Building the Visual Earth

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ABSTRACT

Over the past several years there has been a broad effort towards realizing the Digital Earth, which involves the digitization of all earth-related data and the organization of these data into common repositories for wide access. Recently the idea has been proposed to go beyond these first steps and produce a Visual Earth, where a main goal is a comprehensive visual query and data exploration system. Such a system could significantly widen access to Digital Earth data and improve its use. It could provide a common framework and a common picture for the disparate types of data available now and contemplated in the future. In particular much future data will stream in continuously from a variety of ubiquitous, online sensors, such as weather sensors, traffic sensors, pollution gauges, and many others. The Visual Earth will be especially suited to the organization and display of these dynamic data. This paper lays the foundation and discusses first efforts towards building the Visual Earth. It shows that the goal of interactive visualization requires consideration of the whole process including data organization, query, preparation for rendering, and display. Indeed, visual query offers a set of guiding principles for the integrated organization, retrieval, and presentation of all types of geospatial data. These include terrain elevation and imagery data, buildings and urban models, maps and geographic information, geologic features, land cover and vegetation, dynamic atmospheric phenomena, and other types of data.

Keywords: Real-time visualization, NEXRAD data, Doppler radar visualization, Global geospatial hierarchy, VGIS

1. INTRODUCTION

What we are proposing is not a typical, albeit very large, database organization for either geospatial or other types of data. Nor does it involve a typical interactive visualization capability. What we propose is rather a full integration of a comprehensive data organization with, and in service of, a complete visual interface. This will not be a transaction database of billions or trillions of disparate records with a fundamentally text-based query system. Rather we are proposing a system in which the database, no matter how large, appears to the user as a coherent whole. Queries do not retrieve individual records but rather enact streams of data. And the streams are appropriate to what is in view, at the relevant range and detail. The streams will adapt to user choices, such as navigation or selection choices, and they will be *contextual* rather than limited by the narrow confines of a query (unless that is what the user explicitly wants done). New forms of database organization will be necessary for this type of capability. They will have to be closely connected with the form of the visual result, or the streaming capability and the resultant interactive visualization will not work. The data organization will also have to handle more types of data than are usually handled in a single transaction-oriented database. These include, for example, not only terrain but also time-dependent atmospheric data; and not only simulational or acquired data from various sources, but rather a combination of data from all these sources. Further, new forms of visualization will be necessary that take into account the huge range of spatial and other types of detail, that can handle data that may be highly non-uniform and dynamic, and that brings together visualization tools of various types (e.g., point-based, surface, and volumetric) to produce common visualizations. The result will not be narrow and just for the purpose of visual display. We describe below how this integration can empower a much wider set of capabilities. It may even be that the approach of query by navigation, closely coupled to contextual visualization, can serve as a guide to other very large and complex collections of data [Die97].

One way to think about what we propose here is that it will be a revolutionary software advance that matches and makes use of the hardware and networking that will be available. We can expect before long highly compact, low power consumption computers with computing capabilities and storage capacities that far outstrip any desktop machine available today. A recently funded NSF ITR project, "A Petabyte in your Pocket," addresses this coming capability. There is no need to permanently place these computers somewhere. We can carry them with us or even wear them. On the other hand, if desired and assuming ubiquitous networking, we can scatter them all around. Such massive capacity means that a user can carry a huge database with her and be constantly augmenting this database. (A petabyte is a lot of storage; one could carry a highly detailed terrain model for the whole earth, maps for all cities, and a full-text copy of the complete contents of the Library of Congress to boot.) Full, advanced 3D graphics capability will be available on all these systems. Already NVIDIA, ATI, and other companies are producing 3D graphics chipsets for laptops that have the graphics capability of a SGI Reality Engine from 3 years ago. We can expect even more powerful graphics capability to be ubiquitous in the future, extending even to smaller more mobile systems such as wearables. Wide bandwidth wireless and mobile networking will be available in a few years, backbone networks will have next-generation Internet capabilities, and broadband to homes will be pervasive. The visual earth will fit this range of capabilities. The visualization interface will be deployable on the full range of computers from desktops to wearables, and ubiquitous networking will make it possible to access databases anytime from anywhere. Indeed the ubiquitous network will provide a two-way path so that the databases will become dynamic, constantly receiving updates from sensors or users. The strategy for querying the database and for sending data to it will be shaped by the user's capacity to carry or collect a significant amount of data. Finally, we can expect new interface devices that will ease access to even small footprint devices, which are nonetheless powerful. For example, there are displays with full color video (640x480) that clip on eyeglasses, and new multimodal interfaces using voice and gesture are being developed [Kru02]. Thus one can conceive of full interaction with a device that fits in one's shirt pocket.

In the following we first discuss some of the benefits of the visual earth approach and detail a specific example. We then give an overview of some of the applicable work that has been done and that reveals some of the visual earth's potential. We then describe what needs to be done to fully realize the visual earth, and we offer some concluding remarks.

2. BENEFITS OF THE VISUAL EARTH

1. Hurricane Project

Here is one example of the great impact the visual earth will have. Although predictions of where and when hurricanes will hit have improved markedly, forecasts of the intensity and structural changes as these storms hit land are still not good. Many times significant changes occur within 24 hours of landfall, which can greatly affect emergency response and evacuation plans. When a storm moves over a warm patch of water, as Hurricane Andrew did just before it slammed into South Florida in 1992, it can gain strength rapidly. On the other hand, passing over warmer Gulf Stream water and then colder coastal water, as Hurricane Opal did in 1995, can cause a rapid strengthening then weakening of storm intensity. Understanding and being able to predict these variations require understanding the relations of surface sea temperature (SST) boundaries and storm structure and then being able to measure the SST boundary behavior in detail. Further as the hurricane hits land it can spawn a complicated mix of tornadoes, storm surges, flooding, and other destruction, which must be tracked and, ultimately, predicted. Pinpoint accuracy is also needed to avoid massive dislocations, as precipitated by Hurricane Floyd in 1999, which neared category 5 intensity as it approached the Florida coast, causing the evacuation of millions of people. The storm then swerved abruptly northward and lost intensity before making landfall in North Carolina and causing the worst flooding in that state's history.

NOAA and NASA are undertaking a large scale effort to observe, analyze, and understand these largest and most complex of storms. This year two complete snapshots of active hurricanes will be taken in a region that will extend from the central Atlantic Ocean to the entire U.S. East coast. The observed space will extend over this region from the top of the troposphere, about 10 miles above the earth's surface, to 200 M below the ocean's surface. Air-deployed, geo-positioned instrument packages, subsurface ocean probes, airborne remote sensors, 3D Doppler radars, and weather satellites will collect data simultaneously during the snapshot period. This unprecedented collection of data will permit measurement of air-sea interaction processes and their effects on storm dynamics.

The visual earth will make possible collection of all these data in one place. Accurate terrain structure along the whole Eastern seaboard littoral region, including river basin structure, flow information, and storm surge data, can be brought into the same data organization. The preparation and retrieval of all these data for integrated interactive visualization also prepares them for fast retrieval for weather simulations, storm surge models, flood extent models, analysis for decision support (such as for evacuation or emergency response), and other uses. The retrieved data will be efficiently culled for a selected 2D, 3D, or 4D (including time) frustum, whether for simulation, quantitative analysis, or visualization. Continuous level of detail (LOD) mechanisms can be selectively applied preparing the data for model input, visualization, or analysis. If care is taken in developing the LOD method, these data can be appropriately approximated for any of these cases; error measures and, indeed, access to full resolution data will be retained. The navigable visualization can then be used to get overviews and detailed subviews of the correlated data and modeling results, significantly enhancing understanding of the particular results and increasing overall knowledge. Such a mechanism is being used in a weather visualization system now under construction that is combining real-time Nexrad 3D Doppler data with a mesoscale weather model and flood extent model for a more thorough visual analysis capability [Par01a, Rib01] than was ever possible before. The MM5 mesoscale weather model [Mic95] depends on terrain elevation details that are supplied by the visualization system geospatial database, which also supplies terrain types and elevation information to the flood extent model. The latter combined with rainfall measures from the Doppler radars and other sources provides not only flood height measurements but flood *extent* measurements, which are usually not available and are essential to determine what will be flooded and who must be evacuated.

If one adds the capabilities of a geographic information system (GIS), users can find exactly who and what will be in the path of a hurricane or flood and take action accordingly. Since the system can also contain road information, locations of essential services such as hospitals and electrical plants, locations of dangerous facilities such as chemical plants or sewage treatment plants, the visual earth can be the comprehensive resource for prediction, observation, planning, and decision-making.

2. Other Benefits

The benefits of the visual earth are manifold. As with any novel and powerful capability many new benefits will arise that are now unforeseen. Among the areas likely to benefit are education, weather forecasting, urban planning, emergency response, tourism, military operations, traffic management, construction (especially large scale projects), pollution analysis, various geo-located and mobile services, citizen-government relations (when complex civic projects are vetted), and others. Research will be profoundly affected by being provided knowledge and power that was not available before. The severe weather example shows this. The integrated database provides information for present and future weather models of far greater detail and accuracy than is usually available. The ability to collect weather events into a visually queryable form will result in unprecedented analyses of the effects of terrain features, waterways, and human activity and structures. When the data organization and the visual interface are made available via the Internet, there will be a much broader, more diverse, and more vigorous research activity than was ever possible before.

Consider the benefits to education. The visual interface, annotated with names of countries, towns, rivers, lakes, mountains, road, and brief information about indigenous people (all gleaned from a GIS database), will offer a more direct and more vivid representation of geography, geology, land use, and geopolitics than was ever provided before. Much of the terrain can be presented with richly colored phototextures and, where relevant, maps can be activated. The act of navigation or of selecting a precise viewpoint to look around will give a sense of scale and a feeling of "being there". One will see that Zurich is on a plain that rises south to the Alps or that Amsterdam is criss-crossed with canals (and that much of Holland is at or below sea level). Students will see that Russia covers 10 time zones of diverse topography but that Belgrade is less than 200 miles down the Danube from Budapest and 300 miles from Vienna. They will see land-locked Afghanistan and its mountainous borders with Pakistan. They can fly over to view where the mountain gorillas live on the volcanic slopes in Rwanda; observe how they move; how they are being overrun by war and encroachment. They can see how the tectonic plates move, causing earthquakes in California and volcanoes on the coast of Asia. Then, too, they can see how this movement has jammed India into Asia, crumpling the northern highlands to form the Himalayas. With the Internet, personal computing with 3D graphics, and appropriate data organizations, this navigable visual display and the knowledge it reveals are available not only to school children, but to their parents and everybody else.

3. WHAT HAS BEEN DONE

There are several avenues of research that could provide a foundation for building the visual earth or that show the sorts of applications that would result. We present some general examples; the interested reader can look at the referenced papers for other work.

Our group has done extensive work on developing a global geospatial hierarchy for terrain and buildings [Dav98, Dav99, Fau00] and on developing view-dependent, continuous LOD methods for displaying complex terrain while retaining good visual quality [Lin96]. Both capabilities are necessary for the visual earth: an appropriate global hierarchy provides a scalable structure and an efficient, geo-referenced querying mechanism; and a view-dependent continuous LOD method provides a means to manage what could be overwhelming while ensuring that the visually most important items are displayed. Figs. 1 and 2 show some results using this approach. *(All figures are at the end of the paper.)* Fig. 3 shows the effect of using view-dependence, which must be calculated on-the-fly as the user's viewpoint changes, for a method similar to the above method developed by Hoppe called "progressive meshes" [Hop98]. The main difference between the two methods is that we use a regular mesh of terrain elevation samples [Lin96] whereas Hoppe uses an irregular mesh. A significant outcome of the global hierarchy approach and the continuous LOD approach is that one can formulate an efficient paging and caching strategy for data residing on either local or remote disk storage [Dav98, Dav99]. This is necessary because huge models (such as the whole earth!) cannot reside in memory; pieces must be moved in and out as needed. Standard operating system virtual memory can be abysmally poor for this "out-of-core" process [Cox97]. The hierarchical and LOD structures permit data to be quickly retrieved and transmitted in digestible chunks, at just the resolution that is needed for the current view.

There is work that has been done to significantly enrich display of detail in geospatial visualizations while maintaining interactivity. These rely on the 3D graphics capability that is now becoming available even on laptops and will soon be ubiquitous. For example, dynamic textures on terrain can provide significantly increased feature detail and even high resolution animations of changing detail, such as flood patterns [Dol00]. One can also use effectively placed background images to efficiently render complex urban scenes [Sil97]. In this case impostor structures are introduced that combine view-dependent background images, appropriately distorted for perspective, with 3D geometry. The images are changed if the view changes too much.

Acquired data are giving geospatial databases new richness. There is now the capability to obtain these data on-the-fly. Technologies such as LIDAR permit an airplane to collect large sections of a city with height resolution of an inch or two and lateral resolution of a foot. Overhead imagery from aircraft or satellites is often at meter resolution or less for large areas. Now there are methods to collect and automatically process data at ground level as one moves through urban areas. Früh et. al. [Fru01] use a calibrated laser range finder and camera system mounted on a truck that is driven up and down city streets. Through a set of clever analyses they can get quite accurate absolute and relative positioning of streetscapes over several blocks. These produce impressive and potentially very large 3D urban scenes. A different approach with a similar goal has been developed by Teller [Tel98]. Here accurate view and location information is used to extract 3D urban information from a sequence of images. A mobile apparatus is used for the collection. Ultimately complete models will require the combination of all these sources. But what has been done shows that accurate detail can be collected and automatically processed. When perfected, techniques like these will provide an avalanche of urban detail. Among other things they will change how we think of our urban datasets; they can be continuously updated as the urban scene changes. (This point is made with shocking force by freshly collected LIDAR data, which shows the current 3D structure of the World Trade Center complex, including piles of rubble [Tim01]. These data are being used to plan recovery and salvage efforts.)

Another significant modality of acquired data is atmospheric phenomena collected by various weather radars, satellites, and so on. In the USA, the NOAA runs a network of 160 Doppler weather radar sites called NEXRAD radar. Each radar station collects a volume of radar reflectivity information that measures the general intensity of precipitation and the velocity of that precipitation. The volume of data is collected by sweeping the radar beam around the compass at a number of elevation angles from horizontal. When a storm is brewing, the radar collects data at 0.5°, 1.5°, 2.4°, 3.3°, 4.3°, 6.0°, 9.9°, 14.6°, and 19.5° elevations, out to a radius of 230km. The radar gathers a new volume of data every 6 minutes.

To display radar imagery, we have developed a real-time volume rendering system that allows the user to interactively examine the volume of radar reflectivity (see fig. 4). We use the *splatting* method of volume visualiztion [Wes90], because it fits well with the OpenGL forward polygon rendering system. In the simplest form, we take each data sample, and render it with a square that is rotated to face the user, is textured with the image of 2D Gaussian function in intensity and alpha channels. The square's color is assigned according to the data value from a color lookup table. The visual effect for each such splat is a circular blob that is opaque in the center and gets more and more transparent near the periphery. The semitransparency of each splat allows objects behind the current splat to be partially visible. Fig 4 shows the accretion of many such textured splats as the entire volume is rendered from farthest to nearest the viewer.

In order to manage the large volume of radar data, we have developed a hierarchical data management structure that allows new Doppler radar readings to be read in and visualized. The atmospheric volume is first organized into 2D blocks that align with latitude and longitude boundaries. The Earth is subdivided into 32 45° x 45° zones. Each such zone contains a quadtree hierarchy, which subdivides the zone by 2 in each dimension along lines of latitude and longitude. When the size of the ground area represented by a quadtree node is the same as the height of the atmosphere, we start subdividing 3D space using a hierarchy of octrees. Each octree node subdivides the atmosphere evenly along latitude, longitude and altitude, and represents the mean of its child values. To create an octree for the Doppler radar, we subdivide the atmosphere as we read in and locate each radar sample in space. The fixed layout of the radar scan pattern allows us to generate an octree that has a stable structure as new data flows in. The octree structure is used to generate levels of detail based on the projected size of the octree node on the screen. Thus, when the viewer is far away, we render Doppler radar values that cover large volumes of atmosphere. This allows us to readily access the level of detail appropriate to the task, and to manage data in a flexible manner.

4. WHAT NEEDS TO BE DONE

To complete the visual earth a number of things remain to be done. Several promising steps have been taken in this direction, as outlined above. However, no one has connected data on the scale of the visual earth to an interactive visual interface, and no one has dealt with the scope and variety of data and applications that the visual earth will encompass.

1. Scaling to Databases of Unlimited Size

Much work has already been done on this in the geospatial and GIS realm. The development of hierarchical structures and in particular quadtree-based structures are of use here. However, as described above, the visual earth requires specialized data organizations that, although similar to the traditional geospatial hierarchical structures, are appropriate for treating the entire database as a coherent whole and navigating it continuously with progressive and integrated levels of detail relevant to the view or the application. These require interlinking between nodes so that data can be streamed to support interactive navigation. They require a strategy for making a visual query deliver data in chunks appropriate for immediate, fast visualization. Such chunks might be mesh blocks for terrain, texture patches for photo imagery, cells or splats for volumetric data, and so on. Each of these representations must be tuned for integrated visualization where only those things in view are loaded, at the relevant level of detail, into the display list or scene graph. All aspects of this structure must scale to terabytes of data or beyond while retaining query times that remain constant or nearly so. Since queries are at best Log (N) where N is the number of levels in a geospatial hierarchy, new approaches must be taken in building the unlimited scale structure, and parallel query methods may be necessary. Additionally, there is the issue of organizing and handling the individual chunks or pages of data as the number rises into the millions. Uniquely labeled files and file structures have been applied successfully to geospatial hierarchies [Fau00], but it is unclear how well standard operating systems will handle these as the number of files grows into the millions.

There is the additional question of building and maintaining such datasets since they will not only be very large but will become dynamic in the visual earth environment. Incrementing the dataset must itself be scalable, depending only on the footprint and size of the data to be added. Further, the incrementing process must be fast enough so that fully dynamic data, such as data continuously collected from 3D Doppler radar and other weather sensors, must be organized and inserted in real-time to avoid clogging the collection system. This may require parallel, distributed data processing. Finally, the data representation must be compact yet capable of fast access. The hierarchy provides a uniform data structure that can extend down to the leaf nodes, depending on data type and the approach used. The uniformity provides compactness. However, sometimes uniformity is not achievable, and alternatives must be found to maintain data compactness. Data compression techniques can also achieve significant space savings; but here one must be careful not to slow down fast retrieval.

We have addressed some of these issues for a global geospatial structure containing terrain elevation and imagery data and buildings [Dav98, Dav99]. However, the details and consequences of full scalability must be explored much more thoroughly.

2. A Universal, Dynamic Data Organization

As discussed above, we can expect data to be even more dynamic in the future, and the data organization must handle this dynamism. Microscale sensors are being developed, with the support of DARPA and other funding organizations, at university and commercial labs. Eventually these will be available for general use and will provide large quantities of geo-located data about changing environmental conditions. Automated methods [Fru01, Tel98] are being developed to extract and combine changing or static 3D information from airborne and satellite imagery, range-finding sensors, and other sources. Cameras will be smaller and wearable, so we can expect geo-located, wired users to be mobile, personal collection platforms. All of this means that the data organization cannot just be for archiving static data, it must also be for receiving and digesting real-time data as it is acquired or generated.

A data organization of unlimited size should be considered distributed. A client-server architecture would seem applicable. But this architecture doesn't appear entirely appropriate to the visual earth environment where individual users (or acquisition sites with collections of sensors) may be collecting and sending out data, in effect acting as their own servers. A peer-to-peer model might better fit this situation with its much higher two-way communication. But some of the peers should be recognized as having more resources, or more of a certain type of resource, than their neighbors. They would be "server peers", and the best model may be a hybrid between the two architectures. No one, not even the server peers would have a complete collection of data. Indeed a complete collection could never exist since new data would be added all the time. However, it should be possible to construct a universal data organization, or organizing plan, such that everyone who collects data would know where to put it and, likewise, everyone would know how to retrieve a particular piece of data at a particular location. This universal plan would include a unique way of labeling any piece of data according to its location, type, and the time for which it was acquired or generated (this includes both real-world time and simulation time). The label would contain information about where the data element resides in the hierarchical structure and must take account of the extreme range of scale involved, from hundreds of kilometers to millimeters. Of course, the data elements must be aggregated at a level that balances between the flexibility of using small data chunks and the economy of scale of retrieving and using large collections.

3. Mobility

Such an environment serves distributed and mobile usage and dynamic data organizations. A mobile user who is collecting geospatial data knows both where to put it in her personal data structure and where it should go in the larger data organization, perhaps being maintained by one or more peer servers. The peer server could be chosen by where the new data resides in the overall structure (e.g., a server that maintains high resolution data for the Western U.S.), by whether the peer server is located in the mobile user's neighborhood, by the type of data collected, or by other procedures. The mobile user might also transmit data either directly to members of its group and/or to the appropriate server, which could retransmit or just await requests. Also, peer servers, mobile users, and other distributed servers and users might have redundant, overlapping, or their own unique datasets. *The point is that the* *universal data structure that is the foundation on which all these capabilities could be built. This data structure is virtual, but any part of it could be made real.*

4. Continuous, Progressive Levels of Detail for Data of all Types

A progression of LODs that lead, with a view-dependent, perceptual metric, to smooth and continuous images as one flies through has been successfully developed for both regular [Lin96] and irregular terrain meshes [Hop98,Kra02]. The former has also been extended to the scalable organization and visual navigation of global terrain. This powerful visual query mechanism should be extended to other types of geospatial data as well. As discussed in the last section, one can fit other types of data into a quadtree-aligned structure and thus take advantage of experience gained in developing the terrain data organization and visualization. One can also use some of the same hierarchical components. We have done this for buildings [Dav99]. However, one must go much farther to mold a structure that can handle the extraordinary amount of building and other 3D data that are or are about to become available. Lidar and laser-range-finding methods, as discussed above, are producing citywide data that can be collected on-the-fly and automatically processed. These, combined with a variety of image processing techniques, will make available vast amounts of 3D, textured data. We will need new data organizations and new detail management techniques to support continuous visual navigation from citywide overviews to details on the walls of buildings. There has been some work on citywide views [Sil97] and on detailed collections of buildings [Dav99, Fru01] that provide the basis for possible solutions. But no work has been done connecting these techniques together so that one can switch smoothly, for example, from detail management on the walls of buildings to city blocks and then to citywide views. So far these have involved quite different ways of handling detail, which must now be integrated. Note, too, that one can have the challenging circumstance where building details, block views, and the cityscape can all be visible in the same scene. Indeed terrain and atmospheric features could also be visible. If we can solve the problem of going efficiently and automatically from data collection to data storage and visualization, we will have usable dynamic databases that can be updated automatically and immediately whenever a building or other feature changes and then made immediately viewable. Such a capability will offer great power.

Beyond the acquired building data, there are great amounts of engineering and architectural data for buildings, bridges, and other city features. These CAD models, when considered with associated data with which they are linked, hold a great wealth of knowledge. Cities such as New York have block-by-block data of this type for large downtown sections. These models are completely divorced in their formats and in the amount of detail they contain from what is available for interactive visualization (even though the CAD models are sometimes used for non-interactive fly-throughs).

Beyond terrain and buildings, there is a growing amount of 3D acquired data. Many of these data are time-dependent. They come from atmospheric measurements such as the Nexrad 3D Doppler radar for severe storms or atmospheric and weather simulations of various types. There are also vast amount of seismic data for oil exploration and other types of data acquired from underground exploration. All these data have different spatial formats, some of which are highly non-uniform and dynamic. *There should be a general effort to include acquired 3D data of all types into the visual earth.* As described above, having them available with other geospatial data for visualization, simulation, or other analysis provide important new capabilities in understanding the phenomena they represent. Adapting these data to the global hierarchical structure and then providing mechanisms for handling detail for the specific data types and formats is one starting strategy. Some work along this line has been done for weather data [Rib01]. However, much more work must be done to develop efficiently scalable structures that fit alongside terrain and building structures. Development of specific techniques for detail management, which should have a view-dependent component for interactive visual navigation, has in most cases not been begun. The hope would be that, even as data must be displayed in a common visual environment, the methods that produce these results would also be found to be similar, even for different types of data.

5. Comprehensive Detail Management

To produce interactive visualizations and to produce efficient queries that provide just the right data at the right time, the details for the different types of data must be managed together, not separately. Building, weather data, and other data types must be managed together with terrain if one is to attain interactive visualization of all these.

No comprehensive approach to detail management has been developed, and this will be complicated by the scale of data involved. A comprehensive approach must contain common measures, some of which will be view-dependent measures since an important goal is to provide a common, high-quality picture of the data and the outcomes for such a goal are at some point the same. A complete solution must go beyond the visual properties of data to how important they are. Of course, importance can be adjusted depending on the need. There is some promising work that combines measures of importance and visual quality with maintaining interactive visualization [Fun93], but it has not been applied to highly diverse and complex environments. Beyond this some feature-based approach is needed. Thus in certain circumstances it may be important to retain features such as the precise location of a valley between mountains, the details of a coastline, or the shape of small but destructive storm cells, using measures beyond those for visual importance. There has been some promising work on comprehensive detail management that includes features, but this is only a beginning and much more work must be done.

6. An LOD Strategy Appropriate to Diverse Applications

The visual earth gives primacy to interactive visualization, and that should be part of any application. However, this confluence of data and data types is quite powerful and can boost many applications. There are many general benefits for a wide range of applications in having data from many sources available in one common and scalable data organization with fast query and retrieval. Levels of detail will also be generally useful. Likewise the ability to reach back to the original and highest resolution data, when needed but only for the area needed, will permit precise and focused calculations and analysis. There should be a general effort to build new, novel applications on this powerful capability. (An example application, as discussed above, would combine the terrain database with weather and flooding simulations and then visualize the results together.) But to make this powerful combination of data fully available to the variety of applications that can use them will require extensions to the data organization and, more deeply, a general understanding of how the different types and structures of data for different applications are related. In some cases resampling or reinterpretation of data may be necessary to ensure fast retrieval, visualization, or other capabilities. This is certainly true of the LODs, which will not only provide interactive visualization but also such things as progressive transmission of data and condensed forms. To be fully useful to the many applications that could use them, research must be done on the levels of approximation and uncertainty introduced in using these forms. Such research will be most useful if general principles are developed that apply to a wide range of applications.

GIS is one application area that should obviously be developed. Our VGIS global geospatial visualization environment [Dav99, Fau00] recognizes this and provides access to GIS databases. However, much more can be done. The visual earth can provide a powerful interface and the data organizations can offer a more complete and comprehensive data collection than ever available before. Much work must be done, though, in developing ways to efficiently support the types of queries that are typically done in GIS systems. In addition, online mapping systems and similar environments fall naturally into the visual earth environment. Indeed, the visual interface provides a much more powerful means of accessing and navigating maps than is available now.

7. New Visualizations and Tools for the Visual Interface

As we have argued throughout this paper, visualization tools must be intimately connected to the data organization and the progressive detail structure. In particular we need methods that support interactive visualization with scalably large data. Tools may deal with point, surface, or volume data—all 3 will be needed for a complete visualization capability. Point-based rendering systems, for example, have been applied to highly detailed 3D models derived from acquired data [Rus00]. A natural progressive LOD framework can be developed that produces fast visualization and highly detailed rendering. Such methods could be applied widely to, for example, isosurfaces in volume data or surface details on 3D models. However, point rendering is not effective in rendering flat surfaces; the best approach would be a hybrid between point and polygonal methods.

As Jim Foley states [Fol00], we must fill the gap between image-based and geometric modeling methods. Imagery via textures is still the most effective way of presenting high detail. New image-based methods such as layered depth images [Cha99] or video painting offer new ways of navigating 3D scenes or embedding real-time imagery into 3D environments. Beyond this there is a significant need for new work in applying "abstractions to realism" in visualization, perhaps by applying concept from the visual arts [Kir99] or other fields.

Volumetric rendering methods must be significantly extended from what is available now. There are few interactive methods that can directly handle non-uniform data. Yet most of the volume data in the visual earth will be non-uniform and will be dynamic as well. One could, for example, apply image-based methods [Cab94] to resampled data, but there would be an effect on accurate data rendering and visual quality that could be unacceptable in many cases. Splatting [Swa97] can provide heightened detail and reasonably good interactivity with hierarchical structure for handling large scale data [Lau91]. However these methods have not been extended to non-uniform data and not much work has been done with time-dependent data. It is important to extend volume rendering methods, such as splatting, to general non-uniform data and a view-dependent approach.

5. CONCLUSIONS

We have presented here the arguments for developing the visual earth that builds upon but significantly extends the ideas of the digital earth. The visual earth would provide for the visual query, exploration, and analysis of massive geospatial data stores. The goal is to combine geospatial data of all types, whether on the earth, in the atmosphere, under the water, or beneath the ground into a common hierarchical structure with common metrics for visual display. The benefits of such an approach are manifold and extend to many application areas. New capabilities will grow out of the visual earth that were not possible before. In addition there are new sources and types of data, coming from sensors and data acquisition systems or from simulations, that will make the visual earth more up-to-date, comprehensive, and dynamic than possible with previous geospatial approaches. Recent research indicates that the goals of the visual earth are feasible. However, much further work must be done in the areas of a universal, dynamic data organization for very large amounts of data, new and comprehensive detail management strategies for data of all types, methods that support providing the right detail not only for visualization but for other applications, new visualization tools closely coupled to the data organization, and other areas.

6. ACKNOWLEDGMENTS

We would like to thank the members of the Data Visualization Group at the GVU Center, Georgia Tech, for their help in developing several of the examples and ideas presented here. These include David Krum, Justin Jang, Mitch Parry, and several graduate students.

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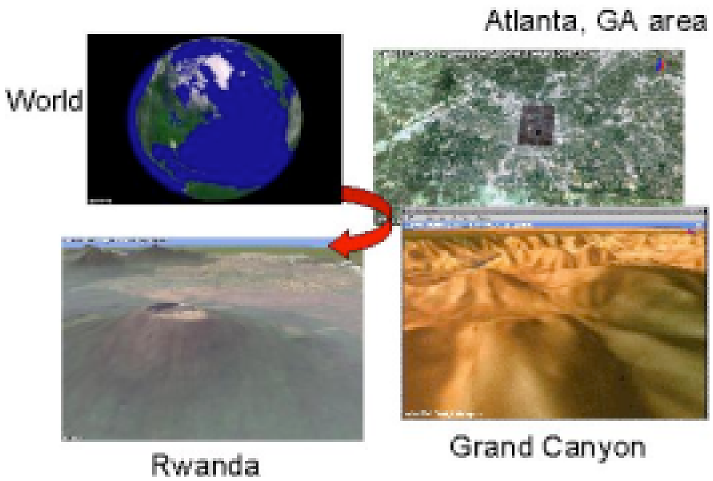

Fig. 1 Views reached by continuous navigation in the VGIS global geospatial system. [Fau00]

Fig. 2 3D models of cities visualized in the VGIS global geospatial system. [Dav99, Fau00]

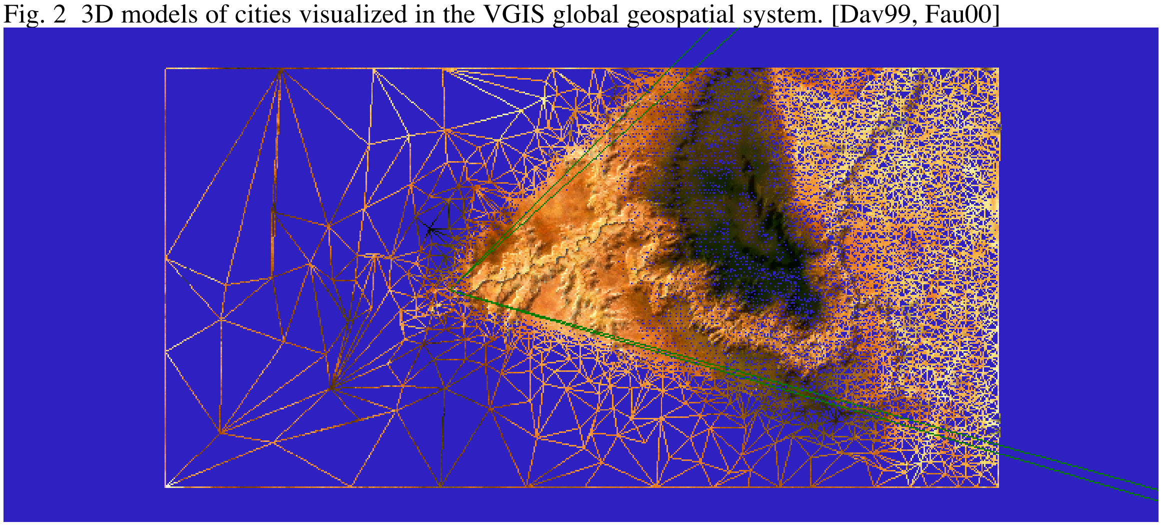

Fig. 3 View-dependent LOD showing the heightened detail within the view frustum. [Kra02]

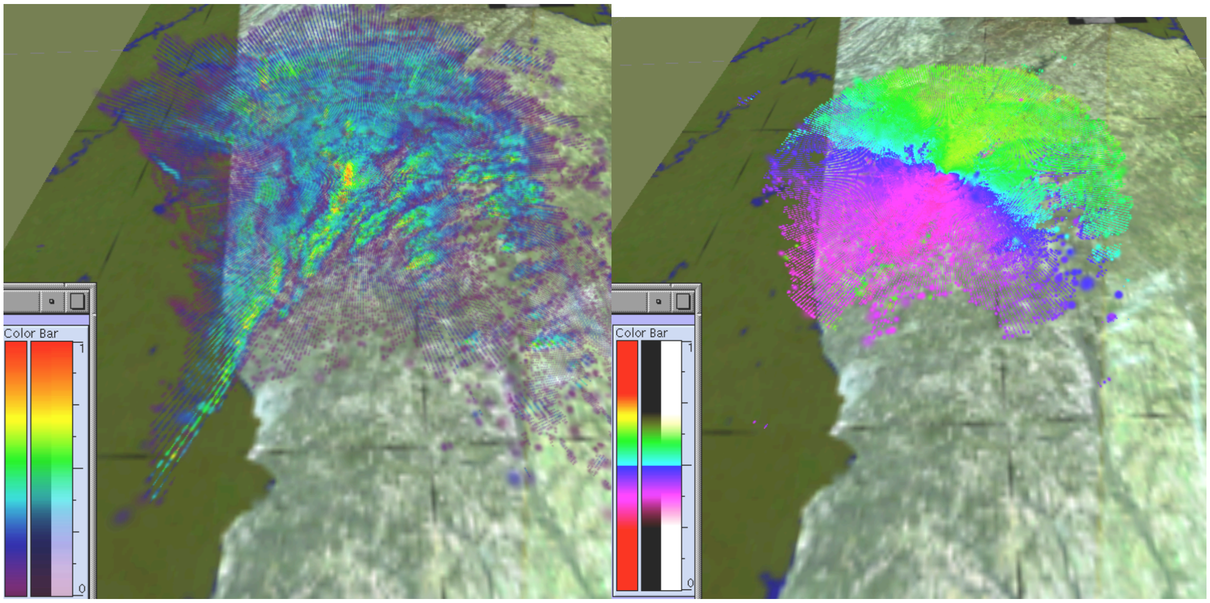

Fig. 4 (*left*) Image of Doppler radar reflectivities over North Georgia. Heavy rainfall is evident along a front from the southwest towards the center (yellow and red splats). Doppler velocities are shown in the *right* image for the same time step. We have drawn a more limited radius of radar. Because the winds are heading northeast, the northeast half show positive velocities (away from the radar) and the southwest half show negative velocities (toward the radar).