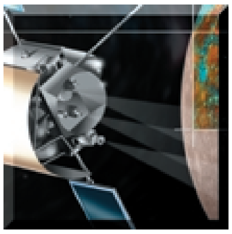

Themes and Trends in Space Science Data Processing and Visualization

Stuart R. Nylund and Douglas B. Holland

Data processing and visualization in the APL Space Department have been developed as tools to support scientific research. Every space mission has required the basic tasks of spacecraft telemetry data access, decoding, conversion, storage, reduction, visualization, and analysis. The research goals of each mission are different, requiring customized development and support of these standard tasks that draw upon our heritage of experience. Along with these changes in research goals, there have been revolutionary developments in the computer software and hardware environment. However, there are common themes and trends among all of these changes, which provide perspective on past work and insights into future development. (Keywords: Data processing, Space Department history, Space science data, Visualization.)

INTRODUCTION

With the start of operations, each new mission enters the phase of accumulating the data necessary for achieving its science objectives. These data as received on the ground, however, often bear little resemblance to the original sensor measurements needed to support study and analysis. They have been fragmented through buffering, intermixing, and encoding in engineering shorthand to fit the most information into the limited telemetry bandwidth. Noise and data gaps may further compound these changes.

Before even the most basic research can start, the processing step begins: the measurements are extracted and decoded using the detailed telemetry map provided by the instrument engineer. Data are organized and stored so as to allow easy access. Through the application of calibration information, sensor influences on measurements are removed to produce data of the actual environmental conditions. Now ready for analysis, the data are transformed and condensed optimally to address the research questions. The final derived data are often best presented graphically to efficiently reveal complex levels of detail. With the production of visualizations, the data are finally returned to the science process.

In the Software and Data Systems Group of the Space Department, we design data processing and visualization systems for a variety of space science missions (Fig. 1). These systems perform the operations to restore, archive, and access the data for scientific analysis. The design must be developed within cost, schedule, and

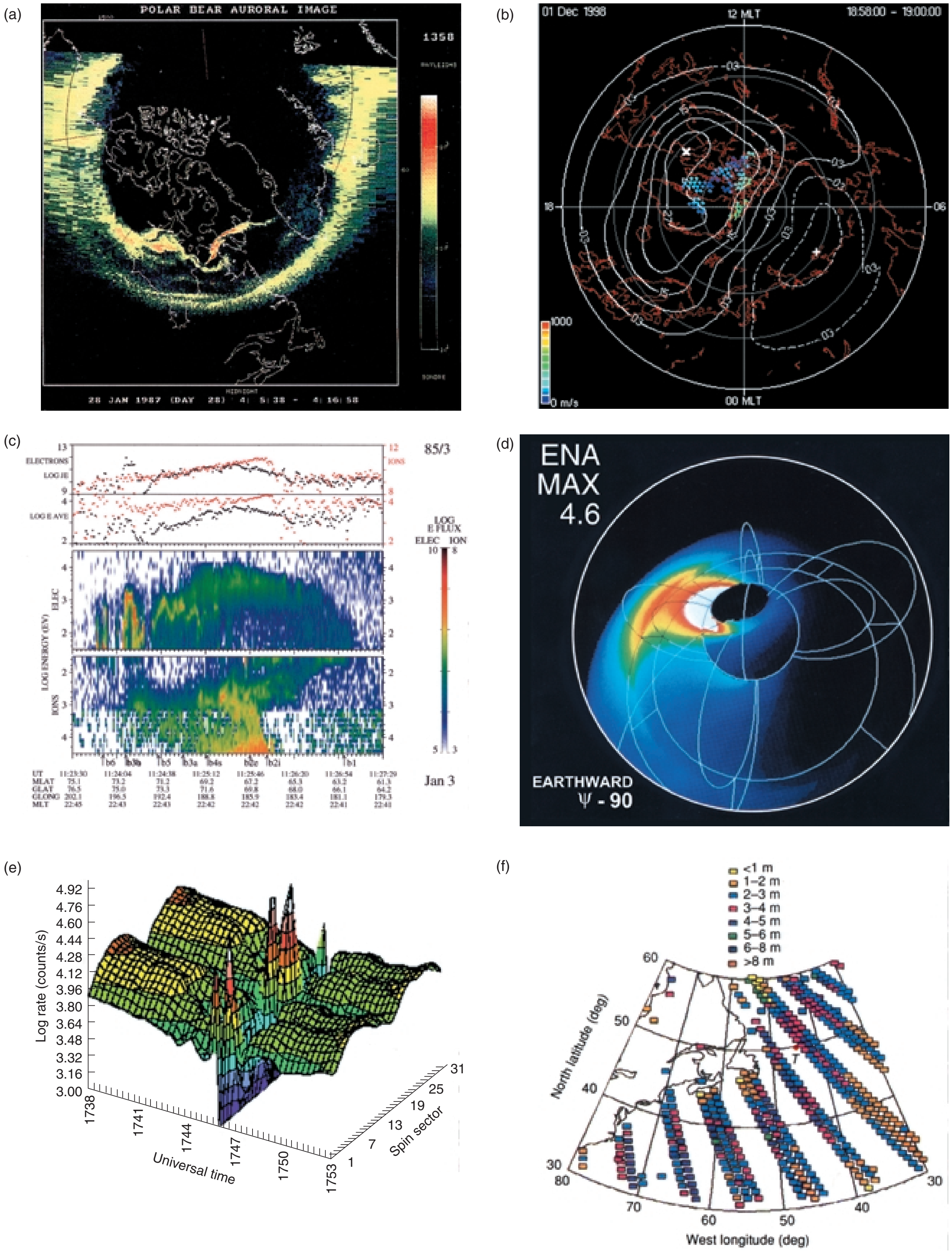

Figure 1. Examples of visualizations for Space Department missions. (a) Polar BEAR Ultraviolet Imager auroral image, (b) SuperDARN radar real-time ionospheric convection, (c) Defense Meteorological Satellite Program F7 ion differential energy flux, (d) Energetic Neutral Atom (ENA) imaging model of Earth's ring current, (e) Galileo Energetic Particles Detector electron intensity anisotropy, and (f) Geosat radar altimeter sea surface waveheight.

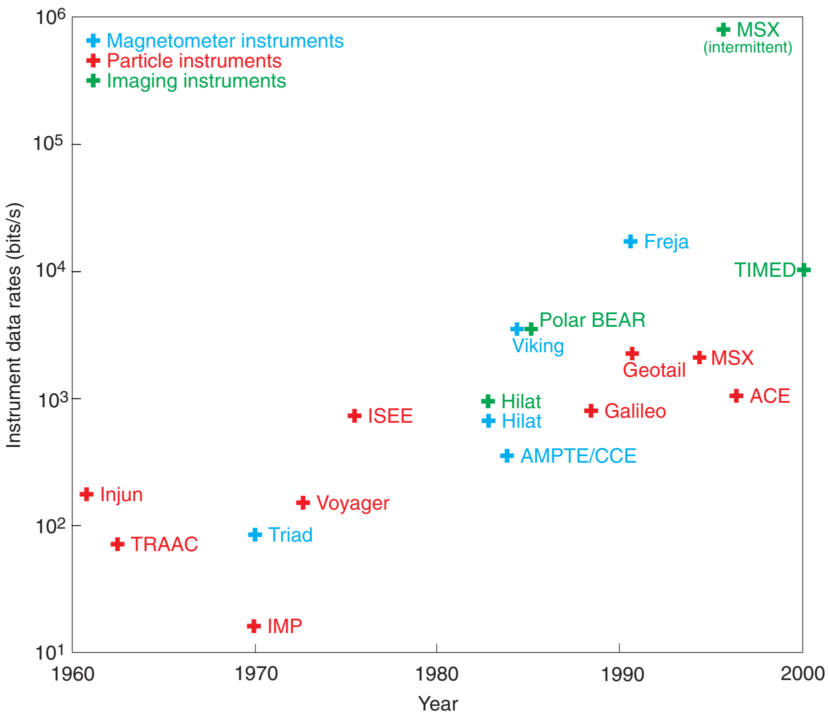

Figure 2. To derive the most scientific return for a mission, the data rate for an instrument is set as high as possible. The figure shows the upward trend in sustained data rates for particle, magnetic field, and imaging instruments permitted by increases in telemetry downlink capacity and instrument sampling and processing power. Onboard processing also allows the data rate to be more efficiently used through the application of data compression algorithms and onboard data reduction and analysis. (NEAR = Near Earth Asteroid Rendezvous, ACE = Advanced Composition Explorer, ISEE = International Sun Earth Explorer, IMP = Interplanetary Monitoring Platform, AMPTE/CCE = Active Magnetospheric Particle Tracer Explorer/Charge Composition Explorer, TRAAC = Transit Research and Attitude Control, TIMED = Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics, MSX = Midcourse Space Experiment.)

performance constraints. Whereas the general procedures of data processing and visualization are repeated for each mission, each application is unique owing to the influences of data, science objectives, and the current computer technology. Because of the research nature of these missions, we work closely with the scientists to ensure that the design meets their needs. The final design draws on our background in space science data processing and visualization systems to make the best trade-offs to maximize the science results.

Changes in Mission Data Processing

The patterns seen in present data processing work are evident in the APL space missions of the 1960s. Although lacking the complexity of later missions, they illustrate all aspects of data processing and visualization.[1] The data processing and visualization of earlier time involved analog and digital signal processing tasks. The whole scope of the task was likely to be performed by the researcher with a minimum of automated tools. Data were often processed manually to remove bad data and then were plotted manually by a graphic artist.

Whereas these higher-level tasks remained the same in later missions, scientific understanding matured with successive missions and general measurements became more focused and detailed. For example, simple isotropic measurements of relative particle count rates were expanded to absolute flux resolved in three-dimensional space as well as differentiated among particle species and at times even among specific charge states and isotopes. In addition to increased measurement complexity, the volume of measurements has also increased with the capabilities of the spacecraft and bandwidth of the telemetry systems (Fig. 2). Fortunately, the capabilities of ground networks, computers, and storage facilities have also increased, fueled by the same technological advances.

Computer science has matured, with advanced software development environments providing more rapid and complex methods for both data processing and visualization.[2] The roles of the developer and the researcher have continued to change and overlap. The varieties of data processing for APL missions and the types of instruments and research fields have continued to increase into many new areas.

Trade-Offs

A mission, which originates as a scientific enterprise, becomes an engineering effort. Trade-offs similar to those of spacecraft engineering are made in development of the data processing and visualization system. Ease of use is often in opposition to rapid development. The need to preprocess the data to speed subsequent access must be balanced by the need to keep the data as unprocessed as possible to retain the maximum information. The complexity and volume of data in the final display can slow production. The needs of the current mission must be balanced against the recognition that the data are a significant national resource[3] that must be preserved for the future. Automation, which can repeatedly create standard results, must be traded with manual control, which can produce a limited number of individualized results.

DATA PROCESSING AND ARCHIVING

Basic Data Processing Operations

Data processing and archiving are the operations required to make data available for research. Of the six stages shown in Fig. 3, three are basic processing operations. The first data operation is reconstruction, which re-creates the original instrument measurements from telemetry. It requires undoing the effects of transmission, which may include buffering, commutation, multiplexing, packetization, encoding, and compression, and results in a data volume similar to that originally created at the instrument. The reconstruction in some cases will include time ordering and missing data handling. The data as received are ordered by requirements of the transmission system; for example, all of the data from each downlink are together. Reconstruction operations often include a reorganization of the data by mission event, like orbit number, or by time (e.g., by year and day). This first level of cleaned reconstructed data is often saved as a raw data archive because it contains all of the instrument measurements that will ever be available to the researcher.

The second basic operation is data conversion, which corrects instrumental effects on measurements to reconstruct original environmental conditions by accounting for sensor efficiency, view aspect, flight processing, and sensor noise. The results are measurements in engineering units that are held as floating point numbers, a format that allows a large dynamic range of values. At this stage, the data are ready for the project engineers to use and are a starting point for researchers.

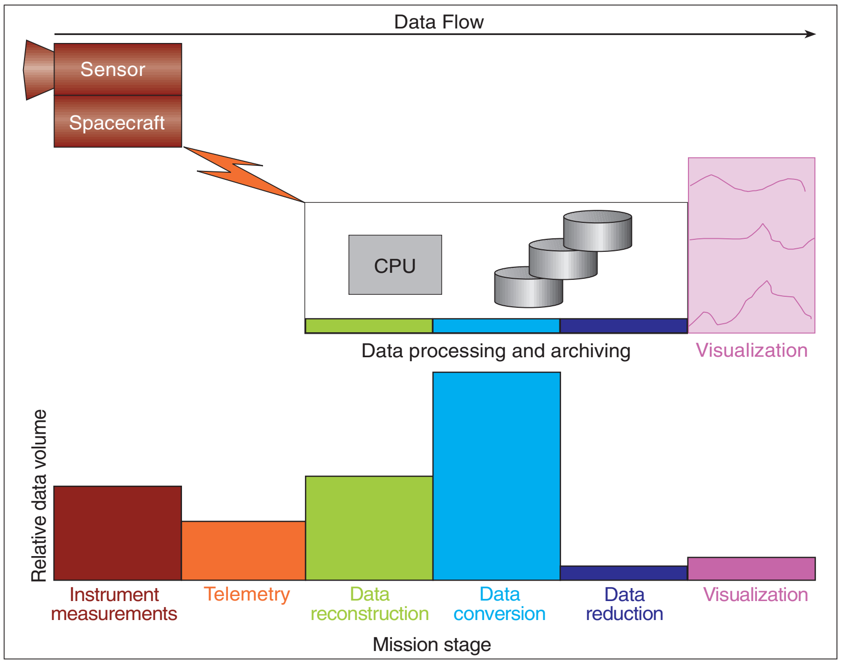

Figure 3. Process flow diagram. The volume of data varies with the stages of the mission. Whereas the relative volume differs from mission to mission, similar contractions and expansions in the data occur at each stage along the data flow.

The third basic operation in processing is data reduction. This most often requires operations for selecting just part of a data set and decreasing the temporal and/or spatial volume, usually by averaging operations. A further analysis step is often the removal of noise and backgrounds. Beyond these common steps, the processing development varies with each instrument, each mission, and differing research objectives.

Archiving

Data archives serve the researcher in several ways. They can speed access to the data, create a standard form to facilitate further analysis and visualization operations, and preserve the data for future use. Processed data archives can be tailored to the research need, with standard operations already performed and unneeded data removed. These advantages may become disadvantages if the processed data omit an important part of the raw data or if information is lost in the conversion and reduction processes, making it necessary to go back to the raw data. For this reason, one of our goals in archive creation is to keep it at as low a level as is consistent with access requirements.

Another value-added step to archiving can be the creation of indexes and key parameters extracted to facilitate data browsing. This step is especially critical in missions with extremely large volumes of image data. The MSX (Midcourse Space Experiment) mission, with imagers such as UVISI (Ultraviolet and Visible Imagers and Spectrographic Imagers), which had an intermittent data rate of nearly 10^6 bits/s, defined a standard set of parameters that were created to summarize image characteristics and thereby speed selection of images of interest.

The archives of older data sets must be preserved, as they are recognized as a timeless resource containing the only historical measurements in a field. Designs for this long-term preservation are becoming a standard part of newer missions. With the increased use of networks to support research, archives are increasingly on-line facilities. Many of the missions presented on the Space Department Programs Web site (http://sd-www.jhuapl.edu/programs.html) have or are preparing such access.

Trends in Data Processing

When we design a data processing system to meet the requirements of a new mission, many factors are balanced, but the primary ones are science requirements, cost, and schedule. These basic, driving forces are further divided into requirements of staffing and computer hardware and software development. These factors are traded to find the best mix for each mission. Early missions relied heavily on staffing because of hardware and software limitations. Newer systems such as the NEAR (Near Earth Asteroid Rendezvous) Science Data Center rely much more heavily on hardware and software automation to perform tasks.

Delays between measurement and availability depend on the balances in the design. Early missions had low data volumes and little delay. As the spacecraft systems evolved, higher mission volumes and the need for real-time access drove the development of faster processing systems. The trend for higher data volumes accelerated as imaging instruments became part of missions.

Standardization

It is critical for the processing system to support the science objectives of the mission. Mission requirements define the data characteristics, timing, volume, packetization, and delay. In early missions, system designers worked very closely with the research team. These systems were as individual as the mission. More recent systems developed by our group have begun to include standardized processing components. This trend has been accelerated by standards such as those from the Consultative Committee for Space Data Systems on data transmission in the space science community. The NEAR, TIMED (Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics), and FUSE (Far Ultraviolet Spectroscopic Explorer) missions share design components of the telemetry distribution process. These missions have taken advantage of the efficiency of having a single data center perform some of the common functions for distributed science teams.

This concept of a central data center was advanced in the AMPTE/CCE (Active Magnetospheric Particle Tracer Explorer/Charge Composition Explorer) Science Data Center, designed and operated by APL, which provided mission researchers with nearly instant access to processed real-time data from all instruments. This dedicated facility also served as the data archive and analysis center for all subsequent studies.[4] Data centers have continued to evolve with the design of later facilities for the MSX, NEAR, and TIMED missions. The recent trend for "faster, cheaper, and better" missions will promote further efforts to standardize and thereby reuse parts of the data processing systems.

Development standards are also evolving for instrument science centers. Examples are the centers for analysis of data from Voyager LECP (Low Energy Charged Particle), Galileo EPD (Energetic Particle Detector), and Geotail EPIC (Energetic Particle and Ion Composition) instruments. These centers use the heritage of specialized knowledge required for processing data of a particular instrument. The standardization of processing systems is creating the need for specialists in areas of data archiving, databases, space science data analysis, and network data distribution.

Archives are also becoming more standardized. The NASA Planetary Data System and Earth Observing System both have standards for data distribution to a wide community of users and plans for long-term data set preservation. Early development work is being done to establish standards for instrument data representations. The goal is to find a lowest common denominator form of the data that will allow similar instruments from many missions to be used in common studies, making use of standard data interchange, processing, and visualization tools.

Software Development

The development of larger processing systems and the increased need for them to support many users have increased the need for quality in the software development process. The Space Department is continuing the development of a quality assurance process. The challenge is to tailor the process for our environment and for the requirements of each program.

This balancing of requirements has led us in many unexpected directions during the history of the Department. In early missions, the researchers themselves processed data. Processing requirements and computer capabilities led later missions to move toward central processing facilities, which often caused delays. This trend evolved to the use of minicomputers in an effort to reduce delays but at the initial sacrifice of raw processing power; this problem was then alleviated by around-the-clock processing. Now, PC cost decreases and power increases are leading recent missions back to desktop processing (Fig. 4).

In the software design area, early missions focused on assembly language development. As processing power increased, higher-level, more algorithmic languages like Fortran became the standard. The newest missions are using higher-level languages such as IDL, C++, and Java, which allow the developer to more easily perform a task that could take much longer in lower-level languages. Such high-level languages offer specialized support to data analysis and visualization, graphical user interfaces, network communications, and network information sharing paradigms. They may also provide built-in support for software quality development methods. Most importantly, these tools are bringing software development back closer to the researchers and encouraging interactive development.

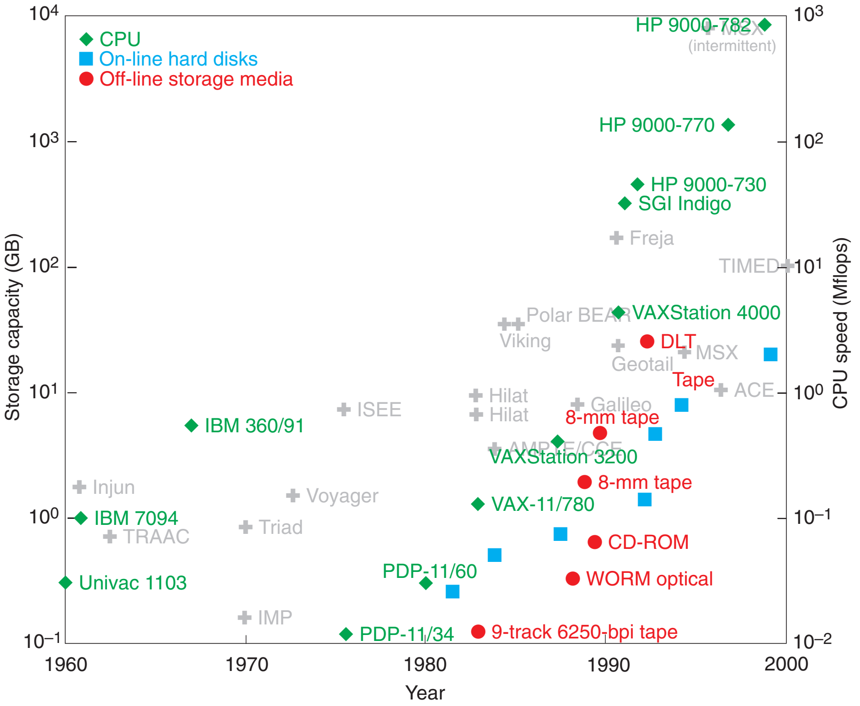

Figure 4. Against the backdrop of rising instrument data rates from Fig. 2, it can be seen that the computing resources available within the Space Department have also increased. In the 1970s, minicomputers began to be used more than mainframe systems as a way to increase user interactivity with the data and reduce processing turnaround. The resulting loss in processing capability relative to data rates was temporary. (DLT = digital linear tape, WORM = write once/read many.)

VISUALIZATION

Once processed and archived, the mission data are ready for the researchers to use. Whether used directly in archival form or reduced by additional processing, there must be a way to examine the data. Textual and tabular presentations of data are inadequate for analysis and interpretation of large data sets.[5] Visualization, the presentation of data as graphical images or abstract depictions, gives researchers far better access to quantitative information by leveraging their perceptual capabilities.[6] Graphical displays attempt to convey large amounts of data in a compact format that simultaneously presents both an overview and details.[7]

We develop software applications that provide researchers with these views into the archives of data. The design of these applications results from the influences of scientific needs, the data, and computer technology. Our software specialists, working closely with the scientists to understand their needs as well as the complexities of the data, select display formats such as line plots, images, and spectrograms for each type of data and arrange them with supporting information into page layouts. We are responsible for deciding the languages, formats, and methods by which the software will interact with the user, access and manipulate the data, and construct these layouts.

Although we have no single design consensus because of the diversity of scientific needs and data influences, there are commonalities in software design. Because our data archives often contain uncalibrated data, visualization must include elements of data processing software to convert and reduce data for display. At present, our designs maintain a distinct division between data processing and visualization software. By treating these two operations as discrete modules of function, the visualization function is more standard and reusable. The separation also makes the visualization design more focused and less complex.

Influence of Science Objectives

Visualization supports scientific research of data in three general endeavors: surveying large archives of data, studying localized portions or aspects of data, and illustrating discoveries for presentation and publication. Each task requires data processing to retrieve items from the archive and to optionally convert and reduce these data by temporal and spatial averaging before they are visualized. These similarities have encouraged the design of a single visualization tool for a mission to support all survey and, to successively lesser degrees, study and illustration efforts.

Advantages of common development and reduced maintenance costs in such a single design need to outweigh design complexity and possible performance reduction. The complexity of a visualization tool could increase unacceptably if it were required to provide all possible display formats of research study as well as illustrations. The alternative for these more demanding but less frequent cases is to rely on other visualization methods. Our common approach is to use a commercial graphics application on a PC (e.g., MATLAB, Mathematica, Igor, Noesys, and even Excel) to create customized displays. The user iteratively constructs a display layout from input data (usually columns of text). Although useful for this task, these applications lack the robust bulk processing capability that the visualization tool provides for survey work.

For publication-quality visualizations, the graphic artist still serves an important role in enhancing computer-generated displays or composing figures that are beyond the ability of either of the previous methods. In the early missions, this was the only method for providing illustrations for scientific journals; however, the quality of computer visualizations has improved dramatically.

Beyond creating views that the scientists need, a visualization system must be intuitive to operate and sufficiently quick in producing results. Tedious or confusing interfaces and long processing delays only distract or frustrate the researcher's focus on science. Commercial programs with pull-down menus have done much to simplify how users can enter input. These interfaces are now often used in our designs, such as that shown in Fig. 5, to guide users to lists of options rather than requiring them to be remembered. Alternately, visualizations can be used as a key to select further visualizations. When the Galileo orbital path, shown in Fig. 6, is clicked on at any point along its track, detailed data are displayed for that period.

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Collecting data ...
Displaying data ...
Display Complete
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Action Required: None Required.

Figure 5. An example of a multiple-window widget interface for a visualization tool. To control display options, the user interacts with a base window and is presented with pop-up windows containing default choices that the user may change.

Researchers are regaining a direct involvement in visualization that was once common in early missions when data volumes were low. Although far from true for all, some researchers have been limited to interaction with data through programmers. This trend is reversing in the Space Department. The desktop PC is the central location for the researcher's activities of e-mail correspondence, word processing, and information retrieval via the World Wide Web. With graphics applications, telnet connections, and ftp transfers, personal computers have become functional platforms for analysis in which our visualization designs must also be able to operate.

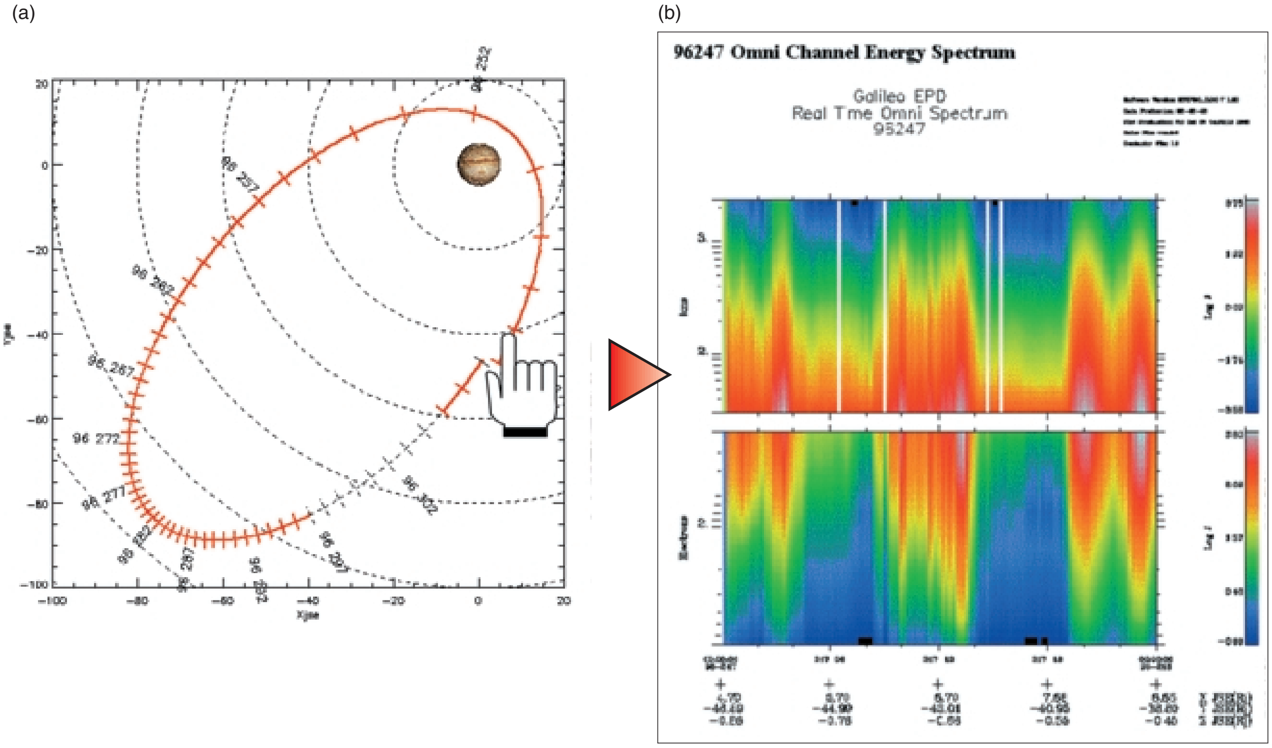

Figure 6. A touch-sensitive orbital plot display (a) provides access to Galileo EPD energy spectrograms (b).

Influence of Data

Space Department missions have resulted in measurements of charged particles, magnetic fields, cosmic rays, and the electromagnetic spectrum (from radar through infrared, visible, and ultraviolet frequencies to gamma rays) as evidenced in Fig. 1. These measurements can be grouped as either remote or *in situ*. Remote measurements are of distant conditions that propagate to the sensor, such as starlight measured by photometers, whereas *in situ* measurements are of conditions directly encountered by the sensor, such as the field measured by an orbiting magnetometer. For visualization, the distinction is significant because the display construction and formats differ. Remote sensing data are rendered most usually as an image, meaning a likeness of the actual object, while *in situ* data are rendered abstractly, e.g., a line plot.

Creating an image display is more than assembling picture elements, or pixels, in rows and columns on a screen. Each pixel represents a data measurement by a sensor element that must be adjusted for size in the final display using supplemental information. As seen in Fig. 1a, the pixels from the orbiting Polar BEAR Ultraviolet Imager are more finely grained in the center of the image than at the edges where the Earth curves from view. Such tuning is derived from a detailed understanding of the attitude of the spacecraft and look direction of the sensor. To enhance the understanding of the data, geographic coastlines and map gridlines may be added, when appropriate, by a detailed reconstruction of spacecraft position that is combined with the attitude and look-direction information.

For *in situ* data, a display format must be chosen that is most appropriate for either illustrating the data or enhancing data features. In Fig. 7, several energy channels of particle data are presented in two different display formats. The upper line plot better conveys absolute data values while the lower spectrogram gives a better overall relational view of the channels. A wire diagram as illustrated in Fig. 1e conveys still different meaning. In general, increases in data complexity, defined as more distinct but related information, have resulted in the reliance on more densely populated plots. The use of color is a standard method to address this demand.

As much as any factor, the growth of data rates and hence the volume of the data archives have driven the need for automating visualizations. Where it was once possible to plot data by hand with reasonable precision from tables of numbers for the missions of the 1960s, the volume of data to be shown made it necessary to program plotting devices to render line plots in the 1970s and, by the 1980s, color displays.[2] When individual measurements became too numerous to follow, displays of time-averaged data for all or representative data items were designed for researchers to inspect conveniently. Survey or standard data plots, which cover a fixed time interval such as an orbit or a day, have become a routine adjunct of data processing. The number of different types of these survey plots depends in part on the complexity of the instrument. The simple Geiger counters of missions such as Injun I have been replaced by instruments that not only count ions but distinguish their type, time of arrival, direction of travel, and energy. This increase in measured characteristics compounds the number of possible display combinations.

Influence of Computer Technology

Whereas the growth in size and complexity of data has presented new challenges to visualization, improvements in computer technology have often

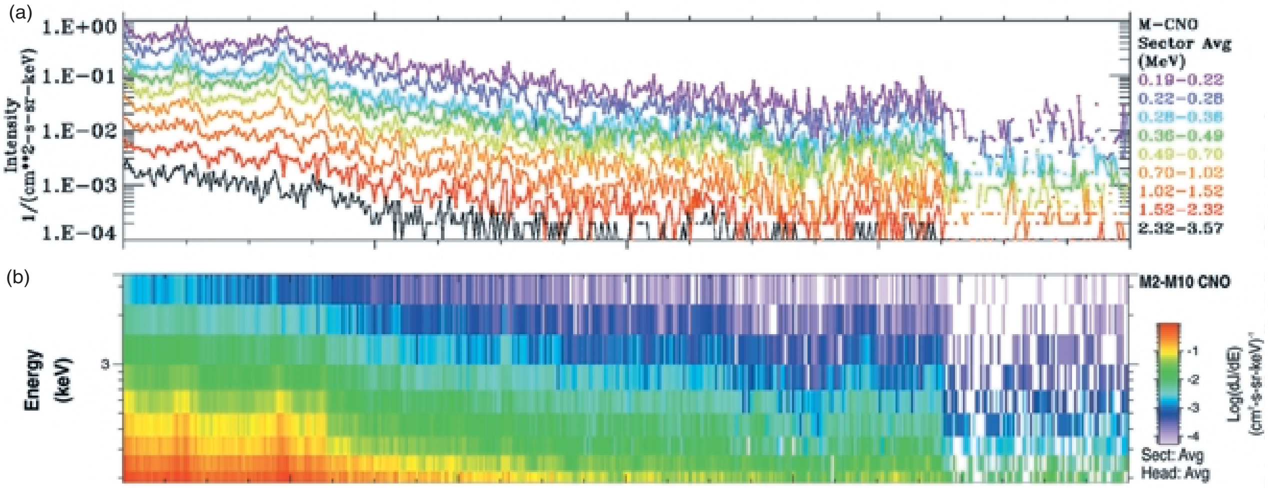

Figure 7. Identical data presented in (a) line plot and (b) spectrogram format to illustrate the data presentation strengths of each.

provided the resources for improved designs to meet these challenges. To illustrate this concept, it is useful to think of two idealized designs for satisfying researchers' views into the archived data. One creates displays of every possible data combination and stores them for instant retrieval. The other uses software that lets the researcher compose and instantly create any possible display. While neither approach is possible, our actual approach is to use aspects of these two methods: to create a limited set of standard plots for survey studies and to provide a software tool for the researcher to create nonstandard displays of data. How well this design works depends largely on its flexibility and how promptly it performs.

Price and performance improvements in hardware and software have improved the achievement of this design. With larger and faster disks, more of the data archive can be stored on-line and read faster; more preprocessed standard plots can be cached for quick display. With faster processors, the software runs through its tasks more quickly to create the displays and standard plots. Newer versions of operating systems and programming languages can produce similar improvements through better efficiency. These returns have the additional benefit that they require little or no change to our application software.

Innovations in computer technology increase the visualization design by providing new methods of design to produce better results. PCs, the Internet and the Web, MPEG and QuickTime movies, and inexpensive color printers are just a few innovations that have greatly improved what can be done. Two successive missions illustrate the effects and the pace of innovations. In 1984, for the AMPTE/CCE MEPA (Medium-Energy Particle Analyzer) particle instrument, researchers walked to a central terminal room to execute individual graphics programs for each type of color plot (see Fig. 8a), which were then displayed on a shared TV monitor. Hard copies of these plots were made with a 35-mm camera, as were the standard data plots that were distributed for the mission as packets of slides.

In 1993, for the Geotail EPIC particle instrument, researchers were able to create more detailed plots (Fig. 8b) using a single software tool that, running on a central workstation, could display the plots on their desktop PC. Color plots could be printed, and standard plots were distributed as books of plots. Since 1995 the entire set of standard data plots has been available as electronic GIF-formatted images for Web users. The entire EPIC data archive is now being made accessible from the Web so that users will also be able to select and download data of interest as text listings to create their own images.

The distinction between workstations and PCs continues to blur. Workstations are being equipped with fast and inexpensive PC CPUs, while PCs are being installed to run workstation operating systems such as Linux. Placing systems on desktops provided the important extension of data access to the scientists. Whether the desktop system performs this visualization, and even the underlying data processing, will largely depend on the performance and pricing of available hardware.

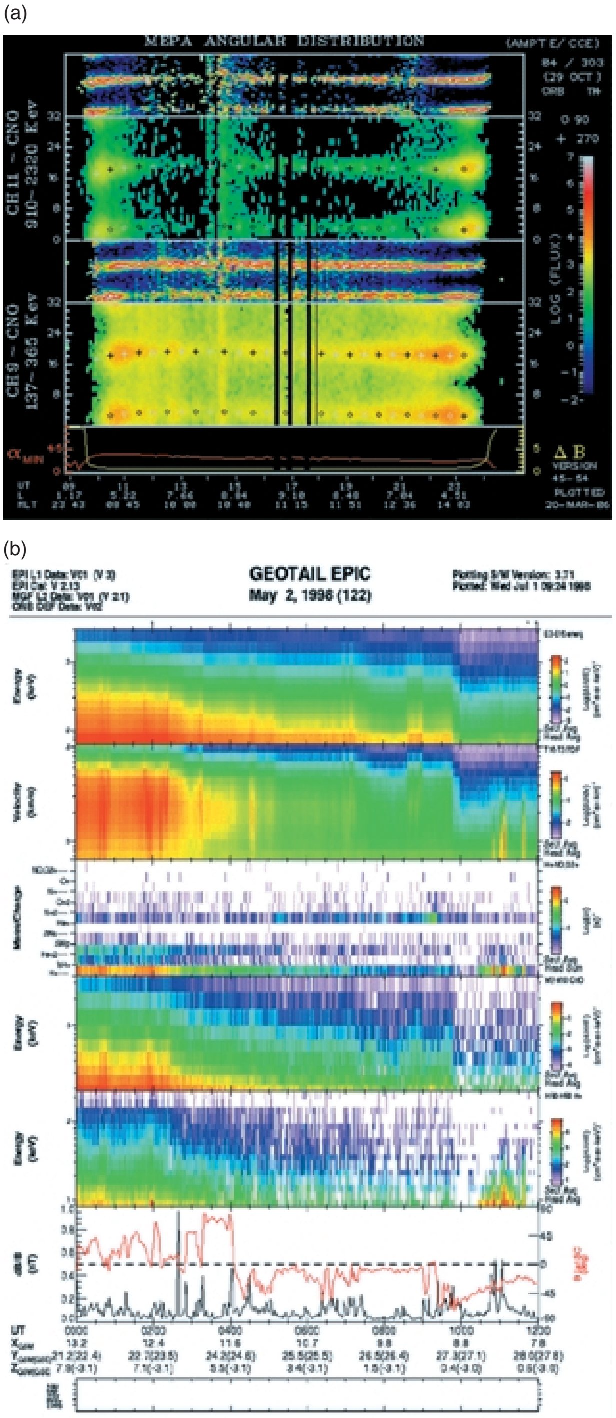

Figure 8. Examples of summary displays for two particle instruments: (a) AMPTE/CCE MEPA from the 1980s and (b) Geotail EPIC from the 1990s. Advances in display and reproduction technologies permitted greater detail to be shown.

User access to visualizations is as important as their creation. Researchers benefited when PCs enabled them to remain at their desks to view graphics displays. Expanding the access to these visualizations across the Internet is equally important. Space science researchers have a long tradition of collaborative exchange of information among the national and international science community; this tradition was the driving force for the creation of the Web by particle physicists at CERN (Conseil Européen pour la Recherche Nucléaire).

Whereas the Internet and the Web will continue to provide new capabilities, much can be done to take advantage of the current potential. Beyond providing only displays of refined archival data, the SuperDARN Web site displays real-time radar images (Fig. 1b) from remote automated arrays (see the SuperDARN entry under the Space Department Programs Web site). For the Polar BEAR Ultraviolet Imager, MPEG movies (Fig. 9) of substorm intervals have been assembled by supplementing the data frames with transmorphosed frames (see the Auroral Particles and Imagery entry at the same site). Views such as these enable researchers to share dynamic images with the community that have only been available at their facility and that were never possible through publications.

FUTURE CHALLENGES

How can we best serve our users in the future? We must remain closely involved with the space science research that we support and informed of the discipline's trends in data processing and visualization. We must also continue to extend our expertise in software and hardware systems so as to take advantage of the rapid advances in these fields.

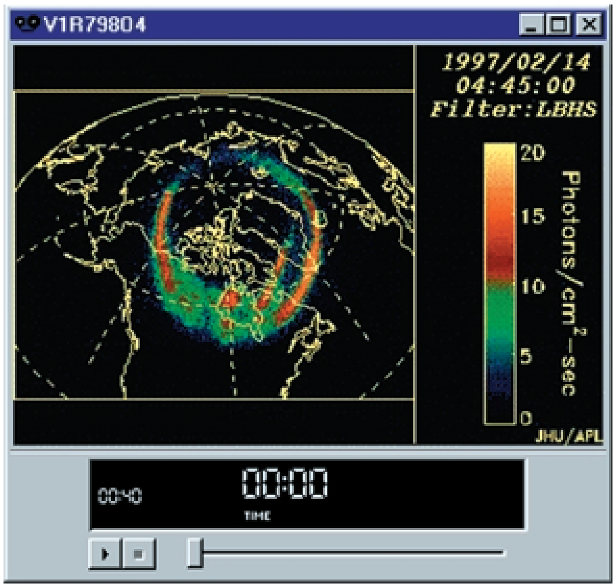

Figure 9. MPEG movie presentation of Polar BEAR Ultraviolet Imager substorm data. This format, available on the Web, shows the dynamics of the auroral imagery.

Researchers are increasingly focusing on multiple instruments and on combinations of ground and space measurements. Standards in data sharing and visualization will aid these efforts. Reductions in spacecraft size make it likely that a future mission will fly a cluster or swarm of satellites. Studies of this type will need processing methods that allow for the effects of propagation delays. Practical visualization techniques will be needed that can display volumetric data. Currently, data archives are optimized for the studies of each particular mission. Future data archives will make the data accessible to a wider range of users and will encapsulate the knowledge of the mission data set in the archive to benefit other users. Sponsors are requiring that data sets be made available to give more return on the mission costs. The challenge will be to meet cost and science goals of active missions while providing the systems to deliver these data to the community from data servers on the Internet to portable laptops employing archives on CD-ROM.

Processing and visualization tasks are currently constrained by the system and the software development time required to best use the bounty of available hardware and software tools. The solution lies in increased specialization of people and of development areas that will allow better use of this focused knowledge. These segmented tasks will increase the ability of software designers to adjust to science and technology advances.

The design of data processing and visualization systems is practiced in an environment of change in which the field of space science is advancing and the field of computer science is refining into an engineering discipline. Given the nature of scientific research to avoid repetitive studies, designs may not be wholly duplicated from one mission to the next. Because of the continual advances in computer technology, no design can be expected to remain unaltered, even for the life of a mission. Scientific research, as an application of computer resources, encourages these new designs to better facilitate its advancement. In this environment of change, the future challenges of our group will be to continue to optimally apply advanced technologies and methodologies of computer science to enhance the research returns of Space Department missions.

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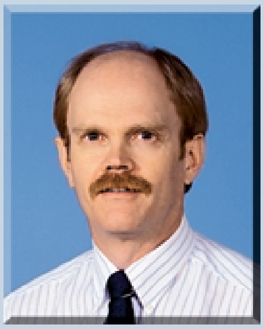

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