LORA L. SUTHER

IMAGING THE SOLAR SYSTEM WITH COMPUTERS

The methods used to analyze spacecraft data have evolved over the past 30 years in response to the increasing complexity of instrumentation and the growth of computer capabilities. A historical view of this process is presented, as well as a glimpse of future problems.

INTRODUCTION

Earth's environment and the solar system have been explored with space probes for more than three decades. The subsequent analyses performed to understand the interactions within our solar system are increasingly demanding. Each generation of spacecraft instrumentation has introduced complex, intricate sensors that produce an ever-increasing amount of data (Fig. 1). The reduction, processing, and analysis of these voluminous data streams require a flexible, interactive computing environment, not only to provide access to the data, but to provide a variety of computing tools to "see" the solar system from the data collected by the spacecraft sensors. Presenting the data in a visible format has evolved from simple hand-generated plots to full-color images generated by computer software. The technology for imaging our solar system has expanded with the availability of ever-improving computer hardware and software. Future processing techniques will evolve as these enhancements in computing technology continue.

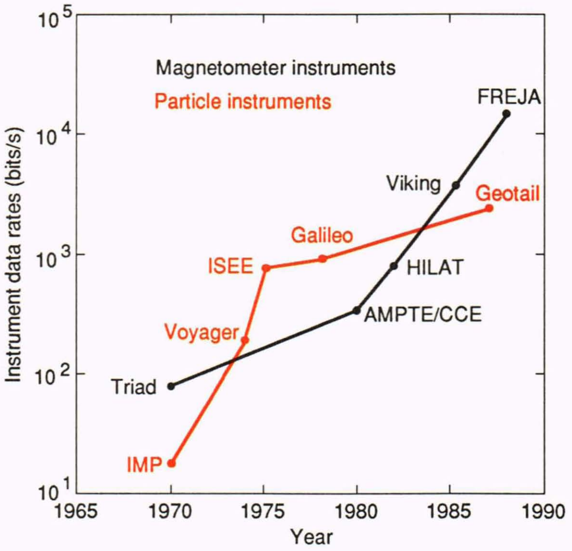

Figure 1. Historical view of instrument data rates for magnetometer and particle instruments. The data are collected 24 hours a day for the duration of the mission.

HISTORICAL METHODS FOR DATA PROCESSING

Space physicists at APL have been processing and analyzing spacecraft data since the early 1960s. Early data were acquired from particle detectors designed and built at APL and launched in piggyback fashion on Navy Transit satellites. Data from early missions (Injun I, TRAAC, Injun III) were collected and processed off-site, generating paper listings for analysis. Initial analyses were performed by poring over pages of numbers ordered by time. From the listings, tedious hand plots were produced for further analyses and publication (Fig. 2). By the middle to late 1960s, APL scientists became involved with early NASA satellites (IMP 4, IMP 5) for which data processing still consisted of listings and hand plots. Missions of this era were hastily planned with very small data-analysis budgets, compared with those of current spacecraft.

In the 1970s, APL became involved with numerous NASA satellites; data processing was improved with reliance on central computers that processed the data at APL and at remote sites. Software was designed and implemented to process the data in a completely automated fashion, generating a standard set of listings and line plots as the final product. These simple line plots, recorded on paper or microfilm, were the scientist's only view of the data. All analysis and any resulting publications would use these plots. Special plots to highlight a particular feature were created by reading the data from the original listings or line plots and replotting the data by hand in a new format.

In 1978, the Voyager program launched us into a new era of data processing and analysis; the environment changed from a batch-oriented, hands-off approach to an interactive approach responsive to the demands of the analysis. To support the data-processing requirements of the Low Energy Charged Particle (LECP) instrument on the Voyager satellites, a small minicomputer system was purchased and installed at APL. This system put the scientists in complete control of processing and analysis for the first time. Similarly to previous data-processing tasks, all data were still processed into standard formats and standard line plots. Additional software was developed to analyze special features. With full access to the data at APL and with a computer available for further processing, analysis efforts were expanded. A single event was displayed in multiple formats, and special fea-

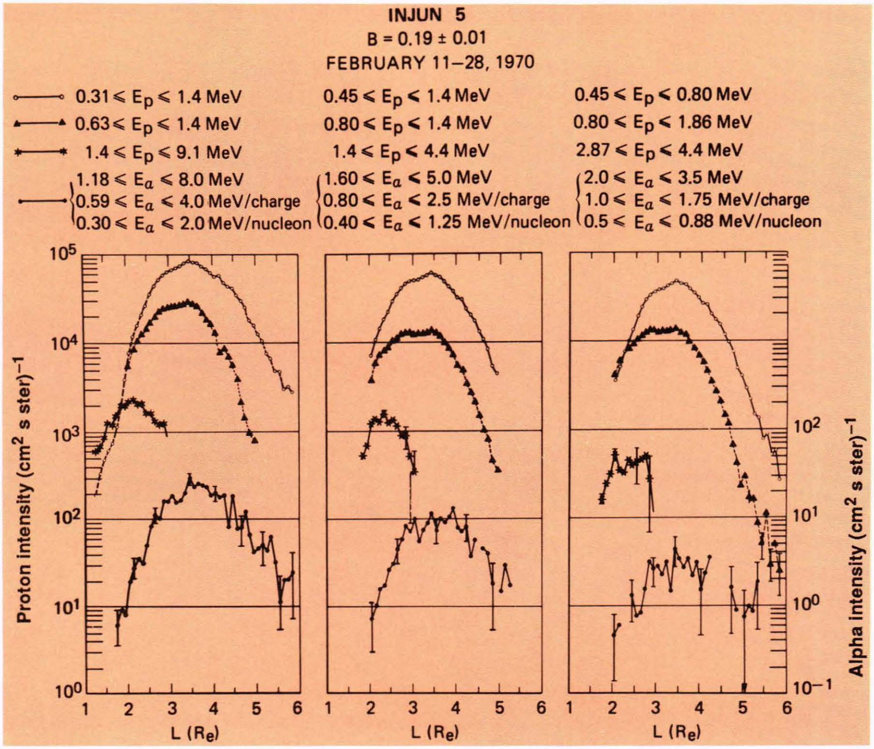

Figure 2. Hand-plotted data from the Injun 5 satellite. Intensity averages over the period 11 to 28 February 1970, computed for the three alpha particle channels, are plotted as a function of L at $B = 0.19 \pm 0.01$. Also presented in the figure, for comparison, are several proton energy channels at about the same total energy, energy per charge, and energy per nucleon as the alpha channels. (L is the radial distance [in Earth radii] to the equatorial crossing point of the magnetic field line through the spacecraft; B is the Earth's magnetic field; E_p is proton energy, and E_α is alpha particle energy.) (Reprinted, with permission, from Krimigis, S. M., and Verzariu, P., "Measurements of Geomagnetically Trapped Alpha Particles, 1968-70: 1. Quiet-Time Distributions," *J. Geophys. Res.* **78**, 7279 (1973); ©1973 Am. Geophys. Union.)

tures could be examined in greater detail. This system also made possible detailed comparisons between Voyager data from the APL instrument and data from other experiments on the same spacecraft.

Since the beginning of the Voyager program, data analysis has grown increasingly more dependent on computers. The addition of color imaging in 1981 provided a medium that could display a large volume of data with features enhanced by the color presentation.

The data analysis that we now perform relies heavily on the generation of standard data products, including averaged, compact data sets, line plots, and full-color images.

DEVELOPMENT OF COMPUTING CAPABILITIES

As stated previously, early data-processing tasks relied heavily on central computing facilities. In the 1970s, we used facilities at the University of Iowa, Goddard Space Flight Center, and the APL McClure Center, as well as a Univac 490 owned by APL's Fleet Systems Department. The processing performed on these computers was simple and slow. The Univac produced one line of output every 45 minutes. Although we still process data at the McClure Center and Goddard, most of our data processing and analysis is performed by a computing system that has evolved over the past 20 years. The progression of computers that have been used in space physics demonstrates the development of our analytical requirements.

Our first "real" computer was a Sanders box, purchased in 1975 to access data at Goddard for the Atmospheric Explorer (AE) satellite. Although it had its own processor, its function was to link via a modem to a mainframe computer at Goddard. The entire system consisted of one full-sized computer rack containing the processor unit, a terminal, and a modem. This intelligent terminal could run batch jobs at Goddard and print listings but was not equipped for graphics.

In early 1975, we acquired a Digital Equipment Corporation (DEC) PDP 11/10 computer to support instrument checkout of the Voyager LECP instrument. Software for instrument checkout and initial data-processing tasks was developed on this computer before launch. The system included the processor (rated at 30,000 simple instructions per second), 32 KB of memory, and a Linc tape system for data storage. The Linc tape emulated a disk, which was a rare and expensive item. For the tape to read a particular block, it first had to rewind, read out to find the directory, rewind, then read out to the desired data. Even a simple Fortran program of 10 lines took 40 minutes to compile and link, making the development process a tedious effort. "Patching" executable code (changing bits in machine language rather than modifying source code) proved to be viable for decreasing development time. This computer system is still used periodically to verify instrument performance.

To perform the data-processing tasks for the LECP instrument on the Voyager satellite, a dedicated system was purchased. It was centered on the DEC PDP 11/34, using a simple, single-user operating system. (This computer has proved extremely valuable over the years and continues to be used as the real-time communications processor for the AMPTE/CCE [Active Magnetospheric Particle Tracer Explorers Program/Charged Composition Explorer] spacecraft.) As originally configured, the total memory for this computer was 128 KB, and it had a removable hard disk that could store 2.5 MB of data. Although that configuration was significantly inferior to the personal computers of today, sign-up sheets were posted and scientists waited in line for access to the system; it operated for 16 to 20 hours a day. The responsiveness of the computer improved programming time, and it cost less to buy and operate than the accumulated charges incurred at the large central facilities. It provided support for the LECP data processing for the first four years of the Voyager mission, including the spacecraft encounters with Jupiter and Saturn.

In 1980, the computing resources were expanded with the acquisition of a DEC PDP 11/60 computer. Whereas the previous system was owned and operated by a single project, this bigger, multi-user computer was shared by a wide range of space physics projects. During the next two years, additions included a digitizer (for input), magnetic disk space (increasing the 20 MB included with the initial system to 600 MB), and a Ramtek 9400 color graphics system. The graphics and display system had direct memory access for high-speed loading of graphics with vector and raster support. It was attached to the DEC processor and supported one color monitor with a display resolution of 640 by 512 pixels and up to 4096 simultaneous colors on the screen, selected from a palette of 16 million colors. The hardware and software of the Ramtek system were modified to support two simultaneous users, each with a color monitor. Although the processor was upgraded in later years to a DEC VAX 11/780 and the magnetic disk space has continued to increase, the color images that have been generated, analyzed, and published during the last eight years have remained the product of this color display system.

Recently, the Ramtek system was supplemented with four graphics workstations. Each workstation has 1024 by 768 resolution with full-color capability and a processor that has three times the power of the VAX 11/780. In addition, the new graphics subsystem is attached directly to the private memory bus of the computer processing unit, which gives it excellent drawing speed. The configuration of this computing facility is shown in Figure 3.

Future enhancements of the computing facility will increase its computing power and imaging abilities. Historically, when additional computing power was needed, the typical response was to obtain a larger, faster computer. That approach required the resources necessary to support a larger computer (e.g., air conditioning, conditioned power, dedicated office space, and raised floors). The dependence on a central controlling computer proved painful when that machine was down for repairs, new installations, and normal maintenance. With the advent of smaller, inexpensive computers, each providing substantial computing power and graphics capabilities, many computing facilities are changing from a central computer to a cluster of smaller computers; computing will be performed in a distributed fashion, with smaller computers performing dedicated tasks. This transformation has started within the space physics programs with the addition of the four computer workstations. Additional, smaller computers, with increased performance, will eventually replace the DEC VAX 11/780 central computer.

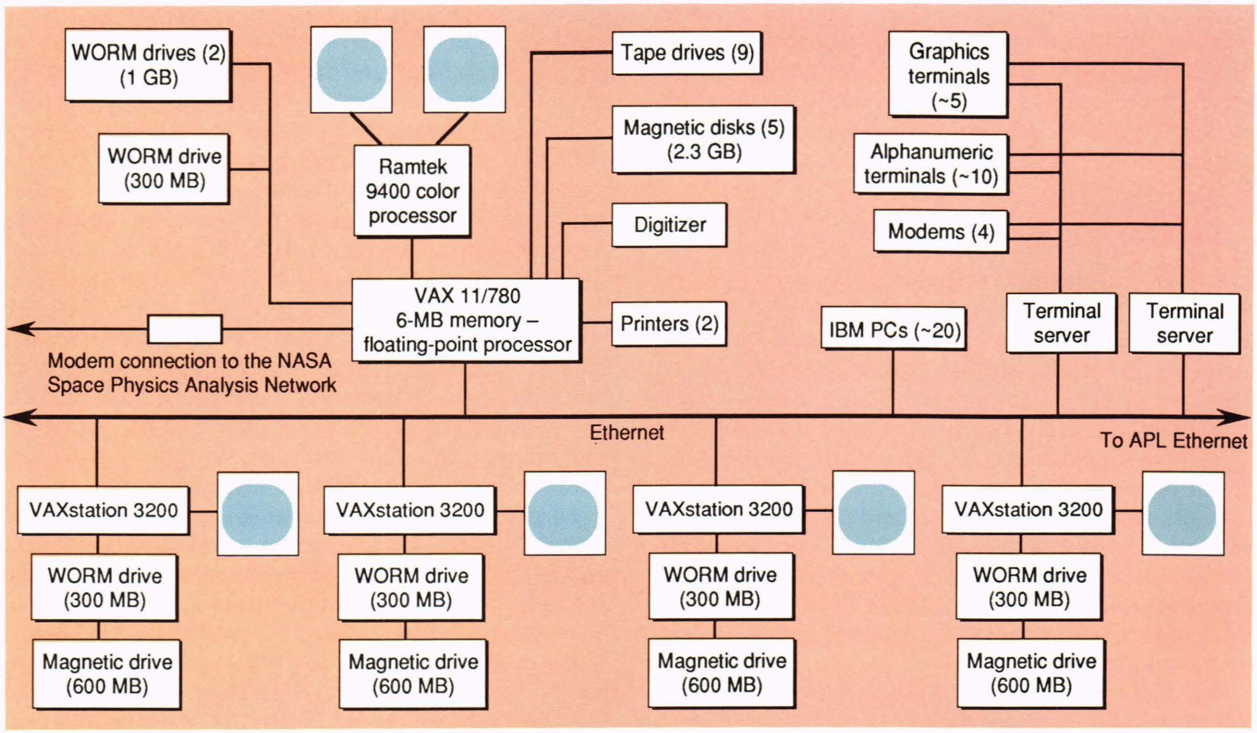

Figure 3. Current computer hardware configuration for our space physics research.

IMAGING PROCESS

A variety of images have been produced from our efforts to understand the spacecraft observations acquired in the solar system. For each data set that we analyze, one or more color images have been developed to present a visual interpretation of the complicated observations. The visual display can provide a large amount of data in a compact format; complex features are highlighted by color. A complete survey of data from a single day can usually be presented in a few images. A researcher can peruse months of data at a time, searching for events of special interest for further analyses.

Many of the data sets we work with are not inherently images of the Landsat type. Rather, they represent time series of counts or voltages versus other observational parameters that have been arranged into an image format. Examples of images that have been generated from spacecraft and radar data sets during the past eight years are described in the following paragraphs.

Magnetic Field Data from Magsat

The image created by the magnetometer data from the Magsat satellite (Fig. 4) presents the data acquired during many orbits. Each orbit is plotted in geomagnetic coordinates and appears as a track across the magnetic pole; color represents the polarity and intensity of the magnetic perturbations measured with respect to a model magnetic field. These perturbations are associated with electric currents that flow along geomagnetic field lines into and away from the auroral zones. The representation shows 24 hours of data per image and provides a "view" of auroral field-aligned Birkeland currents.[1]

Energetic Charged-Particle Data from Voyager

Two image formats have been used to display the data from the LECP instrument on the two Voyager satellites. The first format has been used to present snapshots of the encounters with Jupiter, Saturn, and Uranus. Figure 5 is a representation of the LECP view of the encounter with Uranus for the three days surrounding closest approach.[2] The spectrograms show electron and proton intensities over the wide energy range of the LECP instrument, and the line plots represent count rates of selected channels. Markings above the color-coded displays indicate crossings of the bow shock (BS), magnetopauses (M), neutral sheets (N), and five satellite *L*-shell crossings (T, U, A, M; three marks are not labeled). Markings above the line plots show radial distance to Uranus in planetary radii. A second format used by the Voyager analysis team is shown in Figure 6. The image represents the pulse-height matrix data taken during an encounter with a quasi-perpendicular shock, covering a time span of six hours.[3] The pulse-height analyzers on the LECP instrument provide determinations of various ionic species from protons through iron for energies greater than about 200 keV/nucleon. These data are collected and binned into a matrix; position in the matrix determines species, and the color intensity represents the counts in each bin. Superimposed on this image is the mean track for each elemental species as determined by instrument calibration.

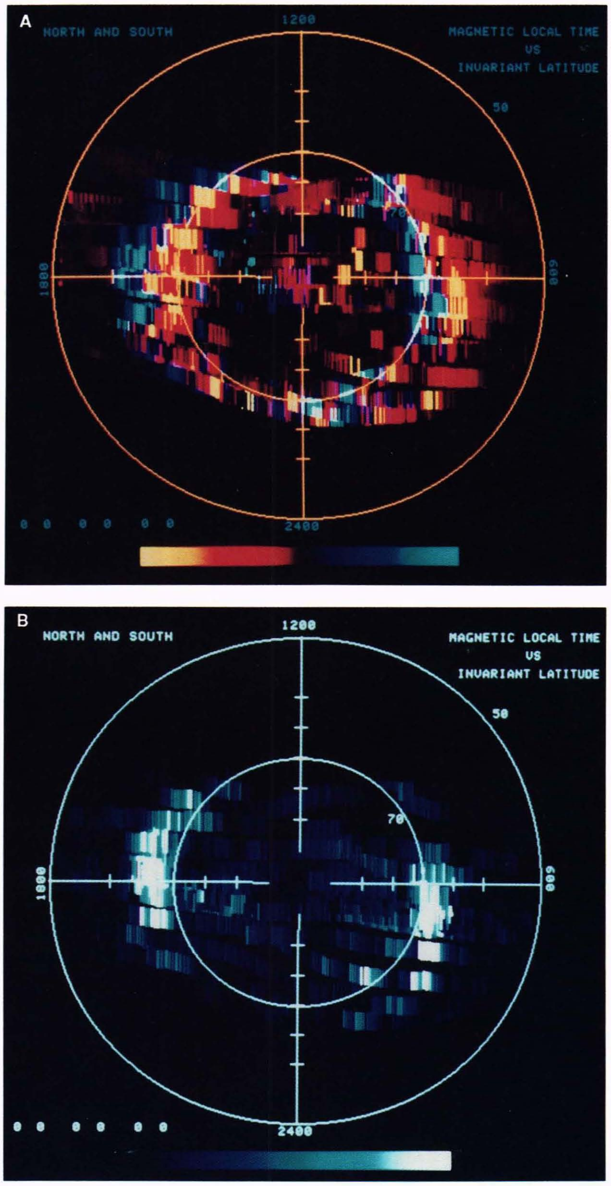

Figure 4. The Birkeland currents for the Magsat data from 21 March 1980. A. Currents are plotted versus invariant latitude and magnetic local time; blue is into the ionosphere and red–yellow is away from the ionosphere. B. A composite of the electrojet current analyses. The magnitude of the current intensity is shown by blue to white, the eastward electrojet is at dusk, and the westward electrojet is at dawn. (Reprinted, with permission, from Ref. 1.)

Radar Data from Goose Bay, Labrador

Figure 7 displays a variety of data received from the high-frequency radar installed at Goose Bay, Labrador.[4] Each panel represents the same period and displays, variously, the measured backscattered power, the Doppler velocity, the elevation angle, or the spectral width. A single panel is created by binning the data and plotting each bin at the appropriate geographic location; the resultant fanlike image represents the radar's actual field of view. An overlay is then superimposed to provide geographic features and references.

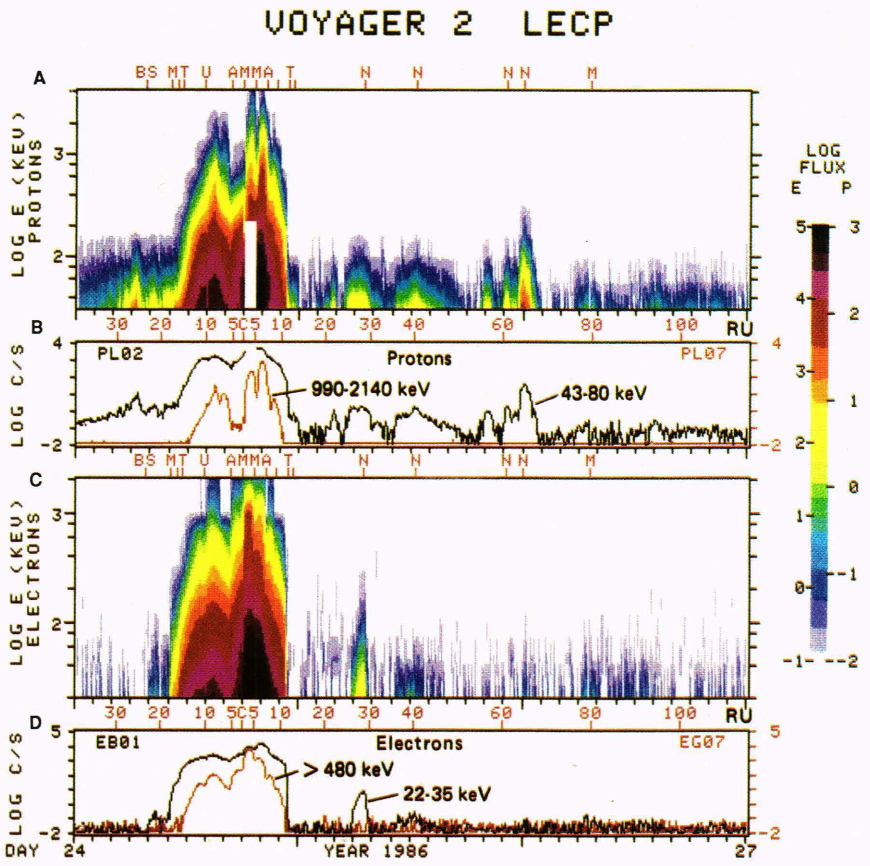

Figure 5. Color spectrograms. A. Energetic protons from 28 to 3500 keV. B. Count rate profiles for two selected proton channels (the 43- to 80-keV channel is black and the 990- to 2140-keV channel is orange). C. Electrons from 22 to 1200 keV for the 3-day period that encompasses the Uranian magnetospheric encounter by Voyager 2. D. Count rate profiles for two selected electron channels (the 22- to 35-keV channel is black and the >480-keV channel is orange). (Reprinted, with permission, from Ref. 2.)

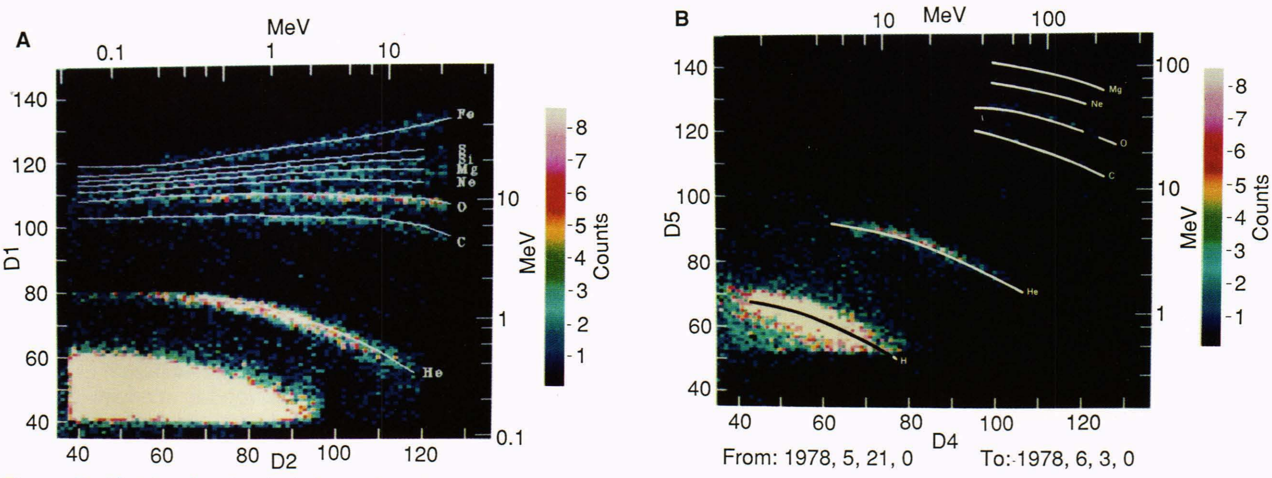

Figure 6. Matrix of pulse-height-analyzed events. The energy loss in detector D1 (5.4 μm) is displayed versus the residual energy measured in D2 (152 μm) during the energetic particle intensity enhancements associated with the 6 January 1978 shock wave at Voyager 2. (Reprinted, with permission, from Ref. 3.)

Energetic Particle Data from ISEE

Figure 8 shows data from the Medium Energy Particle Instrument (MEPI) on the ISEE 1 satellite. Each panel represents a flat projection of the unit sphere that is observed in 36 seconds in 12 spins (3 s/spin) as the telescope scans from north to south (or from south to north). The slight angle of the data relative to each panel results from the spiral track that this continuous scanning and spinning motion traces on the unit sphere. Measured contours of look directions corresponding to particle pitch angles of 60°, 90°, and 120° are overlaid in white. This representation shows the evolution of an event by displaying four nearly consecutive spheres on one image for both ions and electrons.[5]

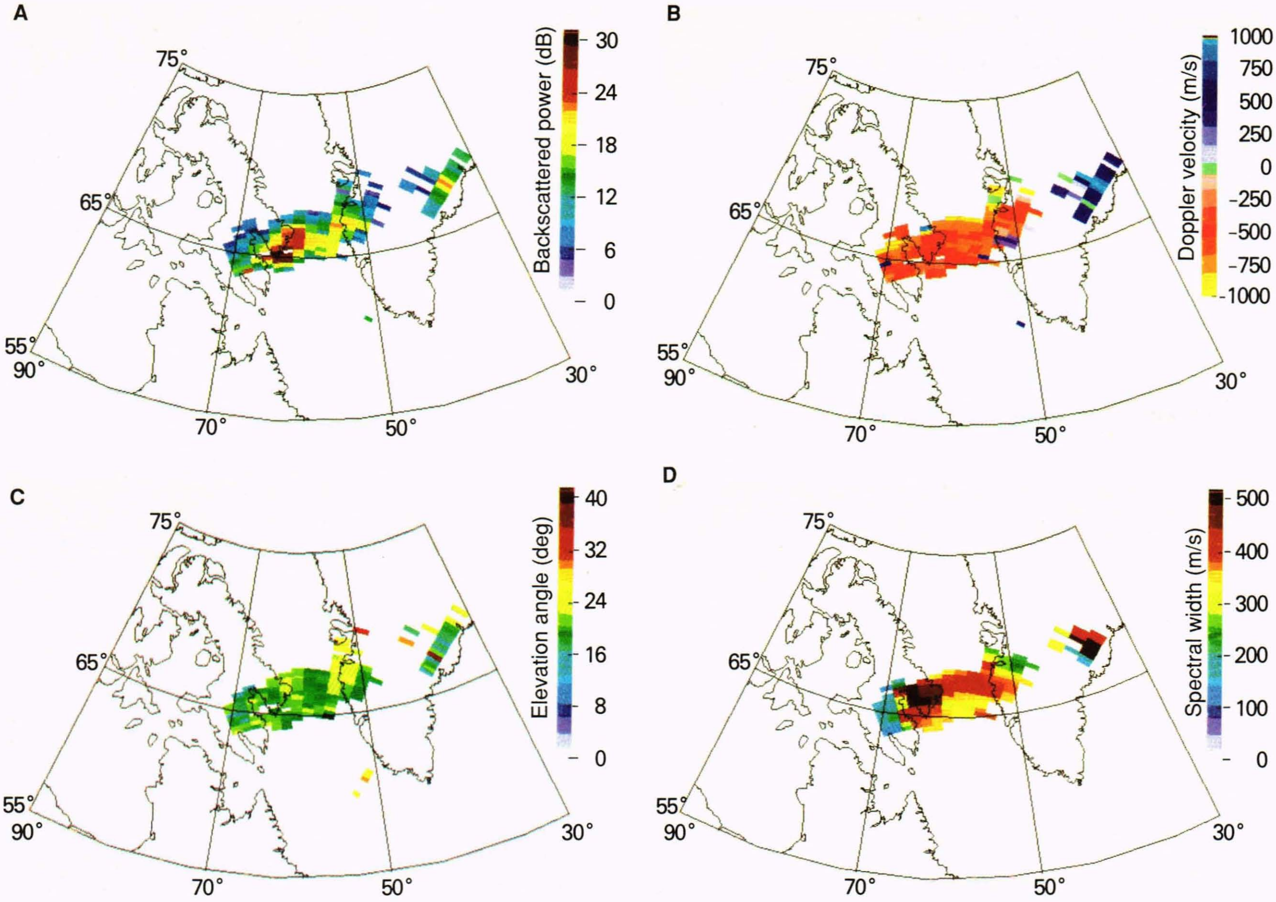

Figure 7. Maps from the Goose Bay radar. A. Backscattered power. B. Doppler velocity. C. Elevation angle. D. Spectral width for the scan beginning at 1434:45 UT on 13 September 1987 (frequency = 11.5 MHz). (Reprinted, with permission, from Ref. 4.)

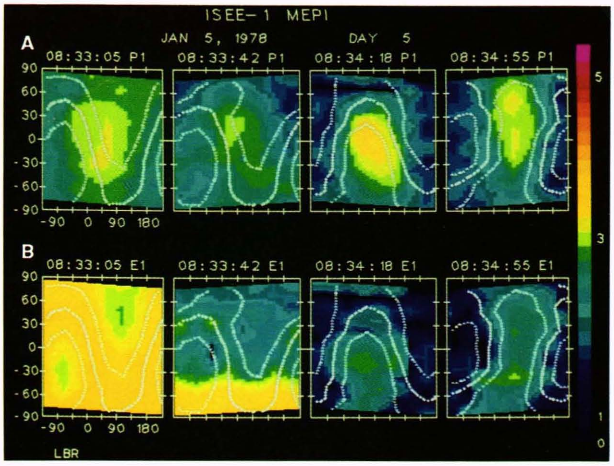

Figure 8. Detailed ISEE 1 MEPI ion and electron three-dimensional distributions. A. 24- to 44.5-keV ions. B. 22.5- to 39-keV electrons. The convention for the angles is the ground support equipment look direction of the detector (e.g., $\theta = 0$). $\phi = 0$ represents antisunward particles. The time given is the center-point time of the 36-s scan. (Reprinted, with permission, from "Kinetic Aspects of Magnetotail Dynamics—Observations, *Magnetotail Physics*, A. T. Y. Lui, ed., Johns Hopkins University Press, Baltimore and London, 1987; ©1987 by Johns Hopkins University Press.)

Simulation of Energetic Neutral Atoms

Figure 9 shows the results of a simulation of energetic neutral atoms based on actual observations of the MEPI on the ISEE 1 satellite. The projection of this three-dimensional image provides a fish-eye view of the earthward hemisphere of the sky. The Earth disk and its terminator are outlined; circles in the magnetic equator at 3 and 5 R_e are connected by radial lines every 3 hours of magnetic local time (noon to the right). Magnetic field lines for $L = 3$ and 5 are drawn in the planes of magnetic noon, dusk, midnight (to the left), and dawn (toward the reader).[6] (L is the radial distance [in Earth radii] to the equatorial crossing point of the magnetic field line through the spacecraft.)

Ultraviolet Auroral Images

A view of the aurora in the ultraviolet is presented in Figure 10, as seen by the Auroral and Ionospheric Remote Sensing instrument on the Polar Beacon Experiment and Auroral Research satellite.[7] As the satellite moves in its orbit, a 3-second horizontal scan of Earth is made from side to side. Each position along the scan (236 steps) is mapped to a geographic latitude and longitude; corrections are made for limb brightening and the curvature of the Earth. Once the image has been

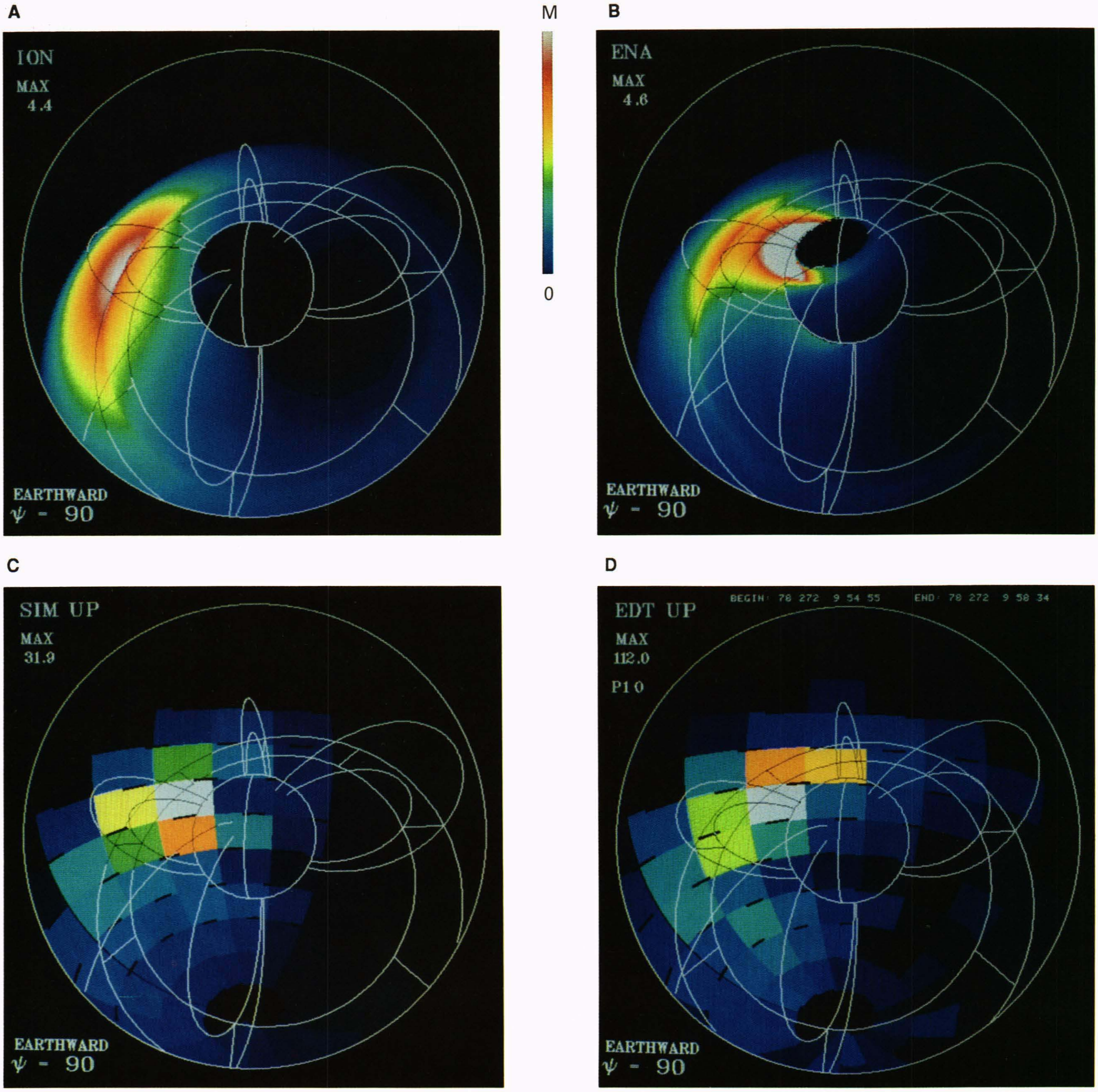

Figure 9. Simulation of an energetic neutral atom image of a storm-time ring-current population, represented in the earthward hemisphere, as viewed from the ISEE 1 satellite. (Reprinted, with permission, from Ref. 6.)

created, geographic features and magnetic local time are added.

FUTURE TRENDS IN DATA PROCESSING

The processing tasks and analytical requirements of space physics research have expanded rapidly over the past 28 years; the next decade will prove just as challenging. Driven by the data rates predicted for future instruments (estimated now to be in the range of 5 to 10 MB/s for imaging instruments and 30 KB/s for nonimaging instruments), we must rely on new hardware and software techniques for our analyses.

The first problem that arises is storage of large quantities of data. Current projects such as a solar magnetograph produce 4 to 8 GB of data per day. Future instruments may require larger volumes of data. Additionally, about 15,000 of our existing data sets reside on nine-track tapes that must be spun periodically to prevent degradation. Data storage requirements call for a higher-density, longer-lasting, and more reliable storage medium. Numerous products are now available: compact disc read-only media; write-once, read-many (WORM) optical platters; and magneto-optical (erasable optical) platters. All of these media offer compact and reliable data storage while providing quick, direct access (no spacing down the tape to get to the correct position), although lack of standards for media format has restricted their usefulness.

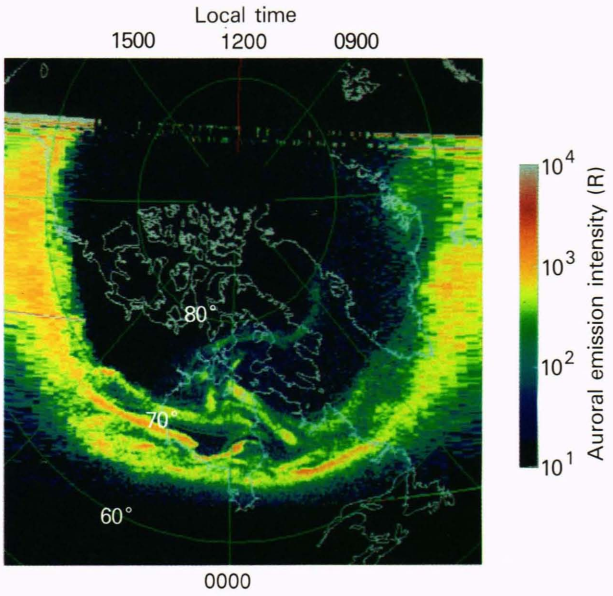

Figure 10. A global auroral display during an active geomagnetic period on 29 January 1987, from 0436:19 to 0446:49 UT, observed from Sondre Stromfjord station. Note the enhanced auroral brightness of a few thousand rayleighs and active discrete auroral features in the midnight sector in this 135.8 ± 15 nm emission band. (Reprinted, with permission, from Ref. 7.)

Another solution to massive storage requirements is data compression. For many years algorithms have been available that can decrease total storage requirements by one-half or more (the compression factor is highly dependent on the data type). Data compression (and decompression), however, is a computationally intensive task. Historically, this method could not be implemented, because of limited computing power. This limitation is disappearing as computer workstations double in computational power every 12 to 18 months (on average), making it feasible to work with algorithms that were previously unreasonable to implement.

A more significant problem facing the space physics community is how to view the quantity of data that an instrument can now produce. As shown previously, in the 1960s and 1970s, two-dimensional vector plots could summarize many data sets. The 1980s were truly an era of color images, and the use of this third dimension has been very successful in summarizing our data. Although the computer will continue to provide us with such a visual representation of our data, expansion into new areas will be needed. With the advent of new computer hardware (parallel processors) and new software techniques (neural networks),[8,9] the computer can "learn" what to look for. The computer may pore over gigabytes of data each day, reporting what it saw and, most important, what looked "unusual."

SUMMARY

Techniques for processing and analyzing data in space physics research have evolved with the rapid advances in computing hardware and software. The evolution has taken us from listings and graph paper to the networked environment of high-power graphics workstations. Color has dominated the past 10 years of our analyses and will continue to be essential in imaging our solar system. Enhancements of computing hardware and software will enable the development of new techniques to meet the analytical demands of the future.

REFERENCES

[1] Zanetti, L. J., Baumjohann, W., Potemra, T. A., and Bythrow, P. F., "Three-Dimensional Birkeland-Ionospheric Current System, Determined from Magsat," in *Magnetospheric Currents*, Potemra, T. A., ed., AGU Geophysical Monograph Board, Washington, D.C., pp. 123-130 (1983).

[2] Mauk, B. H., Krimigis, S. M., Keath, E. P., Cheng, A. F., Armstrong, T. P., et al., "The Hot Plasma and Radiation Environment of the Uranian Magnetosphere," *J. Geophys. Res.* **92**, 15,283-15,308 (1987).

[3] Sarris, E. T., and Krimigis, S. M., "Quasi-Perpendicular Shock Acceleration of Ions to ~200 MeV and Electrons to ~2 MeV Observed by Voyager 2," *Astrophys. J.* **298**, 676-683 (1985).

[4] Greenwald, R. A., Baker, K. B., and Ruohoniemi, J. M., "Experimental Evaluation of the Propagation of High-Frequency Radar Signals in a Moderately Disturbed High-Latitude Ionosphere," *Johns Hopkins APL Tech. Dig.* **9**, 131-143 (1988).

[5] Mitchell, D. G., "Kinetic Aspects of Magnetotail Dynamics—Observations," in *Magnetotail Physics*, Lui, A. T. Y., ed., Johns Hopkins University Press, Baltimore and London, pp. 207-224 (1987).

[6] Roelof, E. C., and Williams, D. J., "The Terrestrial Ring Current: From *in Situ* Measurements to Global Images Using Energetic Neutral Atoms," *Johns Hopkins APL Tech. Dig.* **9**, 144-163 (1988).

[7] Meng, C.-I., and Huffman, R. E., "Preliminary Observations from the Auroral and Ionospheric Remote Sensing Imager," *Johns Hopkins APL Tech. Dig.* **8**, 303-307 (1987).

[8] Jenkins, R. E., "Neurodynamic Computing," *Johns Hopkins APL Tech. Dig.* **9**, 232-241 (1988).

[9] Roth, M. W., "Neural-Network Technology and Its Applications," *Johns Hopkins APL Tech. Dig.* **9**, 242-253 (1988).

ACKNOWLEDGMENTS—I would like to acknowledge the help, information, and ideas I received from Thomas Potemra, Robert Gold, Edwin Keath, and Jacob Gunther, including their painful recall of early data-processing methods. Their contributions to this article reflect their involvement in the successful development of our computing system and data-processing techniques.

THE AUTHOR

LORA L. SUTHER was born in Hays, Kans., in 1957. She graduated from Kansas State University in 1979 with a B.S. degree in computer science and then joined APL. Since 1980, she has been working in the Space Physics Group organizing and supervising computing activities. She has been involved in the planning, development, and execution of the data processing procedures of numerous spacecraft missions, including Voyager, HILAT, Polar BEAR, AMPTE, and Delta 180, and continues to develop data procedures for future missions such as Ulysses, Galileo, UARS, WIND, and MSX.