A Wavelet Toolkit for Visualization and Analysis of Large Data Sets In Earthquake Research

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– *Abstract* Wavelets have a wide range of useful functions that permit them to effectively treat problems such as data compression, scale-localization analysis, feature extraction, visualization, statistics, numerical simulation, and communication. We discuss their features and their use in an integrated manner to handle large-scale problems in earthquake physics and other nonlinear problems in the solid earth geosciences.

Keywords: wavelets, visualization, grid computing, collaboration, web-based maps, earthquakes

1 Introduction

As in many other fields of research, data is being produced at increasingly fast rates. Cheap computers, memory, and storage have led to time-dependent, high fidelity simulations of 3D seismic events (ben 1996), and of 3D seismic wave propagation (Olsen *et al.* 1995). Moreover, the accuracy and resolution of experimental techniques are improving at equally impressive rates. For example, confocal microscopy currently produces data at resolutions of 1000^3 (din 2001). In many cases, the data depends on time. Synthetic experiments, in which artificial "data" is fed into simulation codes are proving a fertile ground for model exploration in the absence of reliable "real" data. The size of the experiment output can be made arbitrarily large. The mission of Earthscope, soon to begin, is to collect field data related to earthquakes and other geophysical phenomena at a rate in an expected range of one and ten terabytes daily.

Geophysical data is by its very nature multiscale. Spatial scales range from the grain-size scale of millimeters, to the fault-size scale of 10 to 100 kilometers. Temporal scales range from a hundredth of a second in the rupture process to tens and hundreds of years for the earthquake stress transfer. Thus, there is a maximum of 6 orders of magnitude in space and 10 to 11 orders of magnitude in time. Earthquakes are not the only geophysical phenomena with these characteristics. A close relative is volcanic

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eruptions, intrinsically linked to plate tectonic activity. These eruptions are also intermittent in time, although their spatial distribution is much better understood. Glacier dynamics, currently monitored by satellite, is also very important due to their link to global warming and their severe environmental import if they melt at abnormal rates. They follow a multiscale pattern in time, breaking up over time scales much shorter than the period over which they develop (ANIYA *et al.* 1996). Plume activity in the mantle is also spatially intermittent. At high Rayleigh number, the spatial volume of these time-dependent plumes is a tiny fraction of the total mantle volume. Understanding their dynamics is essential to many fundamental questions related to the heat budget of the earth. There, it is important to accurately monitor the upwelling and downwelling within the plumes. The preceding examples all possess a multiscale structure, produce extremely large datasets, and are intrinsically difficult to analyze. The features of interest to the scientist exist over many spatio-temporal scales, and typically occupy a very small fraction of the physical domain.

State of the art techniques are under development to help compress data, display information hierarchically, and increase the amount of information displayed without overloading the available hardware, e.g., in the visual analysis of the earthquake clustering problem (KANEKO *et al.* 2002, BAUMGARDNER *et al.* 2002, STRELITZ 2002, KRITSKI *et al.* 2002, KEILIS-BOROK *et al.* 2002, LINDQUIST *et al.* 2002). Recent detection of the association of earthquake swarms and stress loading (TODA *et al.* 2002) clearly shows the definite need for analyzing clusters of earthquakes with advanced visualization techniques in 3D. Some trends in visualization can be found in (ERLEBACHER *et al.* 2001A). Over the past 15 years, wavelets have have proven invaluable to analyze data with the above characteristics. They are oscillatory functions that permit simultaneous analysis of a signal in the space and time domains, a property not shared by the Fourier transform. Wavelets have been applied in fields ranging from data compression (MALLAT 1998), visualization (HORBELT *et al.* 1999), numerical simulation (VASILYEV and PAOLUCCI 1997, **?**), video streaming (MARPE *et al.* 2002), feature identification (BERGERON *et al.* 2000, LAINE 2000), to name but a few. Extensive references are found in (KUMAR and FOUFOULA-GEORGIOU 1997, ERLEBACHER *et al.* 1996, BARTH *et al.* 2002).

We describe in this paper how wavelets might be used to perform an entire spectrum of functions useful to the geoscientist. This includes simulations, extraction of features, animations, visualization, data analysis, and collaboration. In the next section, we discuss some issues common across multiscale phenomena. Next, we explain the potential of wavelets and how their different applications interrelate. We then briefly describe how we use Amira (http://www.amiravis.com), a new visualization tool, to analyze our data (ERLEBACHER *et al.* 2002B), and finally, we discuss two web services: remote visualization and web-based maps (GARBOW *et al.* 2002B).

2 Multiscale Phenomena and Wavelets

Figure 1 shows how shear zones can develop over many scales: from the micro (grain-size) scale at the bottom right panel to the San Andreas fault on the bottom left panel. The top panels reveal the multiscale features of faults developed on the Venusian surface (top left) and the tantalizing fracture zones on the icy Jovian moon Europa (top right). We see clearly the pervasive presence of bifurcating features as a consequence of both microscopic forces due to dislocations and tectonic forces from both elasticity and viscoelasticity. In all of these cases, the data is provided over a high resolution grid ($> 10^4 \times 10^4$ points) from both satellite imagery and microscopy (bottom right). This type of imagery will become increasingly pervasive as new satellites like the ECHO come on line, and better data acquisition techniques are developed and deployed.

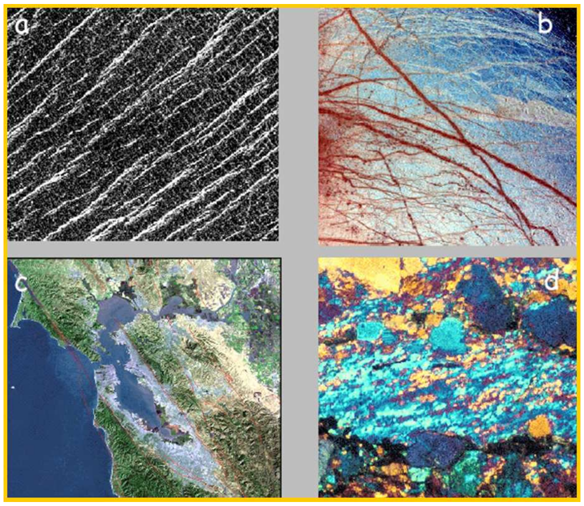

Fig. 1. Shear zones at various scales. Top left: Venus, equidistant wrinkles coering large parts of the surface (image scale: $40 \times 40\text{km}^2$). Top right: Jovian moon Europa, ice ridges and grooves forming a criss-cross structure (image scale: $1780 \times 1780\text{km}^2$). Bottom left: Earth, the San Andreas fault. Bottom right: microstructural image of a mylonitic shear zone (image scale: $4 \times 4\text{cm}^2$).

Faults, small coherent structures, or clusters all occupy a small fraction of the full volume. Scientists are interested in their spatial distribution, their structural properties, their time evolution, and their dynamics. An example of the complexity that can be expected is provided by the distribution of temperature in high Rayleigh numbers ($Ra = 10^8, 10^9$) mantles (MALEVSKY and YUEN 1993, ERLEBACHER *et al.* 2002A). The mantle is modelled by two flat plates kept at constant temperatures 0 (top boundary) and 1 (bottom boundary). The flow is periodic in the two horizontal directions. The hot plumes displayed in Figure 2 show multiscale features and appear

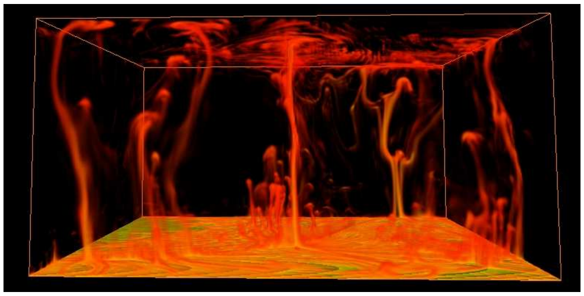

Fig. 2. Rising hot plumes associated with base-heated mantle convection at a Rayleigh number of 10^2. The aspect-ratio of the box is $4 \times 4 \times 1$. The grid consists of 500^3 points. Calculations were done by F.W. Dubuffet.

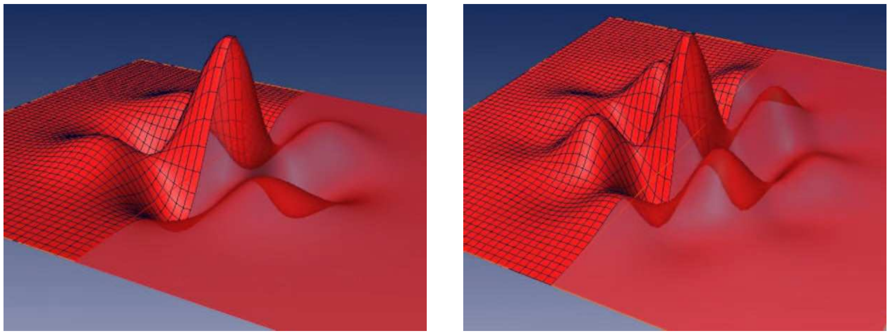

Fig. 3. Left: 2D Mexican Hat wavelet, 2nd derivative of Gaussian, 2nd order, Right: Figure 3b, 2D Mexican Hat wavelet, 4nd derivative of Gaussian, 4th order.

to only be active in a tiny fraction of the physical domain.

Fourier transforms cannot extract information about non-homogeneous properties of the flow. Indeed, any localized feature in physical space is distributed across all frequencies after transformation to spectral space. In contrast, wavelets are a versatile tool that act on the data as a filter with prescribed magnification. They establish a direct mapping between physical location and the pair consisting of the physical location and the scale of magnification. In contrast, the Fourier transform loses information about the location of sharp discontinuities.

Wavelets offer the means to extract this information and only keep the relevant data. It then becomes possible to analyze data simultaneously in terms of spatial location and spatial scale. Spatial and temporal correlations between adjacent scales often provide new physical insight. Figure 3 shows examples of two-dimensional mother wavelets formed by tensor product. More specifically, they are constructed from the second (left panel) and fourth (right panel) x and y derivatives of a two-dimensional Gaussian function. Standard wavelets, now referred to as first generation wavelets, are translation and scale invariant, i.e., their shape constant is independent of scale and dilation. As a result, they have difficulties adapting to finite domains, irregular grid structures, curved boundaries, etc. Recently, (1996) addressed these issues through the introduction of second generation wavelets. Their transforms can be computed more efficiently, yet than can be defined on curved manifolds, unstructured grids, etc. A discussion related to the geosciences can be found in (YUEN *et al.* 2002B) and in these proceedings (YUEN *et al.* 2002A). We expect second generation wavelets to enable a new class of simulations that utilize a number of degrees of freedom far less than is normally required. The key to this gain is wavelet thresholding: wavelet coefficients that lie below a user-defined threshold are set to zero. Of course, the challenge is then to develop techniques that determine the appropriate threshold automatically, which is problem-dependent (DONOHO 1993). The results of the simulation, stored on an adaptive grid must then be visualized and analyzed, without excessive transformation between physical and wavelet space. Well-designed methods will capitalize on the localized nature of the wavelets. A comprehensive set of tools to address these issues is yet to be developed. Wavelet extraction of geodynamical features like plumes (ERLEBACHER *et al.* 2002B), and analysis techniques coupled with the veritable explosion of capabilities of the current and near future generation of graphics cards will deliver to the geoscience community a new suite of simulation, analysis and networking tools. The computational power of these is growing at three times Moore's rate (factor of two every 18 months).

3 Current and Future Applications of Wavelets

Figure 4 shows two panels that catalog the various uses of wavelets into two categories. The right panel considers wavelets as a means to conduct mathematical analysis, numerical modeling, data storage, data analysis and scientific visualization. Some of these applications are detailed in the companion paper (YUEN *et al.* 2002A), which discusses the application of wavelet thresholding to the large-eddy simulation of fluid turbulence on adaptive grids. It further addresses how to unveil plume-like structures in high Rayleigh number thermal convection based on thresholding techniques (DONOHO 1993) and describes its application to feature extraction through visualization.

The World Wide Web has become today's medium of choice to transmit, exchange, analyze, visualize, and acquire information. Wavelets play a vital role within this medium by taking advantage of its intrinsic compression properties. As an illustration of its pervasiveness, the JPEG 2000 standard is based on wavelet compression. An image generated on a server will be compressed before transmission for viewing.

Clustering algorithms might use wavelets to choose the most important data to transmit first. The wavelet thresholding could be performed on the 2D clustered image or on the 3D coordinates of the clusters themselves. Higher compression would provide the user with a general sense of the cluster, without the necessity to view the

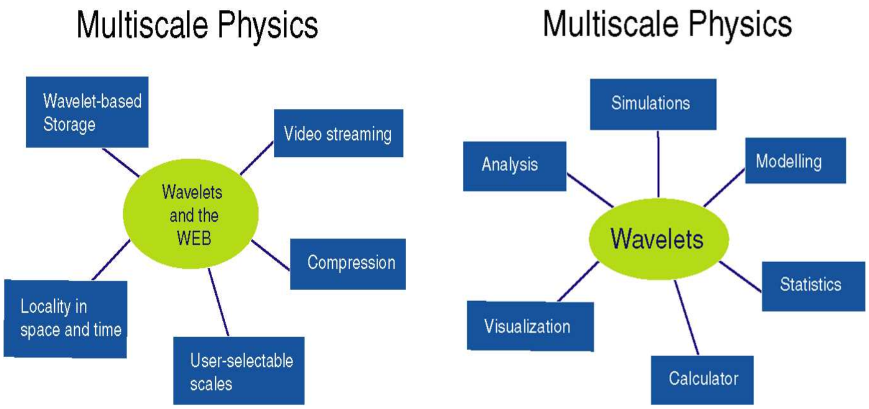

Fig. 4. Usage of wavelets for web-based activities (left) and for simulation and analysis activities (right).

potentially millions of data points. Moreover, since a new set of cluster coordinates will be transmitted, the client can manipulate those in a three-dimensional viewer rather than be constrained to the viewing of streaming bitmaps, subject to the vagaries of unreliable network bandwidth and server loads; the transmission is done only once.

A wavelet-based toolkit serves many functions. Animations are becoming the tool of choice to interact with the data. The sheer number of frames that must be transmittted overloads most networks. Video streaming techniques based on wavelets are pervasive. Results from wavelet-based numerical simulations might be stored in wavelet space (as a collection of coefficients associated with a time-dependent grid). It is then imperative to develop tools to manipulate this data in a manner that minimizes the excessive transformation of data between physical and wavelet space. A useful tool in this regard is the wavelet-based calculator to help users explore their data through the computation of auxiliary variables. Algorithms to multiply, divide variables in wavelet space will permit users to manipulate data in a flexible way over localized regions in space, over a user-specified range of spatial scales. Scale selection is straightforward through the use of band-limited wavelet thresholding.

4 Visualization with Amira

Experimentalists have been using visual techniques much longer than researchers conducting computer simulations (van Dyke 1982). Recently, the data to explore has become so voluminous that the number of pixels on a typical computer screen is three orders of magnitude less than the number of degrees of freedom of the largest numerical simulations, currently on the order of 1000^3 grid points. Clearly, visualization is no longer sufficient in itself to clarify the data. Instead one must combine visualization with datamining techniques to extract from the data features of relevance to the scientist. For example, in mantle convection, hot plumes are coherent structures of geophysical interest. Once the structures are identified, automatic extraction algorithms data must be developed, along with the tools to facilitate their display and interactive exploration. How to visualize these structures is by no means evident. Issues that must be resolved include how to represent data (isosurface, volume rendering, cross-sections), how to express their time evolution, how to use color effectively to convey information that is not misinterpreted, how to provide the researcher with information on the uncertainty in the data, and how to further compress the extracted data, to communicate this information to other collaborators. With the advent of handheld devices, with resolutions on the order of $100,000$ pixels (one order of magnitude less that of a standard flat panel), it is even more important to concentrate attention on features that best illuminate the physics.

Amira is a scientific visualization package (http://www.amiravis.com) that enables researchers to quickly analyze and visualize their data through a wide variety of reduced representations. Techniques provided included arbitrarily oriented planar cuts, isosurfaces, volume-rendering, clustering, and segmentation. Amira handles several grid types, including structured and unstructured curvilinear grids and tetrahedral meshes. The developer version allows users to construct their own modules. With the help of Amira, we have coded specialized feature extraction and statistical modules that are then seamlessly integrated with the already available standard (ERLEBACHER *et al.* 2001B, ERLEBACHER *et al.* 2002A). One of these modules is a wavelet transform tool that allows the user, via a graphic user interface, to select a lower and upper threshold that controls which wavelet coefficients to keep after transforming the data from physical to wavelet space. We use small spheres to display the grid point locations where the wavelet coefficient lies within a range entered by the user. Figure 5 illustrates the use of Amira to extract plume clusters from a 3D dataset of mantle convection at $Ra = 10^6$. The dataset has 97^3 grid points. We note that the top set of plume clusters employed just 1.2 percent of the wavelet coefficients, while the bottom set represents the reconstruction using the full set of wavelet coefficients.

5 Geophysical Applications of Amira Visualization Package

Amira, or other programs like it, offer the earthquake community many outlets through which their simulation, field, and experimental data can be examined. We have already constructed wavelet modules that can interactively dissect subsets of the data, thus acting like a magnifying class. This module is ideally suited to multiscale physical phenomena.

Wavelet techniques are well suited to the extraction of features from two-dimensional imagery. Experimental images are often digitized from shadowgraphs or other local variations of the index of refraction. Similar images can be constructed from numerical simulations by computing the heat flux at the surface. An important quantity to analyze is the nondimensional areal plume or hotspot density and its variations with time in both experimental and numerical investigations. The structure and dynamics

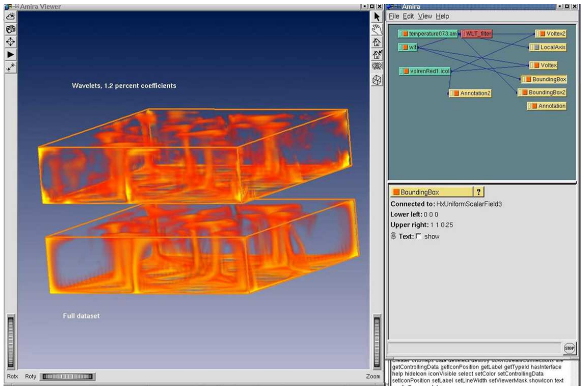

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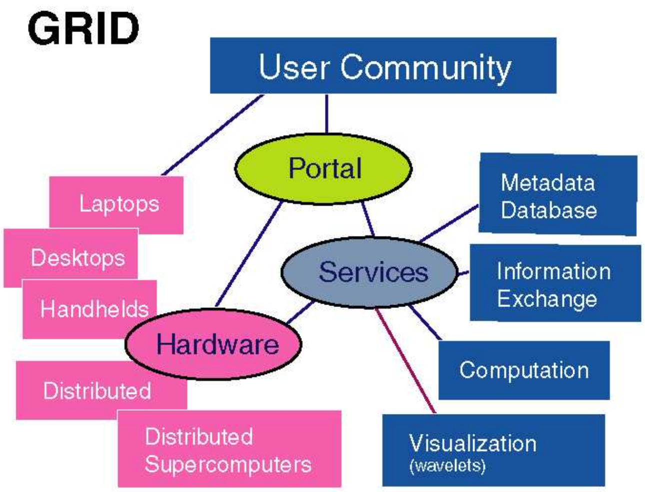
Fig. 5. Example of wavelet module built for Amira. The top right panel shown the general module layout that corresponds to the image displayed on the left panel. Below the flowchart is the user interface that corresponds to selected modules. The bottom panel allows the user to interact with the software via a scripting language. The image on the left represents volume rendered thermal plumes at $Ra = 10^6$ based on the full physical solution (bottom), and after reconstruction of the wavelet transformed temperature keeping the highest 1.2 percent of the wavelet coefficients (top).

for the nondimensional areal plume is different for whole-mantle convection and two-layered convection because of the depth of the layer used to scale the area (DAVIES 1988, SLEEP 1990).

Further applications include counting the number of hotspots (which are the surface manifestation of a hot upwelling) in mantle convection experiments, either in the laboratory or numerically. Identical techniques can be used to detect volcanoes from the surface images constructed from satellite photos. Indeed, volcanoes in Central and South America are difficult to spot from the ground and must rely on downward scanning with satellite-based interferometry synthetic aperture radar (PRITCHARD and SIMONS 2002). Our visualization techniques can help discern whether surface deformation has taken place, which would indicate the potential danger of an impending eruption. Detection of movements from continuous geodetic measurements from plate margins play a fundamental role for our understanding of the potential release of large amounts of strain energy without detectable earthquake shaking (MILLER *et al.* 2002). Time-series that monitor these movements is essential; the Amira toolkit can help clarify the physics.

A final application relates to the time evolution of glaciers. Although they evolve at very slow time scales, the rate of change of their structure sometimes changes dramatically, and has been shown to correlate with important dynamics of the Global Climate System. Measured data is in the form of time series at several locations. Statistical analysis based on wavelets will allow extraction of correlation information on a per-scale basis (MILLER *et al.* 2002, HAEBERLI *et al.* 2000). Our toolkit will also permit the analysis of glacier imagery correlated with the signals continuously collected from satellites and observational guideposts. Amira has been applied to clustering in seismicity (Kaneko *et al.* 2002).

In the current approach, seismic events are identified as flashes on a 2D map that measures earthquake magnitude as a function of location; a clustering analysis is then performed. Transfer of the resulting, potentially large, dataset across the network requires some form of compression, e.g., wavelet compression. An alternative approach is to perform the wavelet analysis directly on the seismic map and perform a cluster analysis based on the wavelets kept at a given threshold. This introduces the interesting notion of scale-dependent clustering to be explored. One should note that a wavelet analysis of the seismic data followed by clustering is not equivalent to clustering of the earthquake events followed by a wavelet compression of the resulting bitmapped image. Both approaches have their advantages and must be explored further. Alternate approaches are also under investigation (Abe *et al.* 2002).



Fox et al., Grid Services for Earthquake Science, ACES 2001: Special issue of *Concurrency & Practice*.

Fig. 6. The user community communicates with a wire range of hardware devices (left of Figure) and wish to access a variety of services, through the World Wide Web or some other medium (right of Figure). The user interface occurs through a Portal.

6 Remote Services for Collaboration

There has been substantial research activity aimed at building a GRID (Foster and Kesselman 1999), a geographically distributed collection of computing resources and services available on a per-need basis. Grandiose in its ambitions, the GRID is very much a research project, not yet used as a major production environment.

Nonetheless, there is very little doubt that as computers keep coming down in price without sacrificing any of their power, an increasing number of earthscience applications will find their niche in such an environment. In addition to standard computing resources, many other services must be provided to users to make their interactions with the system and each other more fluid. These services can take many forms and include visualization services to handle multidimensional, and multispectral datasets, registration services to allow data from multiple sources to be fused into a common frame of reference, datamining services, video creation services, and various classes of collaborative tools to allow remote access to large datasets stored in remote datastores. Figure 6 illustrates these concepts. The user community accesses a variety of hardware that support several operating systems, networking speeds, networking protocols, etc. Many if not all the users have at their disposal local client hardware that also have a range of power and display sizes (ranging from a passive Powerwall, measured in feet, to a workstation to a handheld device, measured in inches). Fox has been leading the effort to promote grid services for the Earthquake community (Fox *et al.* 2002).

7 *Remote Visualization*

Many users still do not have local access to sophisticated visualization programs, due to a combination of expense and lack of adequate hardware. However, these users will most likely have access to a web browser and some form of network connectivity, whether wired or wireless. This access enables them to conduct their simulations from afar, although the data is then only presented in table form, line plots, or surface plots. It is of paramount importance to develop the tools to provide these users interactive tools to explore their data more conveniently. This might include the capability to mine their data and display statistical information, display cuts through the data, conduct clustering analysis and so on. Data compression is one of the issues that must be confronted head on. Wavelets will play a crucial role in this endeavor since by construction, they are meant to capture localized information. This effort will be increasingly important to larger collaborative programs such as ACES (http://quakes.earth.uq.edu.au) and Earthscope (http://www.earthscope.org) as the data collected keeps growing relentlessly.

8 *Portals, Visualization Web Services*

Another type of service is data querying. Although much emphasis is placed on visualizing large data sets, there is only relatively little effort to combine visualization with a comprehensive set of querying tools. For example, users should have the ability to explore their data within a region of interest, and have at their disposal a natural user interface. Recent efforts (Garbow *et al.* 2001, Garbow *et al.* 2002a, Garbow *et al.* 2002b) have focused on the creation of a web portal that would enable users to interrogate their datasets stored on a remote server. The existing framework promotes user interactivity and portability across wired and wireless networks. The challenge was to simultaneously provide users with the flexibility to explore their data, while minimizing the effects of network latency. Currently, the user chooses one of several precomputed slices through the dataset, which is downloaded to the client. After an initial delay, he then has the ability to zoom, translate, perform statistical analysis over the entire region or over a subregion, and display histograms. Some magic lens technology is also implemented. A magic lenses is a localized spatial region through which alternate information can be viewed. For example, thermal conductivity can be viewed through a lens that overlays the temperature field. Figure 7 illustrates the interface in use. These concepts are extended in (YUEN *et al.* 2003) to include the remote visualization of earthquake clusters over the network combined with off-screen rendering, which opens the door to creating server farms dedicated to visualization Web services.

One of the most important challenges that faces these types of portals is compatibility across a range of devices. The largest displays have on the order of $10^6 - 10^7$ pixels, while current handheld devices (IPAQ, Jornada) have screens of resolution 240×320, or on the order of 10^4 pixels. This extreme range makes it virtually impossible to design a consistent user interface. An interface designed for a large screen will be very tedious to interact with on a small screen. On the other hand, a user interface crafted for a handheld device, will waste a lot of space on the larger screen of a workstation. The range of networking speed is also an issue. A fast client combined with a slow network benefits tremendously from a thresholded wavelet transform. Indeed, in this case, the cost of the transform is more than offset by the increased effective bandwidth. On the other hand, if the network bandwidth is adequate for uncompressed data, there might not be a need to perform the wavelet transform since it reduces the computational resources that could be better used for other tasks.

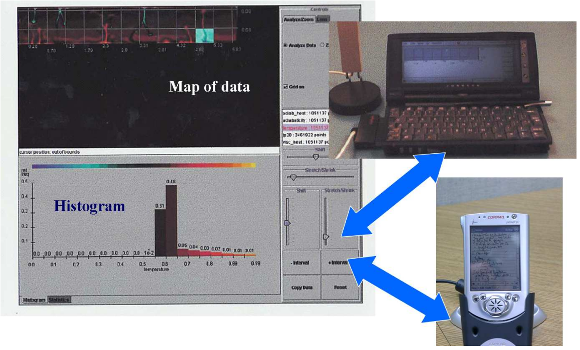


Fig. 7. The top-left panel displays the interface seen by a workstation client. Smaller versions of this interface have been designed for the Jornada and IPAQ.

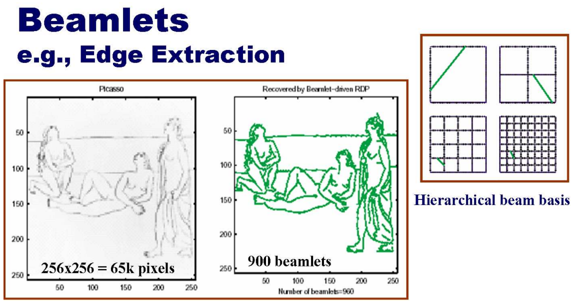


Fig. 8. The beamlet transform is applied to the original Picasso image on the left panel. Edges are extracted in the middle panel. The right panel shows four scales of a hierarchical basis. Edges in the reconstruction process are extracted from this basis. Courtesy Donoho.

9 Future Trends and Perspectives

Wavelets have formalized the notion of multiresolution spaces (Barth *et al.* 2002). Many existing paradigms fall within this purview, including multigrid methods, hierarchical methods, etc. However, these notions can be generalized further. While wavelets provide the most efficient compression of point singularities, they do not provide the best compression when singularities are distributed along curves and surfaces. Improved representations can be constructured from basis functions that are wavelet-like normal to the singularity and smooth along it. These considerations led Donoho and his collaborators (Starck *et al.* 2000, Candès and Donoho 2000, Donoho and Huo 2002) to pursue extensions to the wavelet concept to better extract curves and surfaces from complex datasets by introducing new types of hierarchical bases: beamlets, ridgelets, and curvelets. These new techniques are in their infancy and still very expensive to compute. However, they have the potential to drive many new applications, particularly in the geosciences where singularities are often one- and two-dimensional. Figure 8 demonstrates how a dyadc multiresolution basis of beamlets can be defined to extract the edges from a Picasso painting.

We believe that the current deluge of data that will inevitably result from the next generation of computer and field experiments will inevitably lead to new solutions for the entire spectrum of tasks confronted by the geophysicist, including simulation, data analysis, feature extraction, visualization, and communication. We believe that wavelets will be an essential part of the solution. However, to be most useful, they must be abstracted into toolkits, so that their use becomes completely transparent to the researchers. That is the challenge.

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