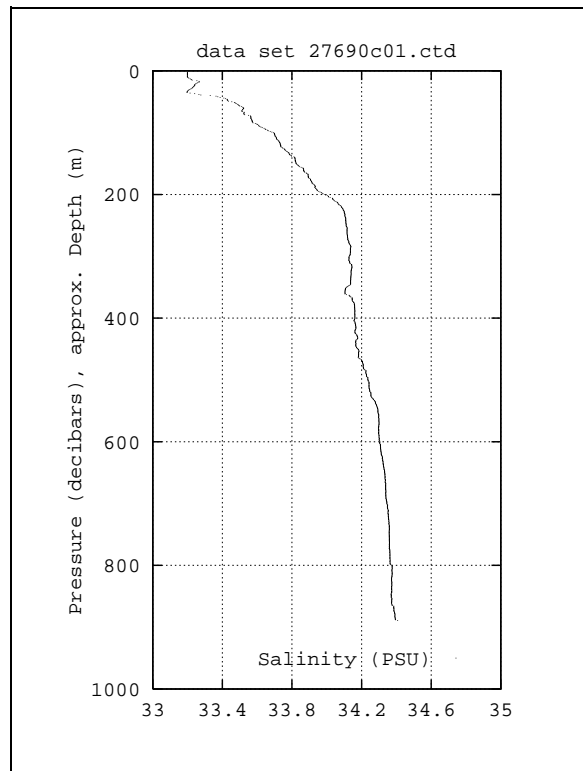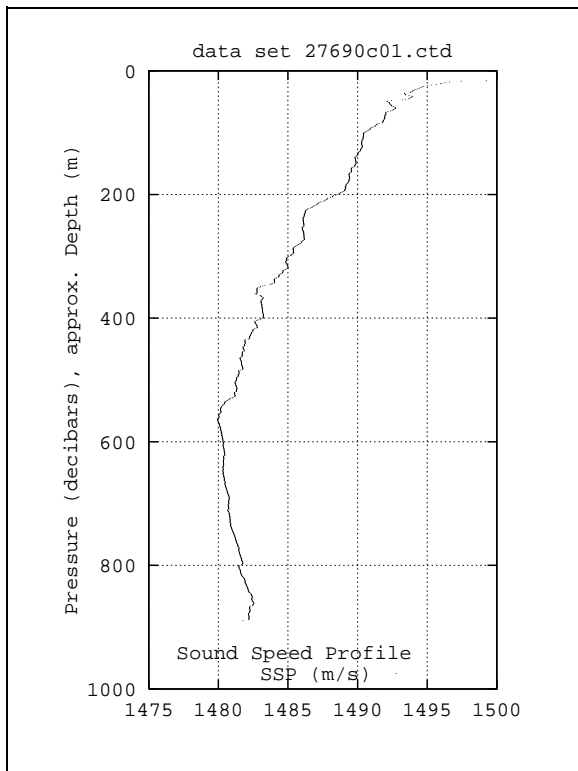
data set 27690c01.ctd

Pressure (decibars), approx. Depth (m)

Sound Speed Profile
SSP (m/s)

1475 1480 1485 1490 1495 1500

data set 27690c01.ctd

Pressure (decibars), approx. Depth (m)

Salinity (PSU)

33   33.4 33.8 34.2 34.6 35

data set 27690c01.ctd

Pressure (decibars), approx. Depth (m)

Temperature (C)

2   4   6   8   10   12   14

data set 27690c01.ctd

Pressure (decibars), approx. Depth (m)

Density (sigma theta)

25   25.5 26   26.5 27   27.5

Figure 8.1   Representative sound speed profile (SSP) plot. Includes component conductivity (salinity), temperature and density (CTD) data plots (Rosenfeld 93).
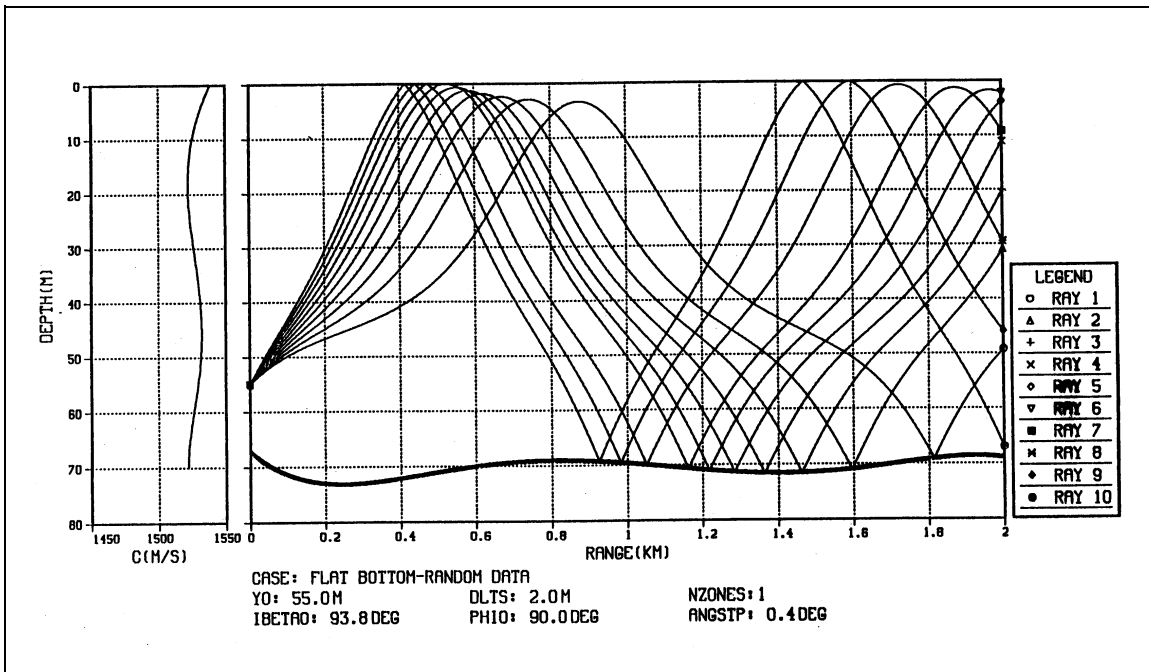
191

Figure 8.2.   Example Recursive Ray Acoustics (RRA) algorithm plot showing sound ray bending due to sound speed profile (SSP) and bathymetry. Initial vertical orientation difference between rays is only 0.4° (Ziomek 93).

C.   MENTAL MODELS AND SCIENTIFIC VISUALIZATION CONSIDERATIONS

The modalities of sonar sensing are much different from that of vision. For active sonar, ranges are measured by the time difference between pulse transmission and return detection. Multiplication of this time difference by the speed of sound in water provides a very accurate range estimate. For passive sonar, ranges to an object producing sound are not directly calculable but can sometimes be deduced by maneuvering and geometric analysis. For both active and passive sonars, bearings are typically accurate only within a few degrees. In contrast, vision techniques typically provide very accurate bearings with approximate ranges. As a result, perception algorithms based on range data and approximate bearing data are counterintuitive. Combined with the complexity of sound travel, it is difficult for individuals to

192

visualize and conceptualize underwater sonar effectively. Sonar operators on submarines typically need a year of schooling and experience to qualify before their mental models become sufficiently familiar to permit unsupervised watchstanding (Brutzman 93b).

It is reasonably conjectured that improved sonar visualization can dramatically improve an individual's ability to understand the intricacies of sonar behavior. It is within current computational capabilities to calculate the physical path taken by sound through a highly variable sonar environment. Rendering the results using 3D computer graphics can provide useful feedback to human observers regarding sonar performance. Such feedback can enable the production of effective analysis and classification algorithms suitable for real-time autonomous use by AUVs (Brutzman 92a, 92e) (Compton 92).

D.   REAL-TIME SONAR MODEL RESPONSE AND THE RECURSIVE RAY ACOUSTICS (RRA) ALGORITHM

As previously described in (Etter 91, 92) a great variety of sonar models exist, but unfortunately most are restricted to highly specific environmental domains. Additionally most sonar models are computationally expensive and are thus unsuitable for real-time performance. Implementation of an AUV sonar model within an underwater virtual world requires real-time response. Multiple model simultaneous real-time response in the virtual world can be accomplished through distribution on multiple processors if necessary. In practice at a 10 Hz rate, multiple processor distribution has not been necessary for the core models interacting directly with the AUV.

Interestingly, the speed of sound in water is relatively slow (typically 1650 yards/sec) compared to the speed of light in air. For active sonars, time of ping travel corresponds to twice the range to target plus any changes due to relative vehicle motion. This implies that approximately one second of processing time can be available for calculating each 800 yards of active sonar travel. Given that effective

193

sonar ranges can be 10 miles or greater in distance, a great deal of computer time may be available for sonar calculations in tactical situations. In offline experiments, implementations of the RRA algorithm have demonstrated adequate computational performance. It is expected that implementation and integration of the RRA algorithm as an online model for active or passive sonar will meet all underwater virtual world timing requirements.

E.   AN EXAMPLE GEOMETRIC SONAR MODEL

At short ranges, timing requirements can be critical. Fortunately at shorter ranges the effects of SSP on sound wave bending are negligible. Rapid calculation of sonar response at short ranges is possible through application of computational geometry techniques. An example geometric sonar model for the 20 ft by 20 ft NPS AUV test tank has been constructed which demonstrates adequate real-time response in this worst case scenario. The geometric model is capable of 10 Hz response without parallelization. A diagram of tank geometry appears in Figure 8.3. A graphics rendering of the NPS AUV ST-1000 sonar in the test tank as calculated by this model follows in Figure 8.4.

The following formulae are used to calculate the coordinates of the sonar echo return (R_x, R_y) based on sonar location (S_x, S_y) and sonar orientation ψ_{sonar}. The *precede* Boolean operator ($\prec$) returns TRUE if the first angle precedes the second angle by less than 180°, expressed algebraically as follows:

$$\{\alpha \prec \beta\} \equiv \{\text{normalize2}(\beta - \alpha) > 0\} \tag{8.1}$$

As previously defined in Chapter IV, *normalize2 (angle)* normalizes an angle to the range $(-\pi/2..\pi/2]$.

For sonar-relative quadrant I $(SA \prec \psi_{sonar} \prec SB)$:

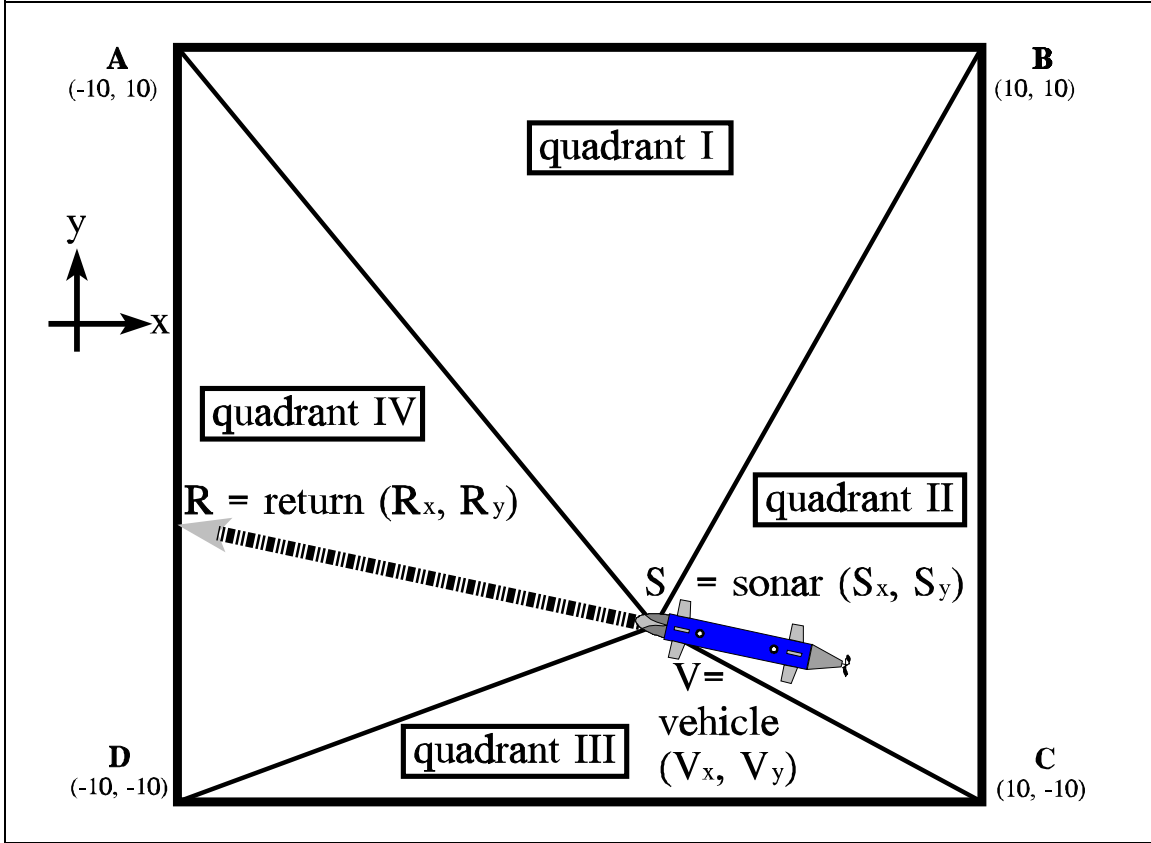$$\begin{aligned} R_x &= 10 \\ R_y &= S_y + \sin(\psi_{sonar})\,(10 - S_x) \end{aligned} \tag{8.2}$$

194

Figure 8.3. NPS AUV test tank geometry.

For sonar-relative quadrant II (SB $\prec \psi_{sonar} \prec$ SC):

$$R_x = S_x - \sin(\psi_{sonar} - 90°)(10 - S_y)$$
$$R_y = 10$$

(8.3)

For sonar-relative quadrant III (SC $\prec \psi_{sonar} \prec$ SD):

$$R_x = -10$$
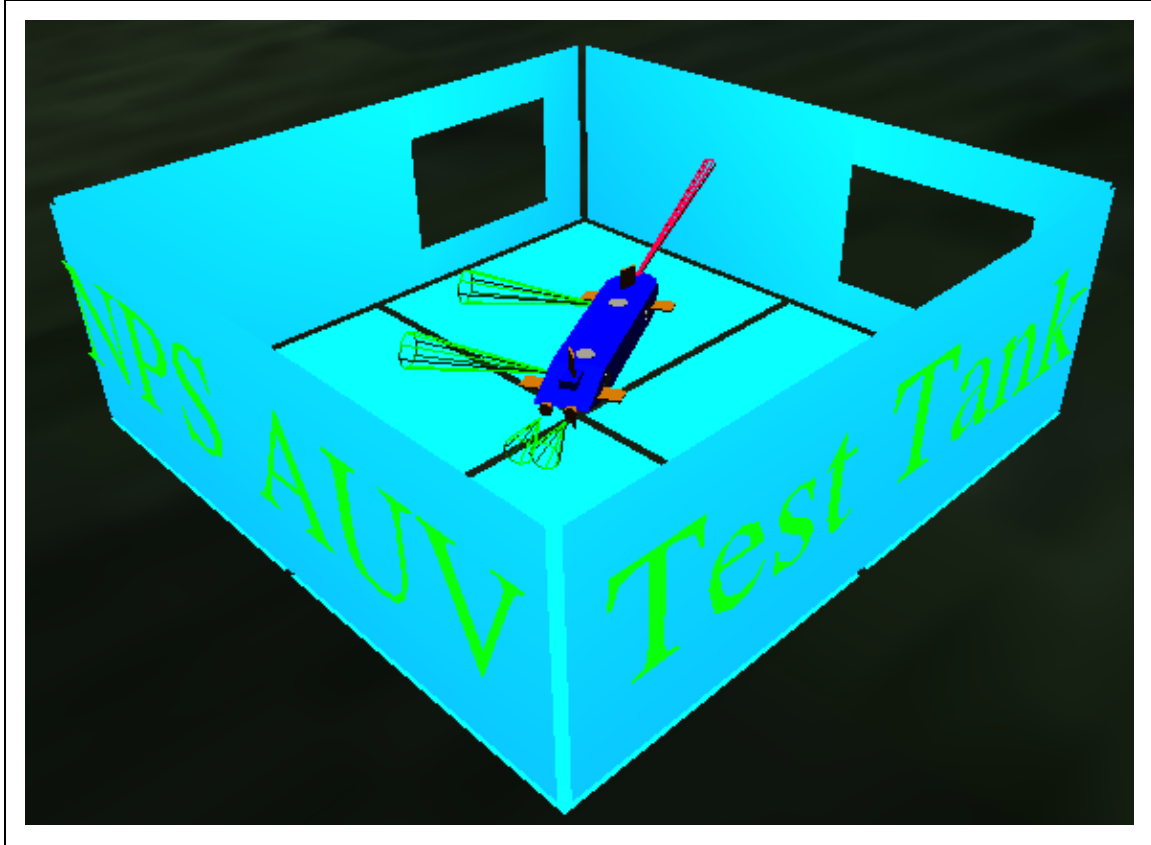$$R_y = S_y - \sin(\psi_{sonar} - 180°)(10 + S_x)$$

(8.4)

Figure 8.4. Sonar pointing towards test tank wall, as seen from behind AUV.

For sonar-relative quadrant IV   (SD $\prec \psi_{\text{sonar}} \prec$ SA):

$$R_x = S_x + \sin(\psi_{sonar} + 90°)\,(10 + S_y)$$
$$R_y = -10 \tag{8.5}$$

Sonar offset coordinates (S_x, S_y) can be calculated from vehicle coordinates (V_x, V_y) using vehicle orientation ψ as follows:

$$S_x = V_x + \cos(\psi)\,(x_{longitudinal\ sonar\ offset})$$
$$S_y = V_y + \sin(\psi)\,(x_{longitudinal\ sonar\ offset}) \tag{8.6}$$

Sonar range is determined using the Pythagorean theorem:

$$sonar\ range\ =\ \sqrt{(R_x - S_x)^2\ +\ (R_y - S_y)^2} \tag{8.7}$$

Development of individual geometric models for the large variety of objects populating a virtual world can be prohibitively laborious. For short and intermediate ranges, this problem is a variation of the virtual world collision detection problem which is solvable in real time for terrain and hundreds of objects (Pratt 93). Computationally efficient collision detection is the subject of active research for larger worlds (such as architectural ship design models) consisting of hundreds of thousands of objects (Zyda 93a). In an underwater environment the density of active entities is typically sparse, and sonar interactions are primarily concerned with terrain and a relatively small number of mobile entities. Thus geometric model switching corresponding to areas of interest in the underwater virtual world is a feasible approach.

Interestingly, graphics toolkits such as *Open Inventor* provide mechanisms for querying the scene database to determine ray intersection points (Wernecke 94a). Conceivably, the same scene database which is used to render the population of objects in the virtual world can also be used for sonar "collision" detection, perhaps independently of graphics rendering. This is a promising approach for automatic determination of sonar detections which is independent of the geometry of individual objects in the virtual world. Such an approach is also highly scalable through reasonably efficient construction or optimization of scene databases.

F.   SONAR RENDERING FOR VISUALIZATION

Sonar data has high dimensionality and ordinarily is difficult to visualize. Scientific visualization methods specialize in the selective application of various graphical rendering techniques to extract the maximum possible information out of

large and abstract datasets (Keller 93). Scientific visualization is therefore a direct example of a guiding precept in computer science:

The purpose of computing is insight, not numbers. (Hamming 86)

A great many possibilities for sonar visualization present themselves. A preliminary consideration of sonar parameters and computer graphics attributes reveals a large number of relatively orthogonal characteristic parameters and primitive rendering operations. They are listed in Figure 8.5. Key criteria when rendering sonar

Sonar Parameters	Rendering Techniques
sound pressure level (SPL)	color variations
depth	intensity
absolute range of travel	transparency
downstream horizontal range	illumination
slant range	directional lights
signal excess for detection	individual rays
phase	wave fronts versus ray groups
pitch angle	density of ray bundles
target intersection	fog
history of previous returns	animation
SSP variations in temperature,	volume visualization techniques
salinity, pressure	blur
attenuation by absorption,	data smoothing
scattering, spreading	data enhancement/interpolation
pulse width	data sonification
frequency and doppler shift	loading and modifying images
background noise, biologics,	previously rendered offline
interference	

Figure 8.5.   Preliminary listing of orthogonal sonar parameters and orthogonal computer graphics rendering techniques for scientific visualization.

data must include the ability to focus on individual parameters of tactical interest, matching orthogonal parameters to rendering techniques which are not mutually interfering, real-time response corresponding to short or long sonar ranges, animation

of spatial or temporal changes, and selectable user control of either visualization primitives or sonar parameters of interest.

As a rudimentary example of sonar-related visualization, a rendering of SSP data appears in Figure 8.6. Formal application of scientific visualization techniques to sonar rendering is a promising topic for future work. It is likely that best results will be obtained by using sonar data structures which are equally suitable for online representation in the virtual world and offline rendering using visualization toolkits.

G.   SUMMARY AND FUTURE WORK

Sonar modeling and sonar visualization are crucial components in an underwater virtual world for an autonomous underwater vehicle. Accurate real-time sonar modeling is necessary to produce realistic sensor interactions with the vehicle. Visualization is necessary for robot designers to create mental models of the often counterintuitive performance of sonar in highly variable ocean environments. Such mental models are of proven benefit when designing and evaluating robot sensing algorithms. SSP effects and an example geometric sonar model are also examined.

Promising areas for future work are dependent on successful incorporation of a general sonar model (or models) into the underwater virtual world. The RRA algorithm shows strong potential for rapid and accurate generation of sonar rays in real time. Additional work includes the formal use of scientific visualization techniques to match up typically orthogonal properties of sonar response to typically orthogonal rendering methods. It is expected that user control of parameters and combined offline/online algorithm analysis will be necessary for best results.

Figure 8.6.   Example graphics visualization of subsampled Sound Speed Profile (SSP). Sound speed is mapped to cylinder color at intervals proportional to local depth, producing a 3D information icon.