

Chapter 15

EVITA - EFFICIENT VISUALIZATION AND INTERROGATION OF TERA-SCALE DATA

Raghu Machiraju, James E. Fowler, David Thompson, Bharat Soni and Will Schroeder

Abstract Large-scale computational simulations of physical phenomena produce data of unprecedented size (terabyte and petabyte range). Unfortunately, development of appropriate data management and visualization techniques has not kept pace with the growth in size and complexity of such datasets. To address these issues, we are developing a prototype, integrated system (EVITA) to facilitate exploration of tera-scale datasets. The cornerstone of the EVITA system is a representational scheme that allows ranked access to macroscopic features in the dataset. The data and grid are transformed using wavelet techniques while a feature-detection algorithm is used to identify and rank contextually significant features directly in the wavelet domain. The most significant parts of the dataset are thus available for detailed examination in a progressive fashion. The work presented here is similar in essence to much of the work in the traditional data-mining community. We first describe the basic system and follow with a discussion of ongoing work, focusing on efforts in multiscale feature detection and progressive access. Finally, we demonstrate the system for a two-dimensional vector field derived from an oceanographic dataset.

Keywords: Feature detection, vector fields, compression, embedded and progressive access, large datasets, tera-scale visualization

1. Introduction

Computational field simulation (CFS) [Jam92, DTZ⁺97, KP97, SG95] is the process of simulating complex physical phenomena via computation for analysis, design, or investigation of fundamental physical phenomena. The computed results are then interrogated for analysis and validation through visualization. In such applications, the objective of visualization is to interactively transform data into pictorial form in a manner which fosters discovery by the viewer.

CFS routinely produces data of unprecedented size (terabyte and petabyte range) which introduces new challenges to data management and visualization. Coupled with growth in data size is the need for increased realism due to more demanding user expectations. Unfortunately, it is often difficult to perform even simple visualization tasks on extremely large datasets since the development of appropriate data-management techniques has not kept pace with the growth in size and complexity of datasets [SvR98]. For many simulations, the storage of the data itself, not to mention transmission over a limited-bandwidth network, is a serious problem.

The research reported here attempts to respond to the challenges posed by extremely large datasets. We believe the key technology needed to facilitate tera-scale visualization is *ranked access of relevant features in compressed representations*. In tera-scale visualization, locating important features of the dataset first is paramount for effective data exploration. For practical reasons arising primarily from resource limitations (e.g., CPU speed, network bandwidth, main-memory availability), only parts of a dataset may be accessed at any given time (i.e., out-of-core analysis and visualization). Thus, it is necessary to create schemes that allow rapid access to significant information by considering only a small portion of the dataset. To this end, automatic detection and ranking of contextually significant features in datasets is of critical importance. Furthermore, often both focus and context views of datasets [Fur86, RCM93, JS98] are required; i.e., certain elements of interest (focus) are enhanced while the remainder of the domain provides a non-distracting context. Under this paradigm, the researcher attempts to search for useful information in the unfamiliar territory of the dataset in question by exploiting a fish-eye focused view. Additionally, based on discoveries along the way, the objective of the search may change, since better understanding of the dataset allows for more refined searches.

The data-exploration and visualization scenario described above is not markedly different from what occurs during a typical data-mining session. Determining correlation and inherent relationships between various entities is the primary goal of a data-mining exercise. These in turn produce a better understanding of the processes generating the data. Similarly, a meaningful scientific-visualization exercise should facilitate discovery of important phenomena. However, essential differences do exist between the scientific domain and typical data-mining applications. CFS data is not abstract and, in fact, is deterministic. The generation of the dataset is dictated by mathematical models representing physical processes. As a result, detection of essential spatial and temporal relationships (and hence coherent structures) can be conducted with deterministic techniques as opposed to statistical and sampling techniques characteristic of traditional data mining. It should be noted that there do exist cases in which non-deterministic and statistical techniques can provide an understanding of certain physical phenomena, e.g., turbulence. However, most of

these techniques are essentially deterministic in nature since realistic physical models are available. Additionally, an important reason for the data explosion in typical data-mining applications is the large parameter space in which the entities exist while, in CFS applications, the disparate spatial and temporal scales required to simulate complex physical phenomenon dictate the growth of the datasets.

For effective tera-scale visualization, data compression is unavoidable given the enormous quantities of data involved. For generality, compressed representations should be appropriate for both scalar and vector fields, with time-varying fields being of particular importance as the time-varying nature of such datasets often yields extremely large sizes. Additional constraints on compression algorithms are as follows. First, it is often desired, for reasons of efficiency, that derived quantities (e.g., gradients, vorticity), needed by various visualization and analysis algorithms, be computed in the compressed domain; therefore, compressed representations should be amenable to such operations. Secondly, perfect reconstruction should be permitted. That is, the compression operation should result in no net loss of information and, if desired, the original dataset should be recoverable from the compressed representation with no loss of data. Finally, and most importantly for ranked-access systems, visualization should be facilitated by an incomplete reconstruction of the dataset. That is, the compressed representation must support browsing by partial reconstruction of the original dataset as defined by viewer requirements. Such browsing capability can be implemented with a client-server model—the client delineates certain *regions-of-interest* (ROIs), while the server manipulates the flow of transmitted data so as to send information from selected ROIs first. In this way, the browsing tool is amenable to distributed- or even remote-visualization uses.

An outline of the remainder of our discussion is as follows. In Section 2, we overview our prototype system for visualizing large datasets, EVITA, and we provide details on a method to create a significance map and obtain rankings for the various ROIs in the dataset in Section 3. Compression and coding of vector fields and their associated grids are discussed in Section 4, while Section 5 outlines a vision for a user interface. Finally, in Section 6, we present preliminary results for our system for a two-dimensional vector-field dataset. We note that the discussion here is of a work-in-progress and much on-going effort is currently being devoted to expand on the reported results.

2. System Description

We are currently developing the EVITA system to facilitate exploration of tera-scale datasets. A scalable system amenable to distributed implementation, EVITA is concerned with the storage and representation of very large datasets, their analysis and manipulation, and rendering and presentation of the resulting

images. Viable tera-scale visualization is possible only through a confluence of knowledge from visualization, coding theory, geometry, and application-specific domains. Consequently, the EVITA system is a sophisticated amalgamation of diverse techniques and will provide an efficient interrogative tool for tera-scale visualization.

In designing the EVITA system, we have focused on time-varying, computational-fluid dynamic/hydrodynamic, environmental-science, and oceanographic datasets on structured rectilinear or curvilinear grids. Many computational investigations are conducted on such structured sampling regimes. Although these structured grids are less complex than unstructured meshes, there are still many difficult and unresolved problems relating to the compression and transmission of data sampled on structured grids. Additionally, wavelet theory has not been fully developed for unstructured grids. Some promising work by Guskov *et al.* exists for surface meshes [GSS99]; however, significant further development is still required before such techniques can be deployed for compression purposes. To reiterate, our focus is on ranked access of relevant features in compressed representations.

Figure 15.1 shows a block diagram of the EVITA system which is comprised of three main components: an offline *preprocessor*, a *server*, and a *client*. The preprocessor takes the original dataset and its associated grid to produce a compact representation. Although this compression process is expected to be quite time consuming due to a computationally expensive feature-detection step, this complex computation is performed only once, offline. The compressed bitstream \tilde{B} resulting from this offline preprocessing is produced under a fixed priority schedule permitting a suitable visualization of the dataset. It is important that features to be detected be chosen with utmost care such that they are sufficiently general for a variety of visualizations.

The interactive ROI operation required of the system is produced by the server, a thread running during the visualization session. The goal of the server is to relay the compressed dataset to the client, taking into account ROIs as specified by the user. While the visualization process is underway, the server accepts ROI information in real time from the client and dynamically effectuates the necessary reorganization of bitstream \tilde{B} to produce the desired priority ranking. In essence, the ROI priority ranking is accomplished by a mere reordering of the bits of the bitstream; as such, this operation is computationally simple and possible at interactive rates (as opposed to the encoding operation itself which is confined to the offline domain).

The final component of the system, the client, decodes the reorganized bitstream arriving from the server, produces the visualization, and accepts user feedback in the form of ROI specification. The decoding process produces frequent reconstructions of the dataset as additional information is received

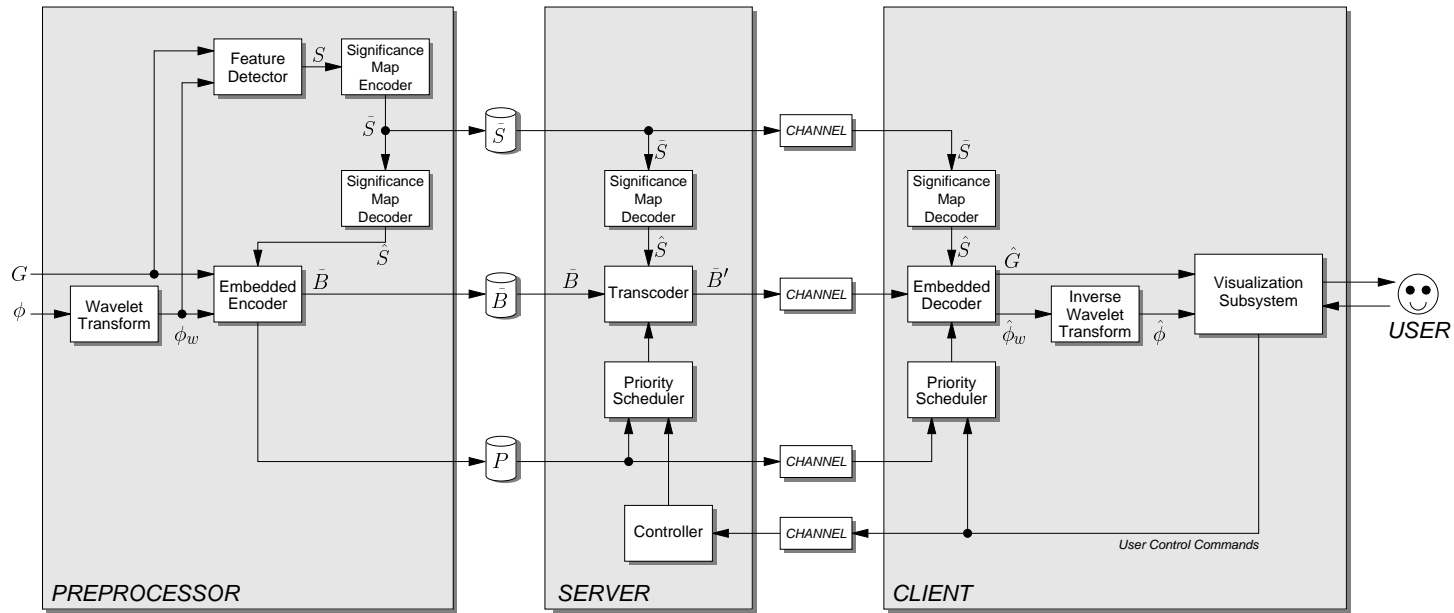


Figure 15.1. EVITA - A Prototype System for Effective Visualization and Interrogation of Tera-scale Datasets. Legend: ϕ scalar or vector data field, G discrete grid, S significance map, \tilde{B} bitstream. \tilde{x} denotes encoded (compressed) quantities, \hat{x} reconstructed (decompressed) quantities, x' reordered (transcoded) quantities, and x_w wavelet-domain quantities.

from the server; these reconstructions are successively fed to the visualization subsystem which updates the current rendering of the dataset.

Development of the system is based upon advances in wavelet transforms, scalar- and vector-field analysis, progressive and embedded encoding, and visualization toolkits. The EVITA system can provide a general visualization environment for any tera-scale dataset with underlying structure similar to that for which the system is designed. The application-specific components of the system lie merely in the feature-detection algorithm and in the generation of the significance map—aside from these two modules, the system, as proposed, is amenable to many visualization tasks.

In what follows, we present an overview of the EVITA system, describing ongoing design efforts in significance-map generation, data-grid coding, and visualization interfaces, and presenting preliminary results obtained from the current system implementation.

3. Significance Map Generation

Mechanisms for location of application-specific features in the data and generation of a ranking of these identified features is critical to the success of the EVITA system. We address the issue of ranked access with a procedure that culminates in the generation of a four-dimensional significance map. The first step is identification of the desired features within the dataset, which then yields a segmentation of the dataset into ROIs. Consideration of time-varying data complicates the feature-identification process since, once identified, features must be tracked across multiple time steps. After segmentation, ROIs are then ranked according to appropriate criteria. In the completed system, a four-dimensional significance map will be generated that will establish the baseline priority schedule for dataset encoding. For simplicity, we describe here techniques to generate a two-dimensional significance map for a steady-state, two-dimensional vector field. The data employed here is from the equatorial region of the Pacific Ocean generated using the Naval Layered Ocean Model [Wal99]. To illustrate the operation of the EVITA system, the features we consider here are regions of swirling flow. However, our approach is applicable to ROIs corresponding to any general feature identifiable from a scalar field.

Linear-Lifting Scheme for Vectors. An extension of the linear-lifting scheme to perform a wavelet transform for vector data is discussed in this section. Intentionally, a simple scheme was chosen for this effort. In general, the lifting scheme consists of three steps: split, predict, and update (see [Swe97] for further detail). For linear lifting, the filter coefficients employed during the predict stage are $g = \{0.5, 1.0, 0.5\}$, while the coefficients for the update stage are $h = \{0.25, 0.25\}$. We use a critically sampled (i.e., decimated)

transform and achieve a multi-dimensional transform by applying a sequence of one-dimensional wavelet transforms along each dimension in succession. For example, for a two-dimensional dataset, one-dimensional transforms are applied first along rows and then along columns, and each transform level yields four subbands corresponding to a smooth decimated representation and details along horizontal, vertical, and diagonal orientations. Transforms for higher-dimensional data proceed similarly. For vector-valued data, the wavelet transform is applied to each component of the vector in an independent fashion.

Feature Detection in Flow Datasets. Computational fluid dynamics (CFD) datasets typically contain one or more features of interest. These features, with specific fluid-dynamic characteristics, include shocks, vortices, flow separations, etc. The focus here is on features characterized by a swirling motion suggested by rotation of fluid particles about a common center, either fixed or moving.

Berdahl and Thompson define a derived scalar quantity called *swirl* which can be used to identify features characterized by swirling flow such as vortices [BT93]. In this procedure, a scalar value based on the local velocity and velocity gradients is assigned to each field point. The swirl value is interpreted as the tendency for the fluid to swirl at a given point. Contiguous regions of nonzero swirl values can therefore be thought of as distinct features. Core regions of vortices are characterized by larger swirl values. This methodology can be contrasted with those methods that determine critical points and then connect them with curves [HH89] or seek to locate vortex core regions [SH95].

A three-dimensional velocity field is characterized by the vector $\mathbf{V} = [u, v, w]^T$ at each point (x, y, z) in the domain. The velocity gradient tensor describes the spatial variation of the velocity field at a point and is given by:

$$\mathbf{\Gamma} = \begin{bmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} & \frac{\partial u}{\partial z} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} & \frac{\partial v}{\partial z} \\ \frac{\partial w}{\partial x} & \frac{\partial w}{\partial y} & \frac{\partial w}{\partial z} \end{bmatrix}. \quad (15.1)$$

A necessary condition for the occurrence of swirling motion is the existence of a region of complex conjugate pairs of the eigenvalues of $\mathbf{\Gamma}$. Associated with the complex eigenvalues is a cyclical motion with a period that is proportional to the magnitude of the imaginary component of the eigenvalues. This period can be computed using

$$t_{orbit} = \frac{2\pi}{|Im(\lambda_{1,2})|} \quad (15.2)$$

where $Im(\lambda_{1,2})$ is the imaginary part of the complex conjugate pair of eigenvalues.

An additional consideration is that a fluid particle may convect out of a region of complex eigenvalues before swirling motion is apparent. Computing the time required to traverse the region of complex eigenvalues is problematic since it would require a detailed particle-trajectory computation. If d is the characteristic length associated with the size of the region of complex eigenvalues and V_{conv} is the magnitude of the average velocity along d , then a simple estimate for the convection time is given by

$$t_{conv} = \frac{d}{V_{conv}} . \quad (15.3)$$

The convection velocity V_{conv} is taken to be the velocity in the plane containing the swirling motion, i.e., the plane normal to the real eigenvectors at the point in question. The length d is typically taken to be unity.

The swirl parameter τ is then defined as the ratio of the time for a fluid particle to convect through the region of complex eigenvalues to the orbit time

$$\tau = \frac{t_{conv}}{t_{orbit}} = \frac{|Im(\lambda_{1,2})|}{2\pi V_{conv}} . \quad (15.4)$$

For small values of τ , the fluid convects too rapidly through the region of complex eigenvalues to be captured in the swirling motion. In regions of large τ , the fluid is trapped in a swirling motion. It is to be noted that the swirl values in this work are calculated as the logarithm of the formula given in Equation 15.4. More details can be found in [BT93]. Figures 15.2(a) and (b) depict the magnitude of the original vector field and the corresponding swirl field, respectively, for a portion of the equatorial region of the Pacific Ocean [Wal99]. Of particular significance is the fact that regions of high velocity, as denoted by lighter shades in Figure 15.2(a), do not necessarily correlate with regions where the fluid is swirling.

Multi-Scale Significance Map Generation. The image in Figure 15.2(b), which shows the swirl parameter calculated on a two-dimensional grid of dimension $N \times N$, is called a significance map and is denoted by

$$S_{single} = \{s(i, j) | i, j = 0, \dots, N - 1\} . \quad (15.5)$$

The quantity S is a scalar that indicates the presence of the desired features. For flows with vortices, the swirl parameter, as defined in Equation 15.4, can be used as the representative scalar. The significance map delineates ROIs in the vector field of size $N \times N$ at a single resolution, usually the finest. However, the wavelet-coefficient pyramid

$$W_L = \{w_k(i, j) | k = 0, \dots, L - 1, i, j = 0, \dots, N - 1\} \quad (15.6)$$

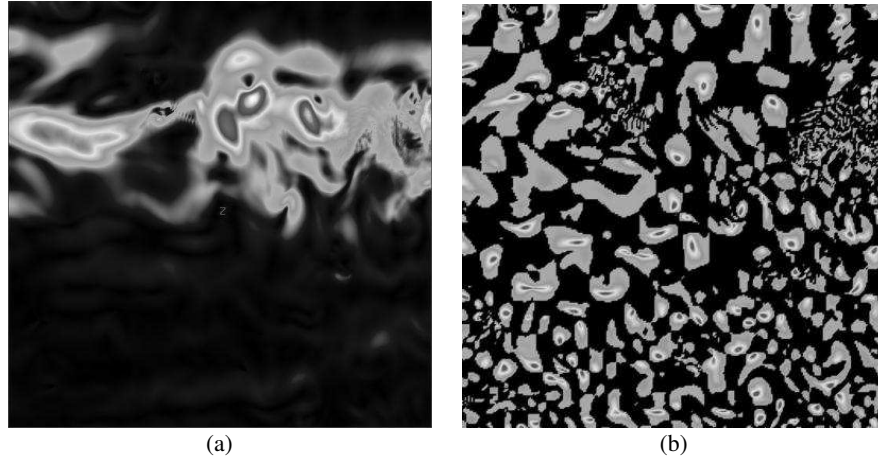


Figure 15.2. (a) Original velocity field (magnitude) (b) swirl field.

obtained from the L -level wavelet transform of an $N \times N$ -sized vector field using the lifting scheme is arranged at multiple resolutions (multi-scale). Thus, the single resolution significance map S_{single} cannot be used directly to rank the wavelet coefficients $w_k(i, j)$. This section focuses on the generation of a multi-scale significance map,

$$S_L = \{s_k(i, j) | k = 0 \dots L - 1, i, j = 0 \dots N - 1\} \quad (15.7)$$

that can be used directly on the multi-scale wavelet-coefficient mask W_L to determine the significance of the wavelet coefficients in terms of their contribution to feature preservation, thereby allowing ranked access to features.

Approximate Reconstruction of Features (Swirl). To generate a multi-scale significance map, it is necessary to perform a feature detection at each scale. The swirl-detection algorithm described previously requires the computation of the velocity as well as the velocity gradient at each point in the domain. Therefore, it is necessary to compute approximations to these quantities using only the local, compressed representation of the data.

A new method for approximately reconstructing the velocity and the velocity gradient using only data in the wavelet domain is now described. This technique corrects for the effects of the linear-lifting scheme as well as truncation error and is based on techniques used in multigrid-solution algorithms [Bra73]. We note that the following discussion is conducted in terms of one-dimensional data and operations. However, since a multidimensional wavelet transform is constructed as multiple one-dimensional transforms applied along each dimension in sequence, we apply the operations we describe below for one dimension in this same fashion to construct an equivalent multidimensional operator.

Let the wavelet approximation obtained after an n -level wavelet transformation of a scalar quantity $u_{j,l}$ defined on the grid $x_{j,l}$ be represented by $u_{j-n,l}$. The corresponding coarser grid is $x_{j-n,l}$ and $\Delta x_{j-n} = 2^n \Delta x_j$. Here j represents the level of the wavelet transform and l indicates the spatial position. Consider first the correction needed to account for the difference in truncation error in finite-difference approximations of the gradient using the same data on two different levels.

A second-order, central difference approximation to the gradient of u on mesh $x_{j,l}$ is given by

$$\left. \frac{du}{dx} \right|_{x_{j,2l}} = \frac{\delta u_{j,2l}}{2\Delta x_j} + \frac{\Delta x_j^2}{6} \left. \frac{d^3u}{dx^3} \right|_{x_{j,2l}} + O(\Delta x_j^4) \quad (15.8)$$

where the central difference operator is defined using

$$\delta u_{j,2l} = u_{j,2l+1} - u_{j,2l-1} \quad (15.9)$$

This approximation is consistent with most CFD solutions which typically have second-order spatial accuracy. Now subsample the same data on mesh $x_{j-1,l}$ to obtain

$$\left. \frac{du}{dx} \right|_{x_{j-1,l}} = \frac{\delta u_{j-1,l}}{2\Delta x_{j-1}} + \frac{\Delta x_{j-1}^2}{6} \left. \frac{d^3u}{dx^3} \right|_{x_{j-1,l}} + O(\Delta x_{j-1}^4) \quad (15.10)$$

Although the difference approximations are of the same formal order of accuracy, there is a difference in the truncation error due to the difference in the mesh spacing. This suggests adding a correction term to improve the accuracy of gradients computed on the coarser meshes. The following result is obtained using Equations 15.8 and 15.10 while generalizing to n levels noting that $\Delta x_{j-n} = 2^n \Delta x_j$:

$$\frac{\delta u_{j,2^n l}}{2\Delta x_j} = \frac{\delta u_{j-n,l}}{2\Delta x_{j-n}} - \frac{1}{6} \left(\frac{4^n - 1}{4^n} \right) \frac{d^3u}{dx^3} \Delta x_{j-n}^2 + O(\Delta x_{j-n}^4) \quad (15.11)$$

Equation 15.11 specifies the correction that should be added to the central-difference approximation on level $j - n$ so that it is equivalent to the central-difference approximation on level j to the order of the approximation. A standard second-order, central-difference can be used to approximate the third-derivative term [Nak99].

Now consider the correction to the transformed quantity u needed to remove the effects of the linear-lifting scheme. Substituting the definition of the detail coefficients in the update step [Nak99] yields:

$$u_{j-1,l} = \frac{1}{8} (-u_{j,2l+2} + 2u_{j,2l+1} + 6u_{j,2l} + 2u_{j,2l-1} - u_{j,2l-2}) \quad (15.12)$$

Using a Taylor series to expand Equation 15.12 about $x_{j,2l}$, yields:

$$u_{j,2l} = \left(1 + \frac{\Delta x_{j-1}^2}{16} \frac{d^2}{dx^2} + O(\Delta x_{j-1}^4) \right) u_{j-1,l} . \quad (15.13)$$

Through recursive application of Equation 15.13 and again noting that with $\Delta x_{j-n} = 2^n \Delta x_j$, a result generalized to n levels may be obtained:

$$u_{j,2^n l} = \left(1 + \frac{\Delta x_{j-n}^2}{16} \left(\sum_{k=0}^{n-1} \frac{1}{4^k} \right) \frac{d^2}{dx^2} + O(\Delta x_{j-n}^4) \right) u_{j-n,l} . \quad (15.14)$$

Equation 15.14 represents an approximation to the data on level j computed using only quantities defined on level $j-n$. Note, however, that this expression also acts as a filtering mechanism because only frequencies that can be resolved by the mesh on level $j-n$ are included in the approximation.

To complete the process, a correction must be made to the second derivative approximation similar to the one given above for the first derivative. The resulting expression is given by

$$u_{j,2^n l} = \left(1 + \frac{1}{16} \left(\sum_{k=0}^{n-1} \frac{1}{4^k} \right) \bar{\delta} + O(\Delta x_{j-n}^4) \right) u_{j-n,l} \quad (15.15)$$

where the operator $\bar{\delta}$ is defined by

$$\bar{\delta} = \delta^2 - \frac{1}{12} \left(\frac{4^n - 1}{4^n} \right) \delta^4 \quad (15.16)$$

and δ^2 and δ^4 are standard second and fourth difference operators given by

$$\delta^2 u_{j,l} = u_{j,l+1} - 2u_{j,l} + u_{j,l-1} \quad (15.17)$$

and

$$\delta^4 u_{j,l} = u_{j,l+2} - 4u_{j,l+1} + 6u_{j,l} - 4u_{j,l-1} + u_{j,l-2} \quad (15.18)$$

respectively.

The resulting procedure to compute approximations to the velocity and velocity gradients using only transformed data is as follows:

- Compute an approximate reconstruction to the velocity components at the current level using Equation 15.15 applied for each direction.
- Compute the gradients using these reconstructed values using Equation 15.11.
- Use these reconstructed values and gradient approximations to compute the swirl.

Current work includes design of new wavelet transforms that better preserve the nature of the physical simulations [TMCJ00]. Additionally, features other than swirling motion are being considered for detection and ranking.

Denoising the Data and Significance Map. The presence of oscillations in the original data can result in detection of spurious features during significance-map generation. Laplacian smoothing can be used to denoise prior to the generation of a significance map [Nak99]. Noise in the significance map S_k itself is also removed based on the persistence of features across scales.

Segmentation and Ranking of ROIs. The segmentation process involves identifying different swirl regions in the significance map and assigning each a label to facilitate later access. Here, a feature is defined as a set of connected points that have non-zero swirl and are surrounded by a zero-swirl region. A simple two-pass scanline algorithm similar to those used in image processing [Jai89] segments the features in the significance map into ROIs.

The segmented significance map identifies distinct regions as ROIs but does not indicate if one ROI is more important than another. A separate process must rank ROIs in terms of relative significance. To date, we have explored three criteria for ranking ROIs, ranking based on 1) the size of the ROI, on 2) the average strength of the feature within the ROI, and on 3) the persistence of the feature within the ROI across scales. The size of an ROI may be measured as the number of grid points contained in the ROI, while the feature strength can be calculated as the sum of the swirl values within the ROI. A straightforward ranking could be based directly on ROI size and strength as determined from a segmented, single-resolution significance map [Nak99].

A more sophisticated approach towards ROI ranking would assign an ROI containing a feature that persists across a larger number of scales a higher rank. To quantify the persistence of a feature across scales, it is necessary to track the feature across scales within a multiscale significance map. A simple tracking can be conducted by identifying features in each scale individually and then checking the spatial location of each—if the spatial locations of two features identified at different scales significantly overlap, then it is likely these features are actually the same feature being manifest at different scales. An algorithm for such scale-based ROI ranking was proposed in [Nak99]. This technique allows features to appear and disappear as the scales are traversed, and, at the end of the tracking process, features that exist from coarsest scale onwards receive a higher rank compared to those that are present only at finer scales.

In the following section we describe how the ranking of ROIs is used to influence a priority schedule among the wavelet coefficients obtained from the various ROIs. This process facilitates the realization of embedded and progressive access for large datasets.

4. Coding

The EVITA system employs state-of-the-art compression techniques that have originated in the image- and video-coding communities. In order to support user-defined priority-based access to ROIs within the compressed dataset, the design methodology underlying the EVITA system is a combination of *embedded coding* [SP96, MGBB00] and *object-based coding* [LL00b].

Embedded coders produce compressed representations at a variety of amounts of compression, where each of these representations are included (“embedded”) at the beginning of a single output bitstream. That is, any prefix of an embedded bitstream can be decoded to produce a valid compressed representation of the original dataset; the longer the prefix, the more accurate is the representation. The fundamental tenant of embedded coding is therefore to put the most important information first in the encoded output. In the EVITA system, the segmented significance map is used in conjunction with user input to dynamically determine a current priority schedule governing the order of occurrence of information in the encoded bitstream.

In the EVITA system, embedded coding ranks information *within* a single ROI; to permit rankings *among* multiple ROIs, the EVITA system employs object-based coding. The philosophy underlying object-based coding is that contextually salient portions of a dataset are coded individually, so that decoding can be restricted to desired portions only. In object-based coding, this random access is supported from a single encoding, without knowledge of which portions are desired in advance of coding or the need for multiple encodings as the user’s interests change.

In general terms, the compression procedure within the EVITA system follows the modern embedded-coding paradigm of wavelet transform, successive-approximation quantization, and entropy coding. Specifically, the EVITA system extends the coder developed in [FF00] for the coding of three-dimensional ocean-temperature datasets. Below, we describe some salient aspects of the EVITA encoding and decoding algorithms.

Shape-Adaptive Wavelet Transform. In the EVITA system, each ROI is encoded individually by applying a wavelet transform, successive-approximation quantization, and entropy coding only to the information in the dataset belonging to that ROI. This ROI-based coding is somewhat more complicated than traditional compression algorithms since ROIs may be arbitrarily shaped in three-dimensional space, and this shape may evolve over time (i.e., an arbitrary “shape” in four-dimensional time-space), whereas traditional compression methods are typically restricted to rectangular shapes.

In the EVITA system, individual coding of ROIs starts with a shape-adaptive wavelet transform (SAWT), such as that recently adopted by the MPEG-4 stan-

dard [LL00a]. Essentially, a SAWT is identical to a usual discrete wavelet transform except at the boundaries of an arbitrarily-shaped ROI, where a symmetric extension adapted to the shape of the ROI is employed. In the EVITA system, we use a lifting implementation of a SAWT as described in [FF00]; this transform is quite similar to the filter-bank implementation specified by MPEG-4 and described in [LL00a].

For vector-valued data fields, the transform of [FF00] can be applied to each vector component individually. Alternatively, multiwavelets [GHM94] can be used to construct more general vector-valued wavelet transforms (VWTs) [XS96] which can also be made shape-adaptive. Whether the latter approach can offer performance superior to that of the former is an open question and is a focus of our current investigations.

Successive-Approximation Quantization. For scalar sources, the EVITA system employs the successive-approximation runlength (SARL) coding technique described in [FF00]. SARL consists of “bitplane coding,” wherein each wavelet coefficient is compared to a threshold, a bit is output to indicate whether the coefficient is greater than the threshold (i.e., a significant coefficient) or not (i.e., an insignificant coefficient), the threshold is halved, and the process is repeated. Thus, coefficients of an ROI are coded in a series of successive “bitplanes,” starting with the most-significant bits of all coefficients in the ROI and progressing to the lesser-significant bits in order. For efficient representation, groups of successive insignificant coefficients are coded together using runlengths, and then the entire symbol stream is subjected to multiple-context adaptive arithmetic coding. SARL is particularly well suited to use in the EVITA system since it is computationally quite simple, easily deployed regardless of the dimensionality of the data, and scales well as dataset size increases (the memory usage of the “significance lists” of many popular wavelet-based algorithms such as [SP96] may quickly grow prohibitive as the size of datasets increases).

As with the wavelet transform, the straightforward solution for the successive-approximation coding of vector-valued data is to apply SARL individually to each vector component. However, more general vector-quantization (VQ) equivalents of scalar successive-approximation quantization do exist—multi-stage VQ (MSVQ) in particular, has been proposed frequently (e.g., [dSG95]) for successive-approximation VQ (SAVQ). We are currently exploring performance of this and other SAVQ coders within the SARL framework described above.

Transcoding. Whereas the preprocessor produces an efficient embedded encoding of each ROI suitable for initial preview representations, the server is critical to the online, interactive exploration of the dataset because it is within

the server that the ROI processing takes place. The key component of the server is the *transcoder*. In general, a transcoder is a processor that converts, or translates, data encoded in one encoding into another encoding. The transcoder in our system is designed to minimize computation in order to maximize interactive response; as a result, the transcoder essentially implements a mere reordering of bits present in the compressed bitstream.¹

As mentioned above, the successive-approximation coding of wavelet coefficients is composed of a series of bitplanes for each ROI. In the encoder in the preprocessor, the bitplanes of all the ROIs in the dataset are “interleaved” in some order and stored in an output bitstream. The order of the bitplanes in the bitstream is dictated by the relative priorities among the ROIs as specified by the significance map; this “default” ordering is intended to provide a suitable “preview” visualization if decoded as is. However, the location within the bitstream of each bitplane of each ROI is noted and output as a priority schedule by the encoder.

When the interactive visualization process commences, the transcoder initially transmits each bitplane to the client in the same order as the bitplanes are found in the compressed bitstream constructed previously by the encoder. However, when the server receives a request from the user to change the current ROI ranking, the transcoder uses the priority-schedule information to quickly locate the bitplanes of the newly selected ROI(s) so that they may be transmitted to the client immediately (or as soon as the new priority schedule dictates). Implementation of the view frustum essentially follows the same procedure as ROI selection; that is, ROIs outside the current view frustum are given the smallest priority, and a change in view frustum moves bitplanes of newly revealed ROIs to the start of the priority list.

Decoder. In essence, the decoder in the client of the EVITA system serves to reverse the operations performed by the transcoder in the server and the embedded encoder in the preprocessor. The goal of the decoder is to extract wavelet coefficients for each ROI from the received bitstream, to reconstruct each ROI via inverse quantization and inverse transform, and finally to “composite” the ROIs together into a representation of the dataset. Since ROI and view-frustum information originates at the client by way of user interaction, the decoder knows at any given time the ROI priority schedule under which the transcoder is operating. Consequently, the ordering of the bitplanes in the received bitstream is known to the decoder at all times.

The decoder interacts with the visualization subsystem by producing frequent reconstructions of the dataset throughout the time that information is being received from the server. In the current implementation of the system, the

¹A similar process is proposed in the JPEG-2000 standard [MGBB00], wherein it is referred to as “parsing.”

decoder performs the reconstruction process after each bitplane is received from the server, although other arrangements are possible.

Grid Coding. Although the above discussion focuses on the embedded encoding of wavelet coefficients from the data field, an identical approach can be applied directly to curvilinear grid points. That is, the point locations of a curvilinear grid (an array of three-dimensional vectors) are treated just as if they were a vector-valued data field—the grid is subjected to the SAWT and SARL coding procedures described above. Then bitplanes of grid information are “interleaved” with the bitplanes of data-field information and output in the embedded bitstream produced by the encoder.

It is an open question as to how “fast” the grid information needs to be transmitted to the client. That is, the server sends bitplanes to the client to refine both the data field and grid simultaneously. Because the number of grid points is the same as the number of data-field points, the simplest approach would be to refine both the grid and the data equally fast; i.e., to interleave data and grid bitplanes in a one-to-one fashion. However, because at least some crude representation of a large number (perhaps all) of the grid points may be necessary to make even an initial preview representation possible, we suspect that the best interleaving will need to include a large number of grid bitplanes initially, delaying many data-field bitplanes to later in the stream. Our initial investigations have confirmed this suspicion and seem to indicate that a large majority of the initial bits transmitted to the client need to be grid, but, after some initial time, a one-to-one mixture is warranted. We are currently devising and testing algorithms to determine optimal interleaving mixtures for data and grid dynamically as part of the transcoding operation.

Time-Varying Datasets. Time-varying datasets will be coded by merely considering time as a “fourth dimension” and employing a four-dimensional SAWT. The SARL-coding procedure generalizes to four-dimensional data trivially, while the transcoder is unaffected by the dimensionality of the data.

5. Visualization Interfaces

The hallmark of a useful interactive system is consistent, reliable response to user input. This is a particularly daunting challenge in tera-scale visualization. In order to achieve this requirement, the user interface will be designed with asynchronous communication mechanisms and an interrupt-driven event loop. Priority-driven incremental rendering (based on feature rank) will be supported and user input will be processed at a continuous rate, with interruption of the rendering process possible at any time. Caching of graphics primitives will allow information to be delivered incrementally. The cache size will be specified at runtime to support graphics platforms of different capabilities.

Additionally, the user interface must support navigation schemes and standard visualization operations such as isosurfacing, streamline generation, cut or probe surfaces, and color mapping. Navigation schemes will enable:

- traversal in three-dimensional space (gaze-directed frustum with clipping planes), time (e.g., linear scrollbar), and feature space (scalar- and vector-field parameters)
- identification and specification of ROI using mouse clicks and picking operations
- automated generation of camera paths and traversal in three-dimensional space, time, and feature space, as well as identification and specification of ROI, including automated generation of camera paths and animations
- facilities for keyframing the evolution of ROI in space and time to enable offline, higher-resolution generation of images and animations.

Information about neighboring regions will be displayed to facilitate appropriate navigation of the domain of interest. The displayed information can include statistics about number or density of feature-rich ROIs in various subvolumes along various directions relative to the current position. Such information can be determined by the preprocessor.

Finally, given the nature of ranked access of features, the system will support parceling of the original grid and transmission of the data field simultaneously with its corresponding grid points. The user can stop this progressive transmission at any time, or, as the progressive access continues across scales, the user can demand higher fidelity of either field or grid representation.

We plan to use vtk [SML98] for its extensive visualization capabilities and engineer the user interface to exploit its interactive capabilities. In the current system, only a primitive user interface exists for one to view the results of feature detection and progressive access of the data.

6. Preliminary Results

We now illustrate the EVITA system through a two-dimensional example. Figures 15.3 and 15.4 depict a visualization of a two-dimensional image of a simulated turbulent region in the Pacific Ocean [Wal99] that was obtained from an analysis of the velocity field. This region roughly corresponds to the upper left quadrant of Figures 15.2(a) and (b). The renderings are the scalar swirl parameter [BT93] mapped into a grayscale image. The swirl parameter is a measure of bulk rotation of fluid with a “large” value of the parameter indicating a highly rotational region; white in Figures 15.3 and 15.4 indicates “large” swirl value.

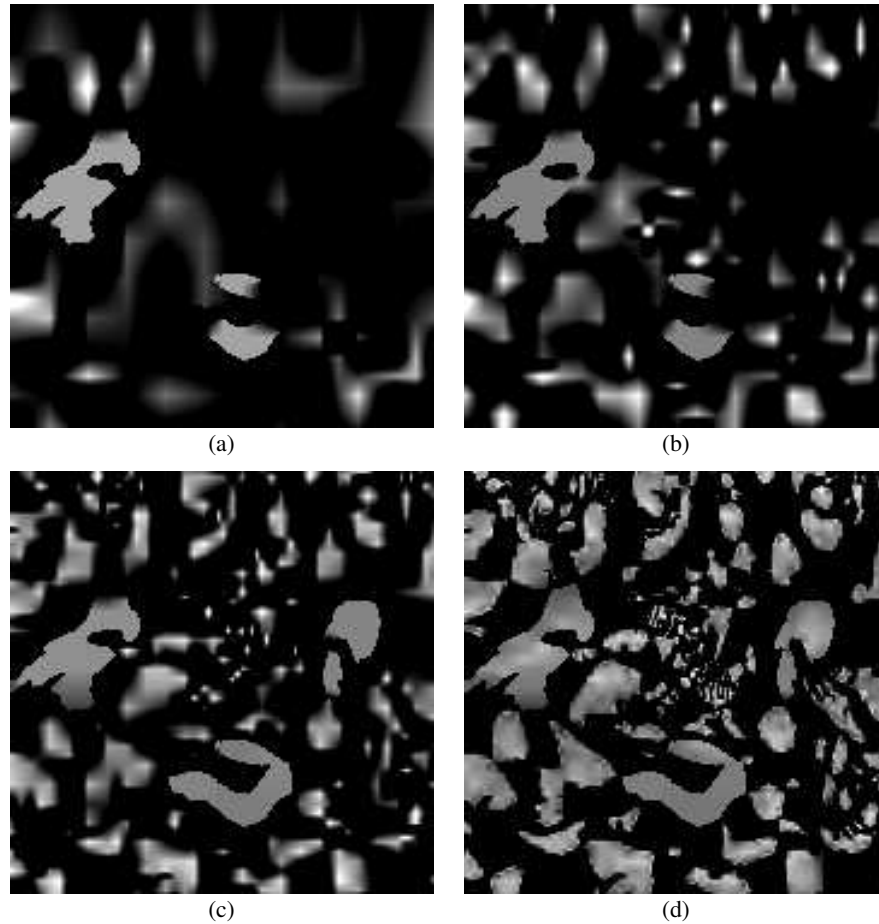


Figure 15.3. Pacific dataset visualization—default bitplane order as output from encoder. (a) 5th frame, (b) 9th frame, (c) 16th frame, (d) 24th frame.

Figure 15.3 shows several images from the sequence of images produced by the visualization of the reconstructed swirl data using the “default” order of the bitplanes, that is, the order of the bitplanes as output originally from the offline encoder. In this default bitplane order, a bitplane is output for each ROI (including the background “ROI”) in turn, resulting in refinement of all portions of the dataset equally as fast.

On the other hand, Figure 15.4 shows the effect on the visualization when one of the ROIs is selected by the user and given priority. In this simple example, the user selects the particular ROI at the start of the visualization process, and all bitplanes of the selected ROI are given priority over all other bitplanes (i.e., the entire ROI is sent before the rest of the dataset); however, the EVITA system will support ROI selection at any time throughout the visualization session, and

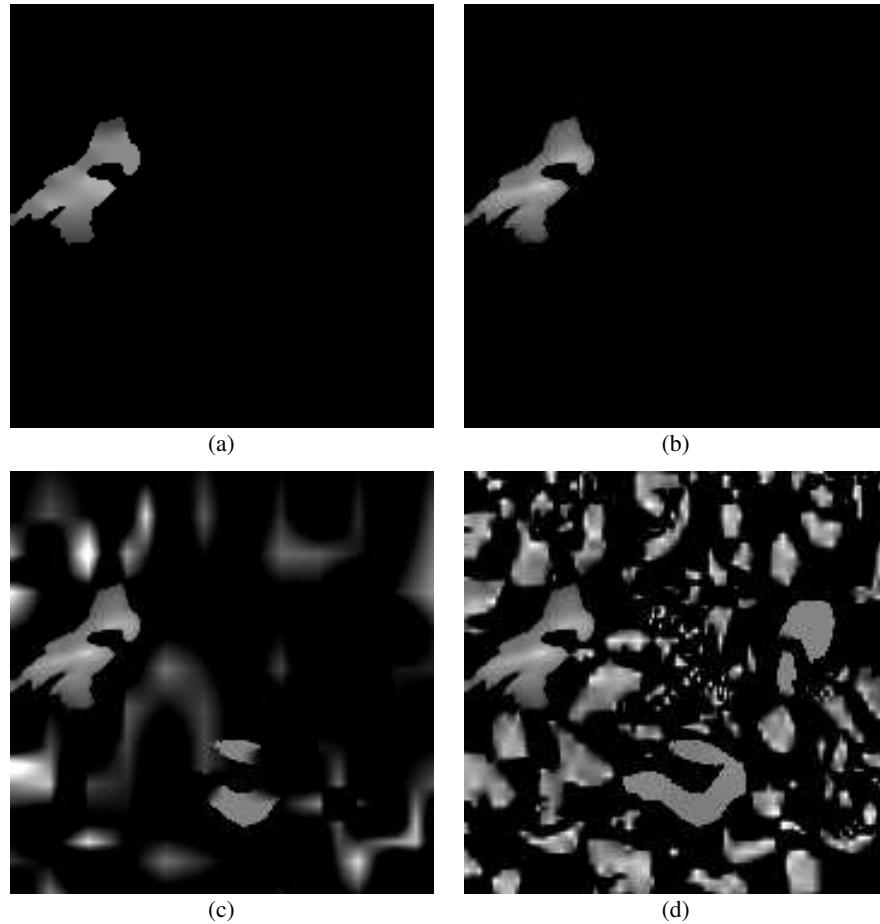


Figure 15.4. Pacific dataset visualization—ROI selected by user at start of visualization process and all bitplanes of selected ROI sent before rest of dataset. (a) 5th frame, (b) 9th frame, (c) 16th frame, (d) 24th frame.

the priority increase given to the bitplanes of the ROI may be more gradual. In any event, it can be seen in Figure 15.4 that, after an ROI is selected, the system produces a quick refinement of the desired ROI, while refinement of the rest of the dataset is delayed. Regardless of the priority schedule in effect at the initial stages of the process, the visualization produced when all of the dataset is received is identical to the visualization of the full dataset.

7. Summary

Large data visualization is an ominous task. We present here a possible methodology to facilitate the exploration of large datasets—the EVITA system. EVITA was conceived to allow the continuous exploration of large datasets

generated from simulations of complex physical phenomenon. Additionally, it will provide a compressed representation of both scalar and vector fields and the underlying grid that describes the physical phenomenon. To achieve both goals, a preprocessing stage constructs an embedded bitstream that includes the most significant data first. A client-server model is used to allow a user to interactively explore a large dataset, so that the client receives from the server only chosen sub-domains of the dataset which, when reconstructed in a streaming manner, allows viable visualization.

Our solution requires the generation of a four-dimensional significance map. Ideally, the significance map will segment the spatial and temporal domains into disjoint regions, or ROIs, that are tracked in time. Additionally, a ranking resulting from multiscale feature detection is obtained among the various ROIs to allow progressive access. In this feature-detection process, a wavelet transform creates a multiresolution version of the field, and the field at the coarsest level is used to measure the strength of specific features. After a process of denoising and segmentation, ROIs are delineated and a final ranking is obtained by either determining the total area and strength of the ROI, or by observing the persistence of features in ROIs across scales. As an example of the feature-detection process, we described here how bulk, macroscopic swirling motion can be located and measured as a basis for feature identification.

To achieve compression, data in each of ROI is subjected to a wavelet transform tailored to arbitrarily-shaped regions. Afterwards, a simple, yet effective embedded coding is performed according to a priority schedule as dictated by the ROI ranking. This embedded coding generates a bitstream that is amenable to partial reconstruction. Interactive exploration results from a client-server system, in which a transcoder (the server) reorders the flow of information to respond to the user's preferential interest in certain domains, while a decoder (the client) generates frequent reconstructions of the dataset as it obtains partial information from the server. In addition, the grid can be coded and transmitted in the same way using similar techniques. In the current system, a simple interface allows for the display of vector fields and rudimentary exploration.

Our preliminary results demonstrate the effectiveness of the EVITA system for a two-dimensional vector field depicting currents in the Pacific Ocean. Sample visualizations illustrate that the user determines the course of the visualization session as it is underway by selecting ROIs as desired. As a final note, we observe that, although this project is concerned primarily with feature detection and coding of fields to aid visualization, many of the techniques employed seek correlation in both spatial and temporal domains. Thus, in a broad sense, these techniques mine features and present them so as to facilitate the user's understanding of a complex physical phenomenon, which is the primary goal of traditional data-mining exercises.

Acknowledgments

This work was funded in part by the National Science Foundation under the Large Data and Scientific Software Visualization Program (ACI-9982344), and through an NSF CAREER Award (ACI-9734483). Additional support was provided by the Engineering Research Center at Mississippi State University. The authors thank B. Nakshatrala for contributions included in Section 3.

References

- [Bra73] A. Brandt. Multi-level adaptive technique (MLAT) for fast numerical solution to boundary value problems. In H. Cabannes and R. Teman, editors, *Proc. Third Intern. Conf. Num. Methods Fluid Mech.*, pages 82–89, Berlin, 1973. Springer-Verlag.
- [BT93] C. H. Berdahl and D. S. Thompson. Eduction of Swirling Structure using the Velocity Gradient Tensor. *AIAA J.*, 31(1):97–103, January 1993.
- [dSG95] Eduardo A. B. da Silva, Demetrios G. Sampson, and Mohammad Ghanbari. Image Coding Using Successive Approximation Wavelet Vector Quantization. In *Proc. ICASSP*, pages 2201–2204, Detroit, Michigan, May 1995.
- [DTZ⁺97] F. Davoudzadeh, L. Taylor, W. Zierke, J. Dreyer, H. McDonald, and D. Whitfield. Coupled Navier-Stokes and Equations of Motion Simulation of Submarine Maneuvers, Including Crashback. In *FEDSM97-3129, ASME Fluids Engineering Division Summer Meeting*, Vancouver, B.C., Canada, June 1997.
- [FF00] James E. Fowler and Daniel N. Fox. Wavelet-Based Coding of Three-Dimensional Oceanographic Images Around Land Masses. In *Proc. Intern. Conf. Image Proc.*, pages 431–434, Vancouver, Canada, September 2000.
- [Fur86] G. W. Furnas. Generalized Fisheye Views. In *Proceedings ACM SIGCHI Conference on Human Factors in Computing Systems*, pages 16–23, Pasadena, CA., 1986.
- [GHM94] Jeffrey S. Geronimo, Douglas P. Hardin, and Peter R. Massopust. Fractal Functions and Wavelet Expansions Based on Several Scaling Functions. *J. Approx. Theory*, 78(3):373–401, September 1994.
- [GSS99] I. Guskov, W. Sweldens, and P. Schröder. Multiresolution signal processing for meshes. *Computer Graphics Proc. (SIGGRAPH 99)*, pages 325–334, 1999.

- [HH89] J. Helman and L. Hesselink. Representation and Display of Vector Field Topology in Fluid Flow Datasets. *IEEE Trans. Computers*, 22:27–36, August 1989.
- [Jai89] Anil K. Jain. *Fundamentals of Digital Image Processing*. Prentice Hall, Englewood Cliffs, NJ, 1989.
- [Jam92] A. Jameson. Computational Algorithms for Aerodynamic Analysis and Design. Technical Report 25th Anniversary Conference on Computer Science and Control, INRIA, Paris, 1992.
- [JS98] D. F. Jerding and J. T. Stasko. The Information Mural: A Technique for Displaying and Navigating Large Information Spaces. *IEEE Trans. Graphics Visualization*, 4(3), July-September 1998.
- [KP97] L. Kantha and S. Piacsek. Computational Ocean Modeling. In *The Computer Science and Engineering Handbook*, pages 934–958. CRC Press, 1997.
- [LL00a] Shipeng Li and Weiping Li. Shape-Adaptive Discrete Wavelet Transforms for Arbitrary Shaped Visual Object Coding. *IEEE Trans. Circuits Systems Video Techn.*, 10(5):725–743, August 2000.
- [LL00b] Gang Lin and Ze-Min Liu. The Application of Multiwavelet Transform to Image Coding. *IEEE Trans. Image Proc.*, 9(2):270–273, February 2000.
- [MGBB00] Michael W. Marcellin, Michael J. Gormish, Ali Bilgin, and Martin P. Boliek. An Overview of JPEG-2000. In James A. Storer and Martin Cohn, editors, *Proc. IEEE Data Compression Conf.*, pages 523–541, Snowbird, UT, March 2000.
- [Nak99] B. Nakshatrala. Feature-Based Embedded Representation of Vector Fields. Master’s thesis, Mississippi State University, December 1999.
- [RCM93] G. G. Robertson, S. K. Card, and J. D. Mackinlay. Information Visualization Using 3D Interactive Animation. *Comm. ACM*, 36(4):57–71, April 1993.
- [SG95] J. S. Shang and D. Gaitonde. Scattered Electromagnetic Field of a Reentry Vehicle. *J. Spacecraft Rockets*, 32(2):294–301, March-April 1995.
- [SH95] D. Sujudi and R. Haimes. Identification of Swirling Flow in 3D Vector Fields. In *AIAA Paper 95-1715, AIAA 12th Computational Fluid Dynamics Conference*, San Diego, CA, June 1995.
- [SML98] W. J. Schroeder, Ken Martin, and Bill Lorensen. *The Visualization Toolkit: An Object Oriented Approach to 3D Graphics*. Prentice-Hall, Englewood Cliffs, NJ, 2nd edition, 1998.

- [SP96] Amir Said and William A. Pearlman. A New, Fast, and Efficient Image Codec Based on Set Partitioning in Hierarchical Trees. *IEEE Trans. Circuits Systems Video Techn.*, 6(3):243–250, June 1996.
- [SvR98] P. H. Smith and J. van Rosendale. Data and Visualization Corridors. Report on the 1998 DVC Workshop Series, Center of Advanced Computing Research, California Institute of Technology, Pasadena, CA., 1998.
- [Swe97] W. Sweldens. The lifting scheme: A construction of second generation wavelets. *SIAM J. Math. Anal.*, 29(2):511–526, 1997.
- [TMCJ00] D. Thompson, R. Machiraju, G. Craciun, and M. Jiang. Feature Preservation Properties of Linear Wavelet Transforms (submitted). In *Proc. Yosemite Multiscale Multiresolution Symp.*, Yosemite, CA, 2000.
- [Wal99] A. J. Wallcraft. The Naval Layered Ocean Model Users Guide. Technical Report 35, Naval Oceanographic and Atmospheric Research Laboratory, December 1999.
- [XS96] Xiang-Gen Xia and Bruce W. Suter. Vector-Valued Wavelets and Vector Filter Banks. *IEEE Trans. Signal Proc.*, 44(3):508–518, March 1996.