A Geospatially Enabled, PC-Based, Software to Fuse and Interactively Visualize Large 4D/5D Data Sets

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***Abstract*-This paper describes the development and main operational capabilities of a PC-based, geospatially enabled software that can fuse and visualize large, multi-variable data sets that change in space (x,y,z) and time (t). The new software has the ability to simultaneously visualize imagery, bathymetry/terrain, and true volumetric (voxel) data in a fully interactive geo-referenced mode. In addition to providing global coverage, a key feature of this software is the capability to interactively visualize large data sets while operating on a desktop PC. This is achieved by using tiling and Level Of Detail (LOD) technology for terrain, imagery, and volumetric data as well as compression techniques and the multithreading capabilities of modern PCs.**

I. INTRODUCTION

Never before in history has there ever been more data collected from sensors deployed all over the globe for scientific and military purposes. Data from these sensors are used in numerical models for oceanographic, environmental, meteorological, and many other applications. The size and complexity of data processed by these models has increased exponentially in recent years. Today it is common for simulations to produce gigabytes or terabytes of data containing multiple variables of interest that change in both space (x,y,z) and time (t). For example, the U.S. Navy is developing the capability to collect high fidelity (both spatially and temporally) environmental datasets consisting of volumetric ocean properties, ambient acoustic noise, bathymetry, sea bottom characteristics and multiple atmospheric parameters affecting ocean dynamics. With an increasing demand on the processing and visualization of these large data sets, scientists and the military are facing a fundamental problem in how to efficiently and accurately manage and interpret the vast amount of dynamic oceanographic and atmospheric data being collected and modeled.

Until recently, due to the lack of efficient tools to extract and visualize relevant features from these data sets, many scientific and military activities were limited to using sub-sets of the data, increasing the possibility of missing important and critical information. Furthermore, most data was, and often still is, being presented using sequences of multiple flat 2D images, which is a very inefficient and time consuming method to extract and analyze information. Therefore, it is critical that new technology be developed which can efficiently fuse and display a richer and more immersive representation of the data in order to improve understanding, whether it is for planning, modeling, simulation, or actual operations.

In the last few years, efforts to develop better tools to fuse and visualize oceanographic data have been on-going [1], [2], [3]. However, most of these tools are still limited in the amount of data they can load for analysis in an interactive mode. Systems that have the capability to render large data sets still rely on cluster and specialized hardware to run interactively [4], [5], and this has drastically limited their use by the general scientific community. Other well known, highly interactive software systems used to view large amounts of terrain and image data (e.g., Google Earth [6], Microsoft Virtual Earth [7], and NASA World Wind [8]) and the true GIS software (e.g., ESRI [9] and Intergraph [10] products) are still not capable of displaying large scientific data sets (e.g., volumetric data) that change in time. They are restricted primarily to display imagery, terrain, and 3D objects. For gridded, dynamic data, software packages such as Viz5D+ [11] and VTK [12] have been commonly used, sometimes combined with other GIS products [1]. However, interactivity is seriously hampered when large-size data sets are loaded. In addition, existing scientific programs were not designed to easily incorporate geo-referenced data such as large image files, elevation/bathymetry and the large number of commonly used GIS data.

II. MOTIVATION AND DESIGN SPECIFICATIONS

In addition to the limitations mentioned for existing visualization software packages, scientists are often forced to use a large variety of tools to pre-process their different data sets before they can input them into existing visualization and GIS programs. The shortcomings in existing data fusion and visualization technology motivated our desire to create a single product that would eliminate most of the above limitations.

For the last two and a half years, Makai Ocean Engineering, with funding from the Defense Advanced Research Projects Agency (DARPA), the National Defense Center of Excellence for Research in Ocean Sciences (CEROS), and the Office of Naval Research (ONR), has been working on the development of a PC-based software tool that provides interactive visualization of large amounts of time-varying volumetric data at interactive frame rates. The goal was to create a stand-alone software package that combines the visualization of imagery, terrain, and volumetric data (both scalar and vector) into a single geo-referenced environment.

Early in the developmental stage, specifications for the final software were established. Main requirements included:

- The ability to simultaneously visualize imagery, bathymetry/terrain, and true volumetric (voxel) data in a fully interactive geo-referenced environment;
- The capability to operate at interactive rates (>15-20 frames/second) while running in a PC environment;
- Be platform independent, operating on Windows, Linux, and Macintosh;
- The ability to efficiently fuse geo-referenced terrain and imagery data from different sources with different datum/projections, and create image and terrain tiles at a desired resolution;
- The ability to easily load multiple terrain and imagery tile-sets and perform quantitative analyses with them;
- The ability to load and render a wide variety of GIS formats and KML objects (e.g., buildings);
- The ability to render dynamic iso-surfaces and full volumes (i.e., voxel rendering) of large grids (> 512^3), including visualization of scalar as well as vector (e.g., flow) data;
- The ability to interactively fuse dynamic data from multiple volumes;
- The use of tiling and Level Of Detail (LOD) technology for terrain, imagery, and volumetric data in order to maintain interactive frame rates without a loss in data fidelity;
- Incorporate multiple tools for user interaction with the scene (e.g., distance measurement, cutting planes, slicing); and
- Be designed to be easily expandable into a web-based system.

Figure 1 summarizes the main visualization components of the software. The software is able to provide a complete dynamic operational view of the 4D environment by combining and rendering imagery, elevation, GIS vector and raster data, with multi-variable time-dependent data sets that change in both space and time.

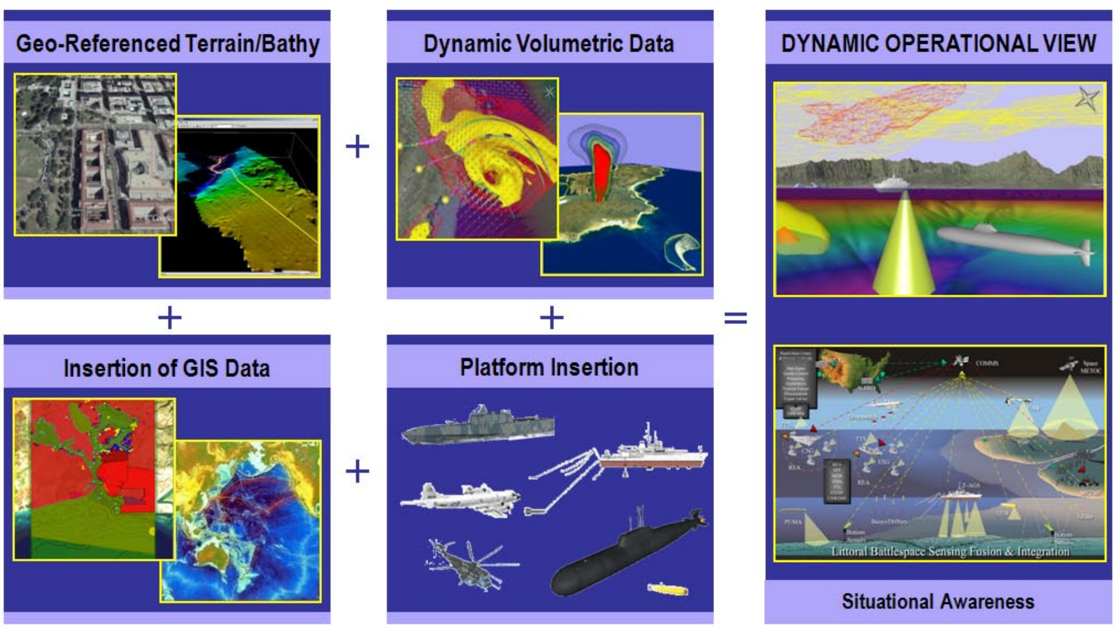

Figure 1: Software combines visualization of terrain/bathymetry, imagery, 3D/4D time dependent iso-surfaces and volume data, asset tracking, and a wide variety of GIS data; all in a complete geo-referenced environment.

III. Techniques Used

In order to combine terrain, imagery, and volumetric data while still maintaining interactive frame rates on a PC workstation, we made use of several important techniques, including:

1. **Efficient compression algorithms.** As an example, the upper left hand side of Figure 2 shows the same image at three different levels of compression for imagery. By using efficient compression algorithms, the software can achieve compression factors of almost 50 without noticeably affecting the quality of the image. Achieving high compression

factors allow us to improve loading speeds of the data. For elevation and volumetric data, lossless compression algorithms are used to prevent data loss after decompressing the data (these algorithms only produce single digit compression ratios).

2. **Multi-threading capabilities of today's PCs.** There are many different operations (I/O, compression/decompression, mathematical calculations for LOD, and rendering) which lend themselves to be executed in parallel. Makai's software has been specifically designed to take full advantage of multi-threading and multi-core processors.

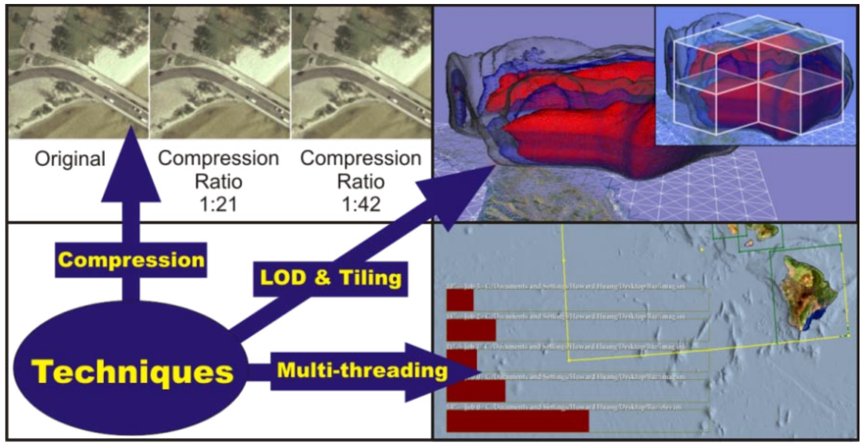

Figure 2: Techniques used to maintain high interactive screen rates include image, terrain and volume data compression, LOD and tiling, and multi-threading.

3. **Tiling technology for both 2D (terrain and imagery) to 3D (volume) data.** Large volumetric data sets are broken into "3D bricks" and several copies of each brick (each with a different resolution or LOD) are stored on the hard drive. During rendering, the software loads the proper brick with the resolution which is appropriate for the current distance to the viewpoint. This technique allows us to minimize the amount of memory required in the computer and the number of points rendered by the Graphic Processing Unit (GPU). In an interactive program, these mathematical calculations must be completed very efficiently since the scene is refreshed at ~1/20 sec. rates.

IV. Data Pre-Processing

Scientists are faced with the task of gathering and analyzing data from many different sources, each having different formats, resolutions, and areas of coverage. In addition, many of these data are provided in different datums and projections, and in some cases, no rigorous information is provided to properly geo-reference the data. To simplify the pre-processing of these data sets, the software described in this paper provides powerful, yet simple, tools that allow the user to resample and merge imagery and elevation data from a variety of sources in order to have complete coverage of an area of interest. These tools can be used to create Level-Of-Detail (LOD) files (a series of images/elevation files at various resolutions which are displayed depending on the distance from the camera viewpoint). Furthermore, they have the capability to import, display, and resample GeoTIFF and many other geo-referenced images, GIS vector data, and a large variety of elevation formats including: BT (VTP binary height-field format); DEM (USGS elevation format); DDF (data description format); GRD (surfer grid format); ADF (another USGS format); HGT (binary height-field format), DBDB-V (Digital Bathymetry Data Base Variable Resolution), and many others. If the terrain data is not originally gridded, several gridding techniques are available to the user.

In terms of software operation, adding elevation or raster images is a simple matter of dragging the image and/or elevation data onto the explorer window (upper left corner of Figures 3 and 4). If the data are already geo-referenced, the software will automatically recognize the datum and projection and will convert it to a Geographic coordinate system. For non-geo-referenced data, the user will be requested to provide some basic information to properly place the data. Once imported, the name of the data files will appear in the explorer window.

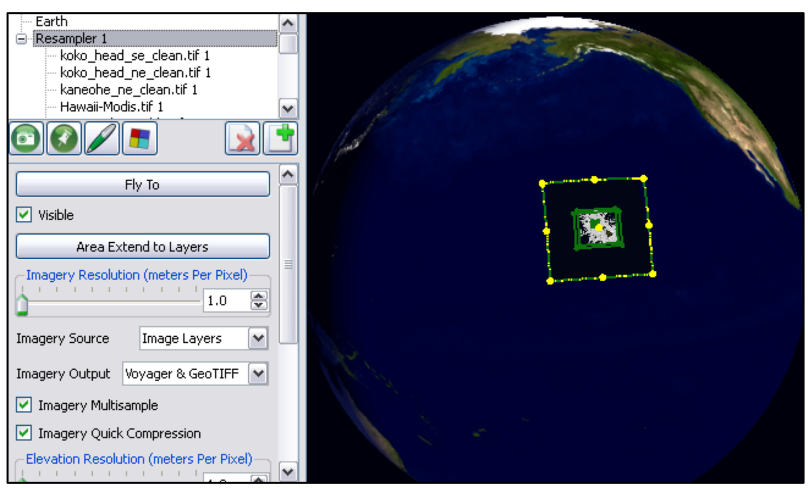

Figure 3: Screenshot of resampling tool.

The main view window will display thumbnail images and green lines outlining the extent (borders) of each imported file (Figure 4). Detailed information about each imported file (e.g., number of columns, rows, and resolution) is readily available to the user. Since data sets can overlap, the user is provided with the capability to assign priorities to each layer. Once priorities are set, the user selects the extent of the area to be resampled (yellow rectangle in Figure 4), the resolution of the final output (e.g., 1 m grid/pixel), and the desired output format. Optionally, the user can select denoising filters and compression algorithms to increase quality and decrease output file size. Finally, the user can select the number of threads the resampler will use to process the data (use of multi-threading capabilities of current PCs is used to speed the resampling process).

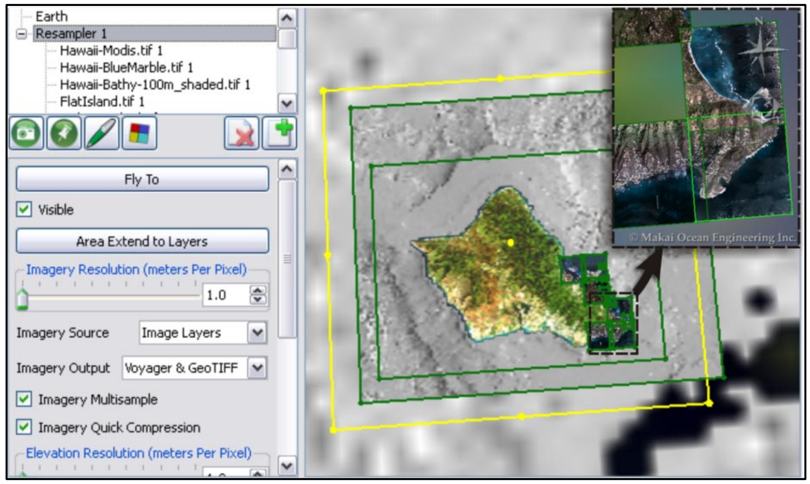

Figure 4: Example of overlapping GIS layers imported prior to resampling. The dark green lines represent independent GIS data, the light green boundary line (in the close-up inset) represents the currently selected data layer, and the yellow line represents the resampling output area.

To view the final resampled output, the user simply drags the output directory (containing the merged tile-set of both elevation and imagery) on to the main viewer. Once loaded, the software can also export geo-referenced output files (e.g., GeoTIFF) for direct loading into other GIS software.

Pre-processing times required by the data fusion/resampling process vary according to the size of the different input files and the size and resolution of the output tile-set. For example, a data set provided by a multibeam survey covering an area of 20 km^2 with a 0.5 m elevation grid size and having multiple, detailed side-scan imagery of the entire area can be processed in 3 to 4 minutes on a four-core PC. Processing 40 GB of imagery and elevation data (e.g., the entire Island of Oahu at 1 ft/pixel resolution and elevation data for the entire Island at 5 m grid) can be accomplished in approximately 6 hours. Adding and merging additional elevation or image data set into an already processed tile-set is very efficient since the software does not need to re-process the original data, but just merge the new data with the overlapping tiles.

V. Relevant Examples and Applications

In this section we present several examples to illustrate the capabilities of the new software.

GIS Capabilities: Figure 5 provides examples of GIS data loaded in the visualization software. A vector, S-57 nautical chart of Pearl Harbor can be seen showing depth contours (yellow lines) and several other attributes. The user has the option to add GIS vector data to the scene or he can select an option to rasterize the vector data (on the fly as the user navigates in the scene) and drape the rasterized GIS data over the terrain. In Figure 5, shape files showing roads (red lines) and parks (green polygons) have been rasterized on the fly and draped over the terrain. Currently, the software has the capability to load over 120 different GIS formats, including commonly used Shape files, several AutoDesk and ESRI related file types, and many more.

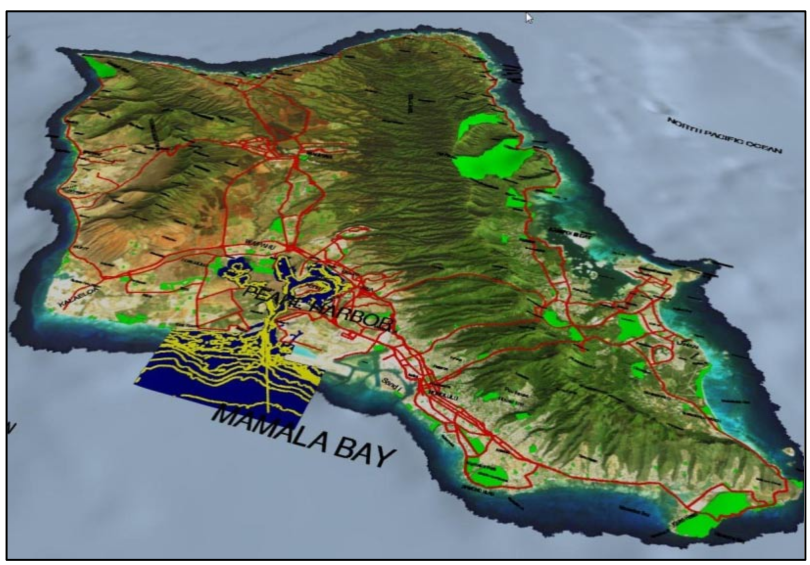

Figure 5: Example of multiple forms of GIS data loaded into the visualization software.

Extracting information from multiple Geo-referenced terrain and imagery: The software has the capability to load multiple elevation grids and images. Colors, opacity, contouring, and blending for each grid and image layer are controlled independently. An important feature of the software is that it allows the user to create and execute mathematical expressions between the different layers. In Figure 6, the user has written a simple expression (middle left section of the GUI window) to compare the values of two elevation datasets with different resolutions. The expression states to display red the areas where the product of the two elevation grids is negative (i.e., it fills the area between the Z=0 contours from the two grids).

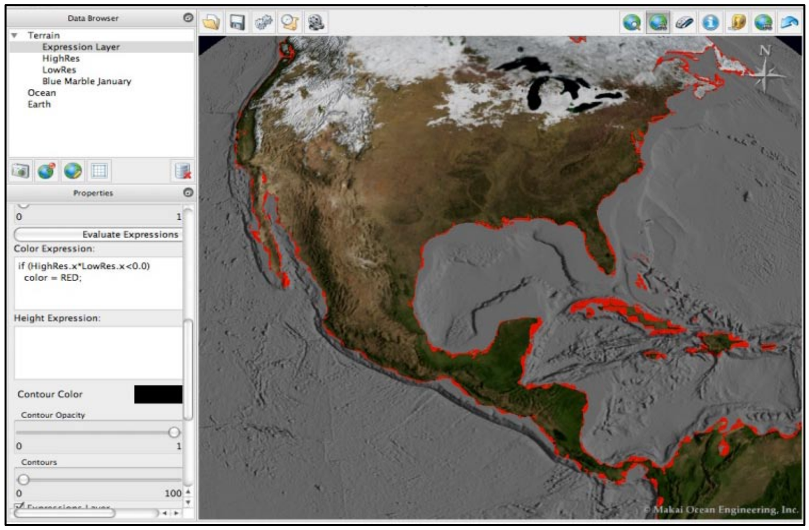

Figure 6: Screenshot displaying the area (red color) where two different elevation grids intersect near elevation zero (shoreline).

Combining Geo-referenced terrain, imagery and dynamic volumetric data: Figure 7 depicts a dynamic scene that combines 3D buildings, detailed imagery (1 ft/pixel), terrain (5 m grid), wind velocity vectors and two, time varying iso-surfaces representing different concentrations of a biohazard plume. The inset shows a time step of a flooding simulation. The software has the capability to simulate dynamic changes in elevation (e.g., ocean surface) by allowing the user to define multiple elevation grids that can either be superimposed or displayed in a time series. In addition, single or multiple image overlays can be readily imported in the scene if desired.

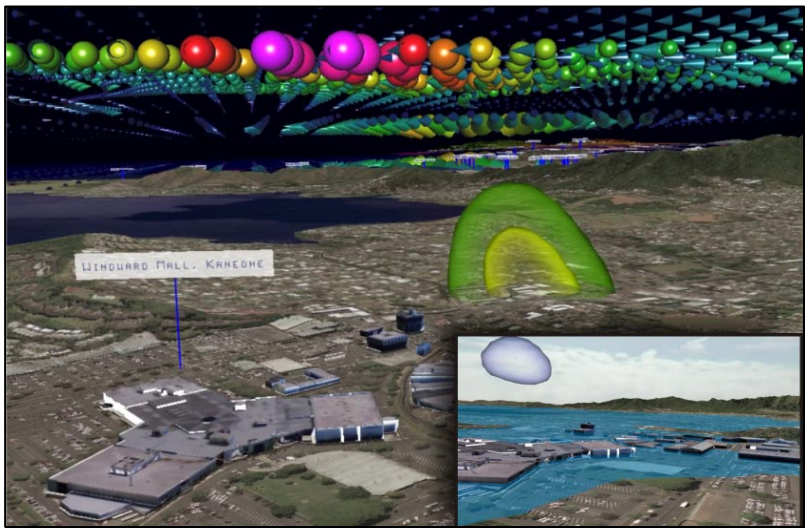

Figure 7: Screenshots displaying a combination of terrain, 3D buildings, and dynamic volumetric data. The inset shows an example of tsunami inundation.

Figure 8 depicts a screenshot of a dynamic simulation rendering terrain, bathymetry, a vessel showing sensor coverage, and dynamic volumetric data above and below sea level. The two iso-surfaces shown in the skyline depict a section of a dynamic grid (256x256x128) containing approximately 8.4 million points that change in space and time. Depending on the degree of interactivity and the rendering quality desired, different methods of rendering volumetric data can be selected by the user, including Slicing or Adaptive Ray Casting with or without pre-integration [13].

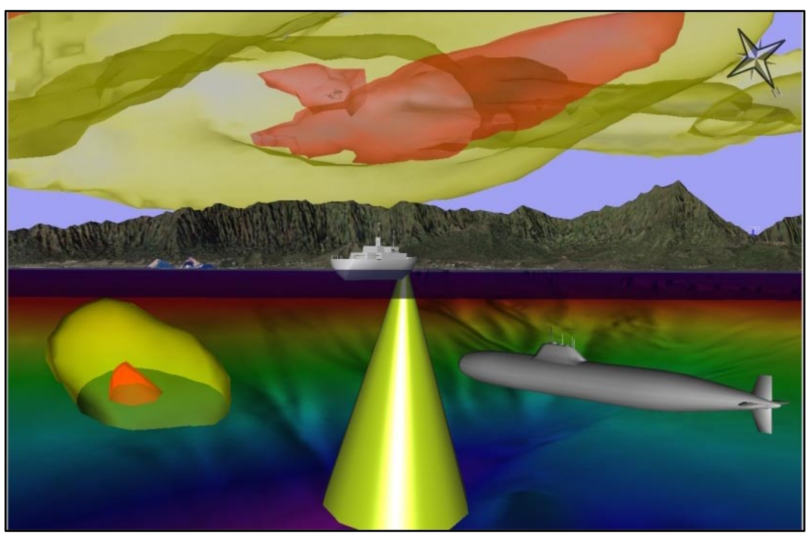

Figure 8: Dynamic simulation depicting terrain, bathymetry, volumetric data, and a vessel showing sensor coverage.

Figure 9 shows a top down perspective of two dynamic iso-surfaces representing two levels of precipitation over the Island of Oahu. Also, shown are small cones (glyphs) depicting the wind directions at each grid point and three cone-lines depicting the trajectory and speed of particles released at different locations. Given a flow field, the software is able to compute and display streamlines and pathlines at any location selected by the user. Elevation, bathymetry and imagery data of the Island of Oahu is shown in the background.

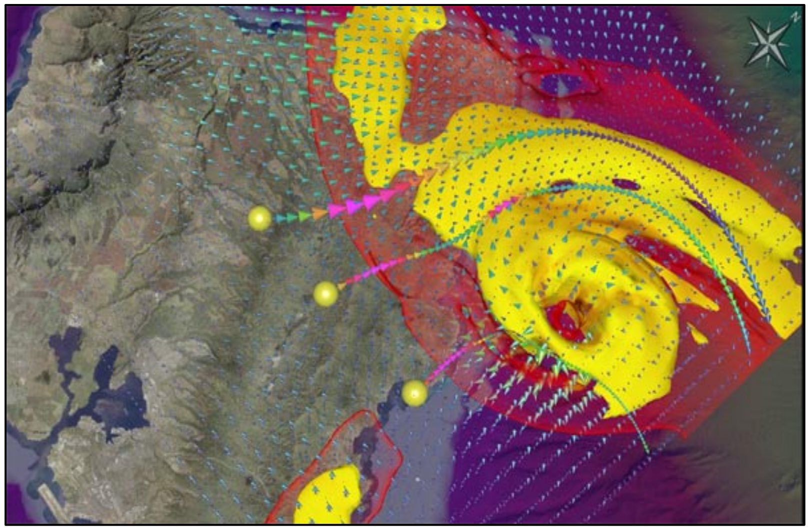

Figure 9: Top view screenshot showing two levels of precipitation and some pathlines over the Island of Oahu.

GPS data track importing: Figure 10 shows the tracklines of a Great White Shark (yellow line) and two different Northern Elephant Seals (red and blue lines) off the California Coast. A different color for each animal has been used to display the tracks. However, the user has the capability to color code the information as a function of depth or speed as well. Note the difference in tracklines between the shark, which maintains a constant depth, and the elephant seals which display a pattern of diving and resurfacing for air. Visualizing the position of the seals and shark as a function of time can allow researchers to detect patterns and potential correlations in their data which can lead to the creation and testing of hypotheses using more rigorous quantitative analyses.

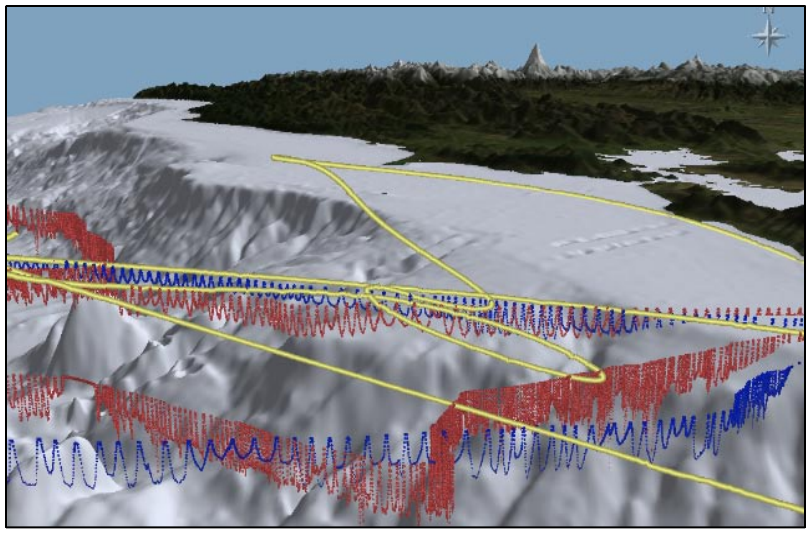

Figure 10: Trajectories of a Great White Shark (yellow line) and two different Northern Elephant Seals (red and blue lines).

Oceanographic data fusion: Figure 11 shows a single time step of a simulation generated by a Navy Coastal Ocean Model (NCOM). The "block" of Ocean Data shown includes multiple parameters:

- Sea surface elevation (contours every 10 cm);
- Surface currents (indicated by white arrows);
- A volumetric grid showing temperature distribution (values shown in legend); and
- A volumetric grid showing a narrow range of salinity values (shown in white).

While Figure 11 shows a single time step, the software can smoothly render an entire simulation with unlimited number of time-steps. [Note that the vertical coordinate has been exaggerated (user controlled) and the bathymetry has been turned-off to better visualize the ocean layers].

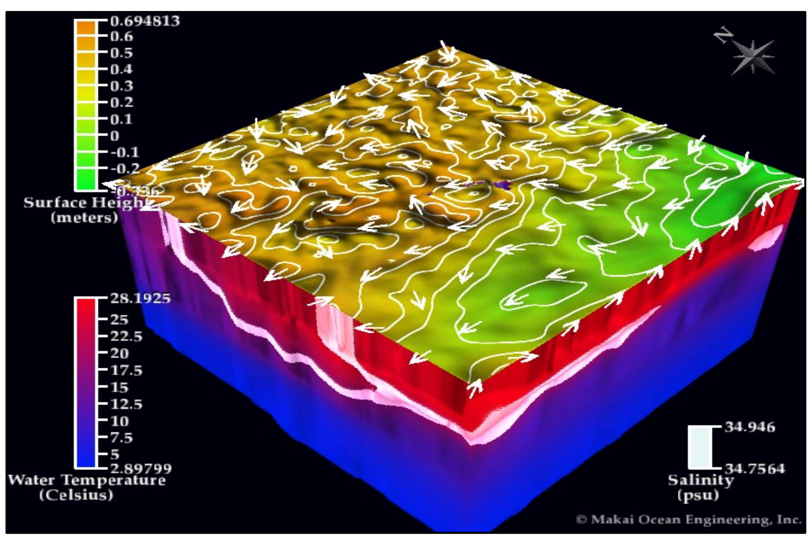

Figure 11: Sample output from the Navy Coastal Ocean Model (NCOM) including volumetric distribution of temperature, salinity, surface elevation, and currents.

VI. Interactive Fusion and Analysis of Volumetric Data

Numerical models typically output many parameters, each of which is evaluated at the nodes of a large predefined grid, and these simulations may involve many time steps. For example, a typical numerical model of a hurricane may involve the use of grids with 500x500 points in the horizontal plane, 50 to 100 vertical layers, and tens or hundreds of time steps for up to 10 different parameters (e.g., temperature, pressure, vapor, precipitation, wind speed components). Given the large amount of output data, it is critical that visualization software includes tools to quickly analyze and simplify the understanding of these data. Specific tools in our software include the ability to: (a) apply lighting and calculate gradients interactively, (b) use cutting planes and slices to better visualize the interior of a volume, and (c) show specific parameter ranges depending upon the values of other parameters (e.g., show the data within a range of temperature between 10°C and 12°C for those areas with a pressure range between 955 and 975 milibars).

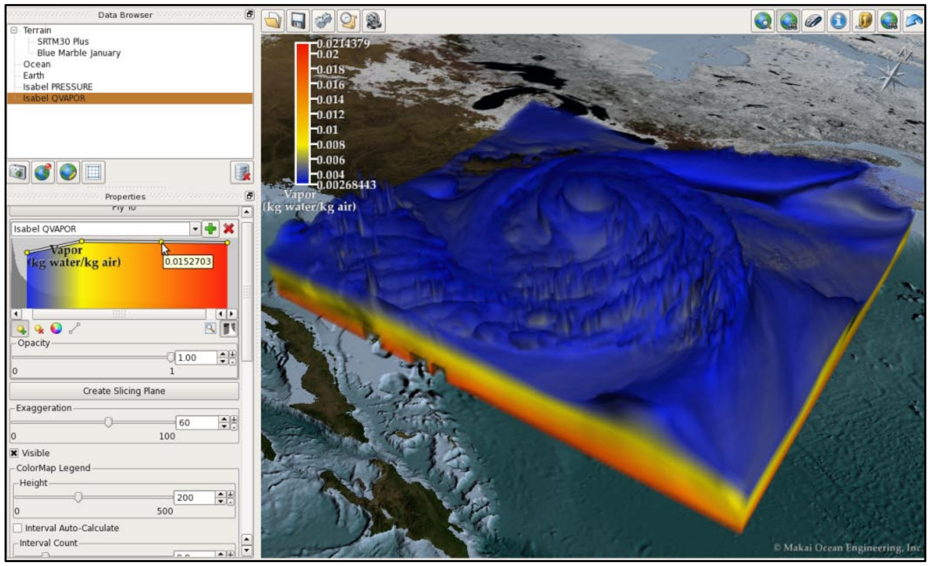

Figure 12: Colors and opacity control help provide a clearer understanding of the volumetric data.

The color map graph (the window containing the blue to red gradient on the left hand side of Figure 12) is a graphics-based-tool which is used to assign specific colors and opacities to a range of values for the specific parameter being visualized. In the color map graph, the magnitude values of the parameter being analyzed is represented in the X-axis and the opacity the user wishes to associate with the magnitude of a parameter is represented in the Y-axis (low opacity values make features displayed to be more transparent). As shown in Figure 12, the numerical values of the parameter analyzed are shown in the color legend on the main display and in the “tool-tip” legend as the user moves the mouse pointer in the color map graph. In Figure 12, the parameter “Vapor” output from a numerical model of hurricane Isabel in the Caribbean (the island of Cuba and Dominican Republic can be seen in the background in the lower left corner of Figure 12) is being visualized. By looking at the color map graph, one can see that high values of vapor have been assigned a red color and high opacity (i.e., not much light going through), whereas low values of Vapor have been assigned a blue color with somewhat lower values of opacity. If the user selected even lower values of opacity for low levels of Vapor, the blue color would be more transparent allowing for a view through the volume. Modification of the color map involves clicking on the graph to insert new points, dragging a point to change the slope of the graph between consecutive points, and changing the colors for each value range interactively by right-clicking in the color portion of the map and selecting a new color.

The software allows for the visualization of multiple parameters, each having its own color map graph. In Figure 12, Vapor was being visualized. To add another parameter, such as “Pressure”, the user drags the Pressure file to the main display window and a new color map graph will appear. The color map graph in Figure 13 shows that the user has selected to visualize a very narrow range of low pressures and has assigned a white color with high opacity to these values. The main display shows the superposition of the Vapor values (exactly as shown in Figure 12) plus the new values of low pressure in white. As one would expect, low values of pressure help to clearly define the “eye” of the hurricane.

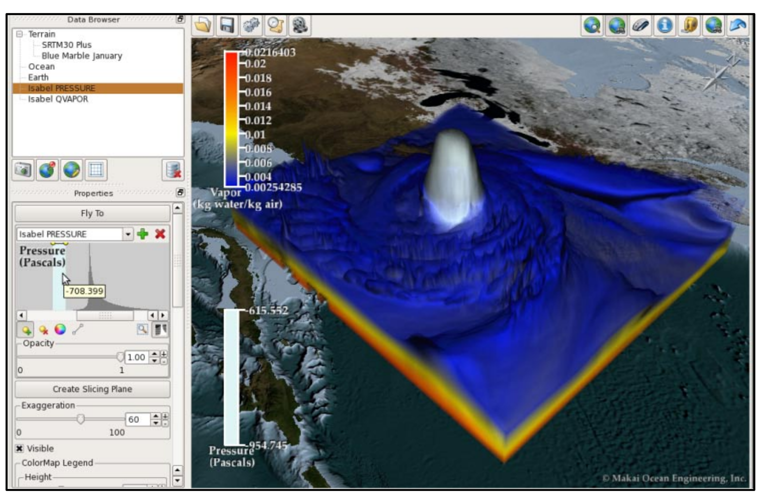

Figure 13: The variable Pressure has now been added in addition to Vapor. Note that only low pressure is being shown and clearly defines the “eye” of the hurricane.

Interacting with the data is also straightforward. For example, if the user drags the pressure range in the color map graph towards higher values of pressure (see color graph map in Figure 14), the user can interactively visualize how the pressure distribution changes inside the hurricane. Figure 14 shows the superposition of Vapor values previously used in Figures 12 and 13 with the new range of higher Pressure values selected.

In addition to superimposing multiple parameters, the user can also intersect multiple parameters which have a specific range of values (currently up to seven different parameters can be superimposed and/or intersected simultaneously). This is a particularly powerful capability of the software, as it helps the user to quickly draw conclusions concerning the relationship among multiple parameters. As an example, Figure 15 shows the intersection of the range in high Pressure values and Vapor values used in Figure 14.

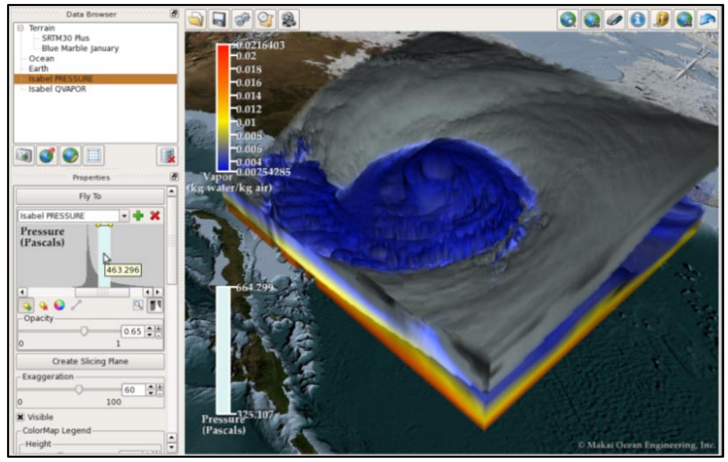

Figure 14: Both Vapor and Pressure are being visualized. Note that only a narrow range of higher pressure values is being shown.

Cutting planes, slices, and contours can also be used to gain a better understanding of the internal dynamics of a volume. Figure 16 shows the simultaneous display of two parameters (low pressure in white, and vapor in a blue-to-red gradient) with "contour lines" clearly visible in the vapor volume. When creating a clipping plane (Figure 16) or a slice (Figure 17), the user is provided with a 3D control (i.e., ball and an arrow) to modify the orientation and motion of the cutting plane. By clicking on the arrow, the user can change the direction of the slice around the ball in a 360° manner. Clicking on the ball and dragging the mouse moves the slice throughout the volume. By using these two controls, the user can position and orient the plane or slice anywhere in the volume, including slices positioned diagonally, vertically, or horizontally at a certain altitude through the entire volume. The user can also cut or slice through a specific parameter to create a "peeling-off" effect.

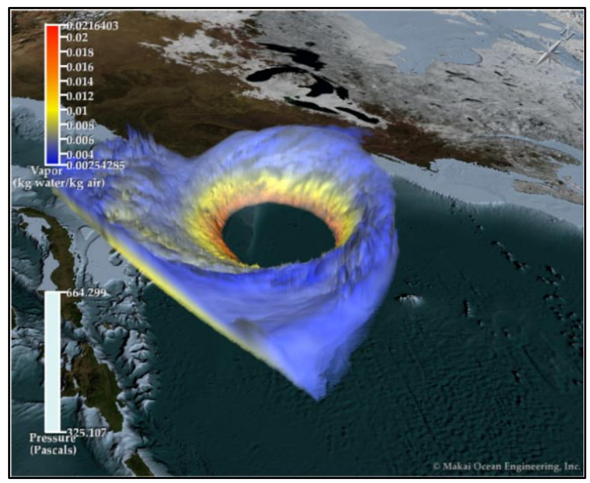

Figure 15: The "intersection" method is used to display Vapor only in areas of higher pressure.

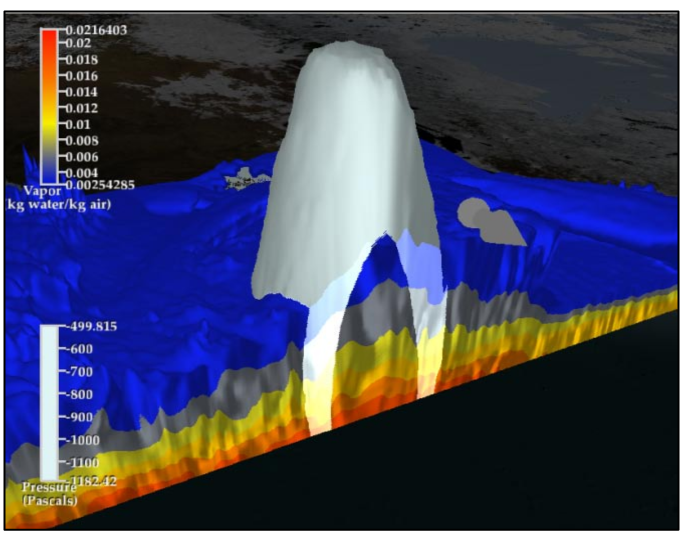

Figure 16: Screenshot showing a cutting plane through the eye of the hurricane. The user can interactively control the direction and location of the cutting plane.

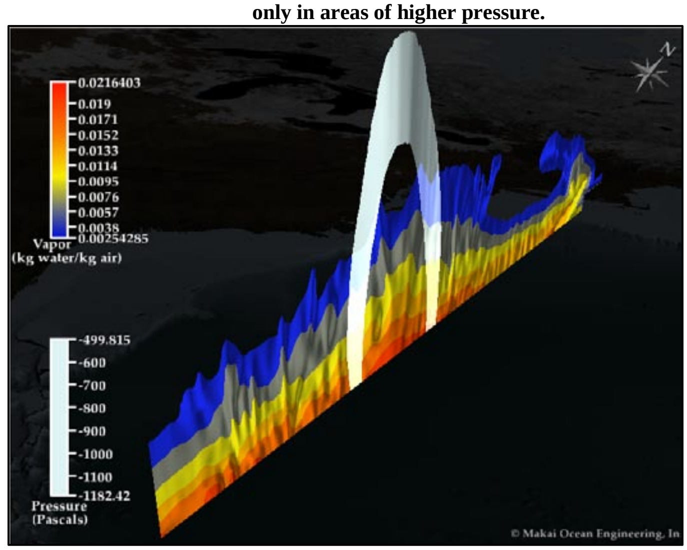

Figure 17: Screenshot showing a thin slice through the eye of the hurricane The white area represents low values of pressure and the blue-to-red gradient contours represent different values of Vapor.

VII. New Development

The initial version of the software requires that data is directly accessible by the computer running the software, either on disk or a local area network (LAN). For many applications, critical data are stored in off-site, centralized servers and not on the local PC. Makai Ocean Engineering is currently adding the capability for the software to connect to and remotely acquire data via Internet/WAN. In this case, the client computer will have the capability to remotely access terrain, imagery, and volumetric data from one of multiple servers. A variety of internet protocols (e.g., http, https, ftp, and sftp) will be supported. Several techniques (e.g., compression/decompression, LOD, pre-fetching in background, adaptive screen resolution) are being implemented to optimize network bandwidth in order to increase download speed.

VIII. Conclusions

1. Software has been developed that allows users to fuse and visualize, in a geo-referenced environment, multiple sets of time-dependent imagery, elevation and large volumetric data. The software is platform-independent and runs on PCs with minimal hardware requirements.
2. By combining into a single application some of the highly desirable features provided by popular geo-spatial tools (e.g., Google Earth, ArcGIS) and by allowing for the additional visualization of time dependent gridded data (typical of numerical models), it is expected that this development will help to fill a specific technology gap for fusing and interactively visualizing vast amounts of 4D dynamic environmental, oceanographic and atmospheric data. Any group wishing to implement a virtual scene to display data which changes in time and space could potentially benefit from this development.
3. The use of tiling and Levels Of Detail techniques applied to images, terrain, and time-dependent volumetric data has provided a significant increase in user interactivity when dealing with very large data sets.
4. The capability of the software to incorporate a large variety of GIS data (> 120 formats) and to allow the user to query for spatial data and render by attributes (as usually provided by standard GIS software packages) provides a powerful tool not usually provided by other scientific visualization programs.
5. The capability to interactively fuse dynamic data from multiple volumes using user defined transfer functions provides users with the unique ability to simultaneously analyze multiple parameters, and their relationships, as they change in both space and time. This capability will enhance productivity of users dealing with complex, volumetric data sets.
6. Extension of the current software to be able to retrieve data from remote servers via Internet/WAN will open the door for other applications in government and private sector markets, and will help enhance productivity and collaboration among different users in areas involving oceanography, meteorology, and general Earth Observing Systems (EOS).

Acknowledgment

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