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SCIENTIFIC REQUIREMENTS FOR SPACE SCIENCE DATA SYSTEMS

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Abstract. In the 1990's space plasma physics studies will increasingly involve correlative analysis of observations from multiple instruments and multiple spacecraft. The solar terrestrial physics missions in the 1990's will be designed around simultaneous observations from spacecraft monitoring the solar wind, the polar magnetosphere and the near and distant magnetotail. Within these regions clusters of spacecraft flying in formation will provide observations of gradients in the plasma and field parameters. Planetary plasma studies will increasingly involve comparative magnetospheric studies. No single laboratory will have the expertise to process and analyze all of the different types of data so the data repositories will be distributed. Catalog and browse systems will be required to help select events for study. Data compression techniques may be useful in designing the data bases used for selecting events for study. Data compression on board the spacecraft will be necessary since instrument data rates will be much larger than available telemetry rates. However, considerable care will be necessary to avoid losing valuable data when applying data compression algorithms.

1. Introduction

Space physics is a wide ranging discipline. It includes solar physics, heliospheric physics (the solar wind and interplanetary magnetic field), the physics of the magnetosphere, the physics of the ionosphere and the interaction between the plasmas in these regions. In addition space physicists are interested in that part of planetary science having to do with the interaction between the solar wind, planets, their moons, magnetospheres and ionospheres.

In this report we will discuss the requirements that studies of space plasmas place on the data systems. We will concentrate mainly on in situ data from spacecraft although many of the requirements are valid for ground based observations as well. The emphasis will be on studies that involve tensor time series data however many of the requirements are valid for remote sensing observations also. One of the main purposes of this volume is to acquaint computer professionals interested in data compression with the data problems encountered by scientists using space derived data. The approach in this paper will be to discuss the requirements on the entire data system from the perspective of a space scientist without trying to detail all of the areas where data compression could be useful. Hopefully this will start a dialog between the two communities which will help us define those areas where data compression techniques will be most applicable.

First we will consider a specific example of space physics research in the 1990's. The case we will examine is a study of the bow shock of Venus which was conducted by using observations from the Galileo spacecraft. We will examine the Galileo magnetometer observations and show how the results obtained in this study will lead to other studies which place requirements on the data system infrastructure. Next we will expand our view by considering the demands that the missions of the 1990's will place on the data systems. In particular we will consider the International Solar Terrestrial Physics Program. This international multispacecraft mission will be the prime project in solar terrestrial physics in the 1990's and will be the main driver for data activities in space plasma physics. Next we will examine the concepts currently being considered to solve some of the data problems in space plasma physics. We will do this by considering the distributed approach in space data management used by the Planetary Data System. Finally, we will briefly consider the applications where data compression has been used in space physics and will consider some of the concerns which arise in the science community whenever the use of data compression is suggested.

2. The Search for Intermediate Mode Shocks

2.1 What is an Intermediate Mode Shock?

Just as a hydrodynamic shock in a neutral gas converts a supersonic flow to a subsonic flow, a magnetohydrodynamic (MHD) shock in a plasma converts a flow which exceeds one of the phase velocities of the plasma to a velocity below it. In contrast to a neutral gas which has just one characteristic velocity, the sound speed, an MHD plasma has three speeds corresponding to three wave modes. They are the fast compressional mode, the slow compressional mode and the intermediate mode. The fast and slow mode waves are compressional (i.e. the magnetic field changes its magnitude as the wave propagates) while the intermediate wave is a shear wave in which the magnetic field changes direction but not magnitude. The changes in the parameters across a shock can be found by solving the Rankine-Hugoniot relations which express the conservation of mass, momentum and energy plus Maxwell's equations (Gauss' Law and Faraday's Law). These equations have six solutions (e.g. [1]) and it is useful to classify the shocks by the relationship between the flow velocities normal to the shock and the phase velocities of the MHD wave modes. Class 1 flows are faster than the fast velocity, class 2 flows are sub-fast speed but super intermediate speed, class 3 flows are sub-intermediate but super slow and class 4 flows are sub-slow speed. Thus the six types of shocks are (1,2) shocks in which the flow goes from super fast to sub-fast but super intermediate, (1,3) shocks which go from super fast to sub-intermediate but super slow, (1,4) shocks which go from super fast to sub-slow, (2,3) shocks which go from sub-fast but super intermediate to sub-intermediate but super slow, (2,4) shocks which go from sub-fast but super intermediate to sub-slow and (3,4) shocks which go from sub-intermediate but super slow to sub-slow.

It was long believed that only two of these solutions could exist in nature, the (1,2) shocks or fast shocks and the (3,4) shocks or slow shocks [2]. Both of these types of shocks have been observed in nature. The most famous example of a type (1,2) shock is the Earth's bow shock while slow shocks (3,4) are found in the Earth's magnetotail. Types (1,3), (1,4), (2,3) and (2,4) shocks are called intermediate shocks. Recently both theory and numerical simulation have suggested that these shocks too can exist [1,3].

Fast and slow mode shocks change the magnitude of the component of the magnetic field in the shock plane but do not change its sign. In an intermediate shock the component of the magnetic field along the shock surface must change sign across the shock [1]. There is only a small range of upstream flow conditions for which an intermediate shock can exist. For (1,3) or (1,4) shocks at $\beta < 1$ (β is the ratio of the plasma pressure to the magnetic pressure) , the upstream flow must have $1 < M_A < 2$ (the Alfven Mach number $M_A = v/c_A$ where the Alfven speed $c_A = B/(4\pi\rho)^{-1/2}$ with B the magnitude of the magnetic field and ρ the mass density). As β increases, the cutoff occurs for smaller M_A. The normal to the shock must be nearly along the magnetic field (such shocks are called parallel shocks). When the sound speed ($c_s = \gamma\, p/\rho$ where $\gamma = 5/3$ is the polytropic index and p is the pressure) is larger than c_A intermediate shocks of type (1,3) or (1,4) cannot exist but (2,3) and (2,4) shocks can. It is expected that shocks of types (1,3) and (1,4) might be attached to the fast mode bow shock while types (2,3) and (2,4) shocks will separate from it.

2.2 Galileo Observations

The Galileo spacecraft flew by Venus on February 10, 1990 as part of its voyage to Jupiter. The spacecraft approached Venus from the nightside on a trajectory which was nearly parallel to the expected position of the bow shock. Figure 1 shows the Galileo trajectory on the inbound leg near Venus. A model bow shock has been included. Since Venus has at most a very small intrinsic magnetic field the bow shock is very close to the surface of the planet near noon. The letters A-F indicate pairs of bow shock crossings. For these crossings on the flanks of the magnetosphere the magnetic field was nearly parallel to the expected shock normal. Thus this is a good region to look for intermediate shocks.

Figure 2 shows magnetic field observations from Kivelson et al., [4]. The three components of the field are plotted in Venus Sun Orbit (VSO) coordinates (x is toward the Sun, y is towards dusk and z is positive northward). The shocks can most easily be seen as sudden changes in the magnetic field magnitude in the bottom trace. The times between shock crossings are shaded. In this example we are mainly interested in the interval E between about 0334 UT and 0343 UT. This is shown in higher resolution in Figure 3. Here the traces in VSO coordinates are at the bottom of the figure as are simultaneous observations from one component on the Pioneer Venus Orbiter (PVO) spacecraft. The top panels show the Galileo magnetic field in shock normal coordinates with (I) along the direction of maximum variation and (K) along the shock normal direction while (J) completes the right hand system and lies in a plane perpendicular to the plane which contains the upstream and downstream vectors. The outbound shock crossing is at 03:43. Prior to that the field in the two transverse components rotates through nearly 180°. *Kivelson et al.*, [4] point out that this is consistent with either a fast (1,2) shock followed by a (2,3) intermediate shock or a (1,3) intermediate shock.

2.3 The Next Steps in the Study of Intermediate Shocks

The observations above are consistent with the 0343 UT event being an intermediate shock. However much more analysis will be required to establish that unambiguously. First we must establish that this is indeed a shock. Here observations from the plasma instrument and the plasma wave instrument on Galileo must be examined. The observations from the plasma instrument will help us determine if shock related heating has occurred. The plasma wave observations will help us determine if broad band radiation associated with a shock crossing is present. The addition of plasma data will give us the flow velocity, the density and the pressure and we will be able to calculate the critical parameters c_S, c_A and ß. With this we can determine whether or not these events are in the regime in which intermediate shocks can exist.

Even if all the evidence supports our suggestion that this is an intermediate mode shock we will still need to examine more data. We will need to investigate the other Galileo shocks looking for other examples of possible intermediate mode shocks and to try to determine empirically when intermediate mode shocks can occur. PVO also provides a potential source to be probed for evidence of intermediate shocks. The Earth's bow shock, too, is a possible source of data on intermediate shocks. The 9 years of data from the International Sun Earth Explorers (ISEE) spacecraft and data from IMP-8 should be examined. It is possible that the event identified above isn't an intermediate shock at all. For instance it could be a rotational discontinuity in the solar wind which reached the bow shock just as Galileo did. Examples with data from more than one spacecraft will be very valuable. With data from one spacecraft in the solar wind and one at the bow shock this possibility can be eliminated. In addition we can look for intermediate shocks propagating in the solar wind.

From a data system perspective, the most important lesson from this example is that modern space plasma physics requires data from a variety of instruments on a spacecraft and frequently from many spacecraft. Often that data must be from several instruments on several spacecraft simultaneously. Getting this data to the scientists in a timely manor is one of the major problems facing the designers of space science data systems. Indeed one of the major new missions in space physics, the International Solar Terrestrial Physics (ISTP) Program is based on this concept of using simultaneous observations from many instruments and many spacecraft. We will discuss it in the next section.

3. Multispacecraft Missions

The very nature of the magnetosphere requires that it be probed by multiple spacecraft simultaneously. The magnetosphere is vast and highly dynamic. Spacecraft observers are required to infer the dynamics of this system from time-series observations constrained to the spacecraft's trajectory. Without multiple point measurements they simply cannot tell what is happening in the rest of the system.

3.1 The International Solar Terrestrial Physics Program

A major question in magnetospheric physics is to understand the flow of energy and momentum through the solar wind, magnetosphere and ionosphere system. ISTP is a cooperative venture between NASA, the European Space Agency (ESA), and the Japanese Institute for Space and Astronautical Science (ISAS) to study this problem. In addition there are a number of associated missions from the Space Research Institute (IKI) of the USSR Academy of Sciences.

In ISTP, the Solar Heliosphere Observatory (SOHO) will remotely observe the Sun and make in situ observations of the composition of the solar wind from the L1 Lagrangian point. The Wind spacecraft will observe the solar wind and will provide the solar input to studies of the interaction of the solar wind with the magnetosphere. It, too, will be in a halo orbit at the L1 point. The Polar spacecraft will investigate the polar magnetosphere and remotely sense the auroral zone. The ESA Cluster mission will provide four spacecraft flying in a tetrahedral formation with identical instruments to measure gradients in the polar magnetosphere. The Japanese Geotail spacecraft will probe both the distant magnetotail out to $220R_E$ and the near Earth magnetotail. ISTP also will utilize observations from several associated missions. These include the Air Force/NASA CRRES satellite which monitors the inner magnetosphere out to about $6R_E$. Two Soviet missions may also contribute to ISTP. One of these Interbol will consist of two spacecraft each with a small subsatellite. One pair of spacecraft will be in polar orbit while the other pair will probe the tail out to about $35R_E$. Another planned Soviet mission is Regatta. Project Regatta comprises a system of four to five small space laboratories. The first of these is planned for the near earth tail with apogee at about 8 to $10R_E$. Later a polar Regatta spacecraft may join the ESA Cluster mission. It would orbit near the Cluster at about 10 times the tetrahedral spacing. Later in the decade additional Regatta spacecraft may join the ISTP group. Please see *Farquhar* [5] for more information on the ISTP spacecraft and their planned trajectories.

In addition to the spacecraft, the ISTP mission also will include coordinated ground observations from magnetometer chains and auroral radar. Finally ISTP will have a major program of theory and simulation investigations. Large scale models of the interaction between the solar wind, the magnetosphere and the ionosphere will be used to help organize these observations and the observations will help us test and refine the models.

3.2 Data System Requirements

Each of the ISTP spacecraft will have a complement of space plasma and fields instruments. The key element of ISTP is that much of this data will have to be analyzed together in a coordinated fashion. The major data system driver in space physics in general and solar terrestrial physics in particular will not be the volume of data but the number of sources of data. The instruments on these spacecraft are very sophisticated and require expert interaction to produce usable data. Thus the data system supporting the ISTP mission must be distributed. The data and the scientists processing it are closely linked. The ISTP scientists are planning to work together on studying in detail magnetospheric events. To accomplish this they will need some sort of browse system to help select events (they call this a the key parameter system). When ISTP is in full operation there may be several groups of scientists studying several events simultaneously. In addition to being able to use the browse systems to help select the events, they will also need to be able to locate the data required for detailed study and to access it.

4. Planetary Data in the 1990's

In the proceeding sections we have examined some of the demands that space physics research in the 1990's will place on data system activities both by considering a specific research example and by considering the problems of the major mission in the field. Now we would like to consider one further example. In this section we will consider the data system requirements of that part of space physics concerned with the planets and how the NASA Planetary Data System is trying to address those needs.

When discussing planetary science it is important to remember that you can't study just one part of planetary science in isolation. The disciplines and sub-disciplines are linked by physical processes. For example if you want to determine whether Mars and Venus have electrically conducting cores and hence dynamos you will need to study the solar wind. Since both planets are at best weakly magnetized you need to first understand the effects of the solar wind in inducing a magnetosphere before you can determine the extent of any intrinsic magnetic field and learn about the precesses within the planet that create it.

Studies of the jovian magnetosphere require an understanding of the physics and chemistry of the surfaces, and atmospheres of the moons as well as plasma physics. For instance the Voyager observations in Jupiter's magnetosphere demonstrated that much of the plasma has its origin at the moon Io. We now believe that charged particles from the magnetosphere remove neutral particles from the surface and atmosphere of Io by a process called sputtering. (The neutrals originally came from ioian volcanoes.) These neutrals are ionized by electron impact ionization or charge exchange and form a plasma. This then is the plasma that interacts with Io and fills the magnetosphere.

Just as was the case in solar terrestrial physics, studies of the planets frequently require data from more than one instrument on a spacecraft and the data is frequently widely distributed at the laboratories where the scientific expertise in found. In addition in planetary science comparative studies involving observations from more than one planet are becoming increasingly important. In planetary science archival studies also are important. There will be no new in situ data from Uranus or Neptune for a very long time. The next Saturn data is over a decade away as is the next particles and fields data from Venus. Data from some new planetary missions is being archived immediately. For instance the Magellan mission has provided archival data to the scientific community from the beginning.

4.1 The Planetary Data System

The NASA Planetary Division has tried to address the data needs of the planetary science community by forming the Planetary Data System (PDS). PDS was founded on the principle that "the data repositories which work best are those in which data are managed by scientists who are actively engaged in research" [6]. PDS was charged to "provide the best planetary data to the most users forever!" [*McMahon, personal communication, 1991*].

Since planetary science is multi-disciplinary and since the data and the expertise are widely distributed, PDS is a distributed system. There are six science nodes, the Rings Node at Ames Research Center, the Imaging Node at the USGS in Flagstaff Arizona, the Small Bodies Node at the University of Maryland, the Geosciences Node at Washington University, the Atmospheres Node at the University of Colorado and the Plasma Interactions Node at UCLA. Since planetary science is too broad for any one institution to have all of the required expertise each of the Nodes has subnodes which provide expertise on a specific scientific instrument or data type. PDS is managed from a Central Node at JPL and they maintain a technology development and testing laboratory. Finally the Navigation and Ancillary Information Facility (NAIF) at JPL acts as a Node for spacecraft trajectory, attitude and pointing data. PDS is responsible for obtaining the data for archiving, making sure it is of high quality and assisting the scientific community with data problems. PDS deposits all of its data in the National Space Science Data Center (NSSDC) for permanent archiving.

Figure 4 shows the projected planetary data archives between now and 1997. By 1997 the PDS archives will total about 2500 GB. Throughout this decade it will grow at a rate of about 400--500 GB per year.

4.2 The Plasma Interactions Node

The Planetary Plasma Interactions Node (PPI) of PDS is responsible for planetary particles and fields data. It is responsible for data relating to plasma physics in planetary systems. This includes the interaction of the solar wind with planetary magnetospheres, ionospheres and surfaces. Also of interest are the interactions of magnetospheric plasmas with the satellites and rings within planetary magnetospheres. These interests overlap those of other PDS nodes and close working relationships are maintained with the Atmospheres Node, as well as the Small Bodies Node and the Rings Node. The PPI Node has subnodes at the University of Iowa, the Goddard Space Flight Center as well as a separate Inner Planets Subnode at UCLA.

The specific goals of the PPI Node include helping to assure that high quality and usable data are available to the scientific community, helping scientists to determine the availability of data, helping them select the data needed for a specific study, helping them access that data and helping them with the analysis of the data.

The PPI Node uses several approaches to assure that high quality and usable data are available to the community. Foremost among these approaches is the peer review. All data submitted to PDS is reviewed by a panel of scientists and technicians prior to its formal release to the scientific community. The data peer review is analogous to the review of papers for publication in a journal. Indeed the entire process of ingesting data into PDS is similar to that of submitting a paper to a journal. The peer review checks both the science data and the metadata describing the science data. The metadata are maintained in the PDS Catalog. It includes descriptions of the spacecraft, the instrument, the data processing and most importantly known sources of contamination. In addition the catalog contains information about the quality of the science data. When a scientist orders data from PPI, PDS or the NSSDC the data are documented with PDS Labels. These labels include information on the quality of the data. Finally to assure that the data are adequately preserved PDS pioneered the development of the concept of placing the data on CDROM.

To help scientists locate the data, PDS and PPI use the catalog system. The high level PDS catalog points to large collections of data while the detailed level catalog is essentially an inventory of all of the data holdings and helps scientists to locate subsets of the data.

The catalogs also help a user select data. The detailed level catalog provides information with a granularity of one hour. In addition the PPI Node has developed a system to browse the PPI data archive. The browse data consists of an averaged subset of the full resolution data. It is maintained on-line all of the time and can be displayed graphically. The software to access the browse data and display it is based on a client server architecture. The front-end of this system can be distributed to assure rapid access to the data. Figure 5 shows a typical graphics display from the browse system. The user can design the display interactively.

The PPI system is based on a file management system which uses a relational data base management system. Figure 6 shows the schema for this file management system. Most importantly the tables contain the information required to build the displays in the browse system (Group Table) and information on the status (Status Table) of the data (i.e. the path to the data and whether it is on-line or off-line etc.). With this information the PPI Node can help users access the data and order it.

The order data subsystem of the PPI Node uses the file management tables in Figure 6 to help a user place an order for data. It uses the file management tables to locate the data, fills the order if the data is already on-line or schedules moving the data on-line if it is not. If orders are relatively small they are filled directly by the PPI Node. Larger orders are routed to the NSSDC.

Finally PPI Node supports a number of data analysis packages. These include the Interactive Data Language (IDL) and the UCLA Data Flow System [7]. PPI will also provide users with access to both theoretical models and simulations of planetary plasma processes. Most importantly PPI maintains a group of experts on various fields and particles data types who are available for consultation.

5. Data Compression and Space Physics

We have seen that in the 1990's space physics will increasingly involve correlative analysis of data from multiple instruments and multiple spacecraft. That data will be distributed because the people who know about the data are distributed. Finally there will be an increased use of both theoretical and empirical models to help us organize these observations and to help promote understanding.

How can data compression techniques help? This is the question that the computer professionals working in this field and space physicists will have to work together to answer. In this section we will discuss a few areas where data compression may be useful. The list in certainly not exclusive. We will also consider the problems involved with using data compression techniques.

It seems fairly clear that selecting the data for analysis will take on new importance in the 1990's. Before starting on a lengthy study scientists will want to assess whether the data needed are available. When selecting between two events for study they will be interested for instance in knowing for which event solar wind data are available, or whether auroral images are available. They will want to know where other spacecraft were located in the magnetosphere. Thus we believe that browse systems will take on increased importance. Being able to look at subsets of the data quickly will help in this selection process. Speed of access is very important for browse data. Researchers don't want to spend too much of their time in the selection process. Therefore the browse data should be on-line. This makes browse data a very good candidate for data compression. Since the user can always go back to the full resolution data when they conduct the detailed study, the browse data is also a likely candidate for lossy compression.

Some data compression is already being planned for instruments for future missions. The data rates of modern instruments have increased faster than the available telemetry. For some of the experiments the instrument data rate is as much as 20 to 40 times that which can be telemetered. Since the data rates of the instruments are closely coupled with the science, data compression is an attractive way to get the data back to Earth. Consider, for example, the magnetometer experiment on the ISTP Polar spacecraft. The minimum rate of data return is 10 vectors/s. Unfortunately this rate cannot be maintained by the allocated spacecraft telemetry. Here data compression by about a factor of four is required. A second differencing algorithm is being developed for use on the spin plane components. A second differencing algorithm will work on a spinning spacecraft like Polar since most of the signal is a sinusoid. Another limitation of the choice of the compression algorithm is that the on board processor must be able to carry out the compression in the time available with the available memory. Many powerful data compression algorithms have been rejected because they require more resources than are available on the spacecraft. So far the second differencing approach for the magnetometer is the only algorithm which will both provide the required compression and is fast enough to keep up with real time data.

The data compression being studied for Polar is lossless. This brings us to one of the major concerns which space physicists have when considering data compression algorithms. Instruments are designed to provide the data required to study a given phenomenon or set of phenomena. The instruments are carefully designed to provide the required measurements. Every bit is important for some potential study and scientists are reluctant to give up bits for data compression. Therefore lossy data compression is looked on with a great deal of suspicion. The computer professionals working on data compression techniques for space physics data will have to demonstrate that they aren't asking the scientists to give up science for compression.

Acknowledgments

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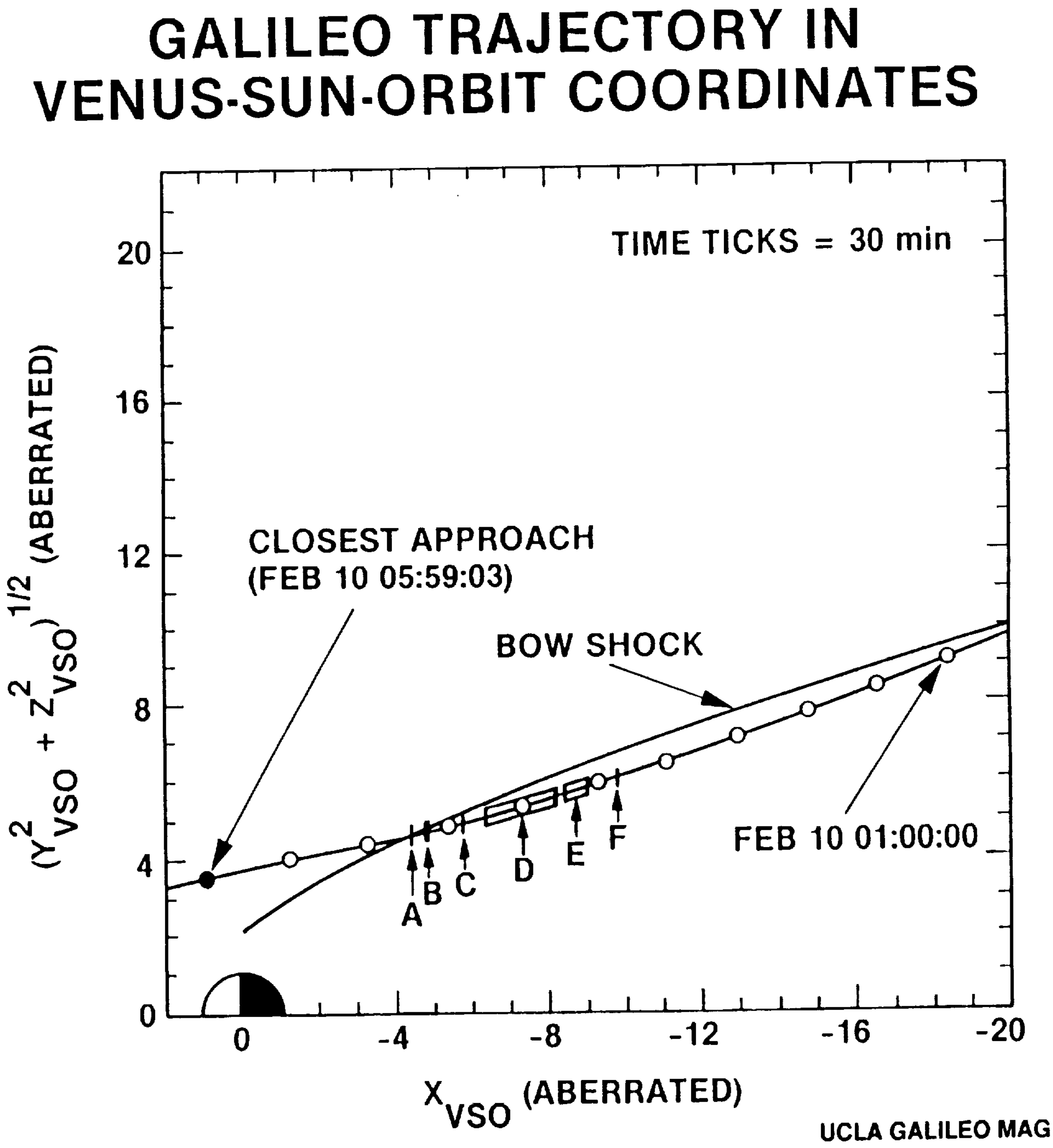

Figure 1. The Galileo trajectory near Venus in aberrated coordinates [4]. This view gives the trajectory in the plane of the spacecraft in terms of the distance along the solar wind aberrated planet-sun line and the perpendicular distance from that line. A model of the shock location is shown and the pairs of shock crossings (from upstream to downstream and then downstream to upstream) are labelled A-F.

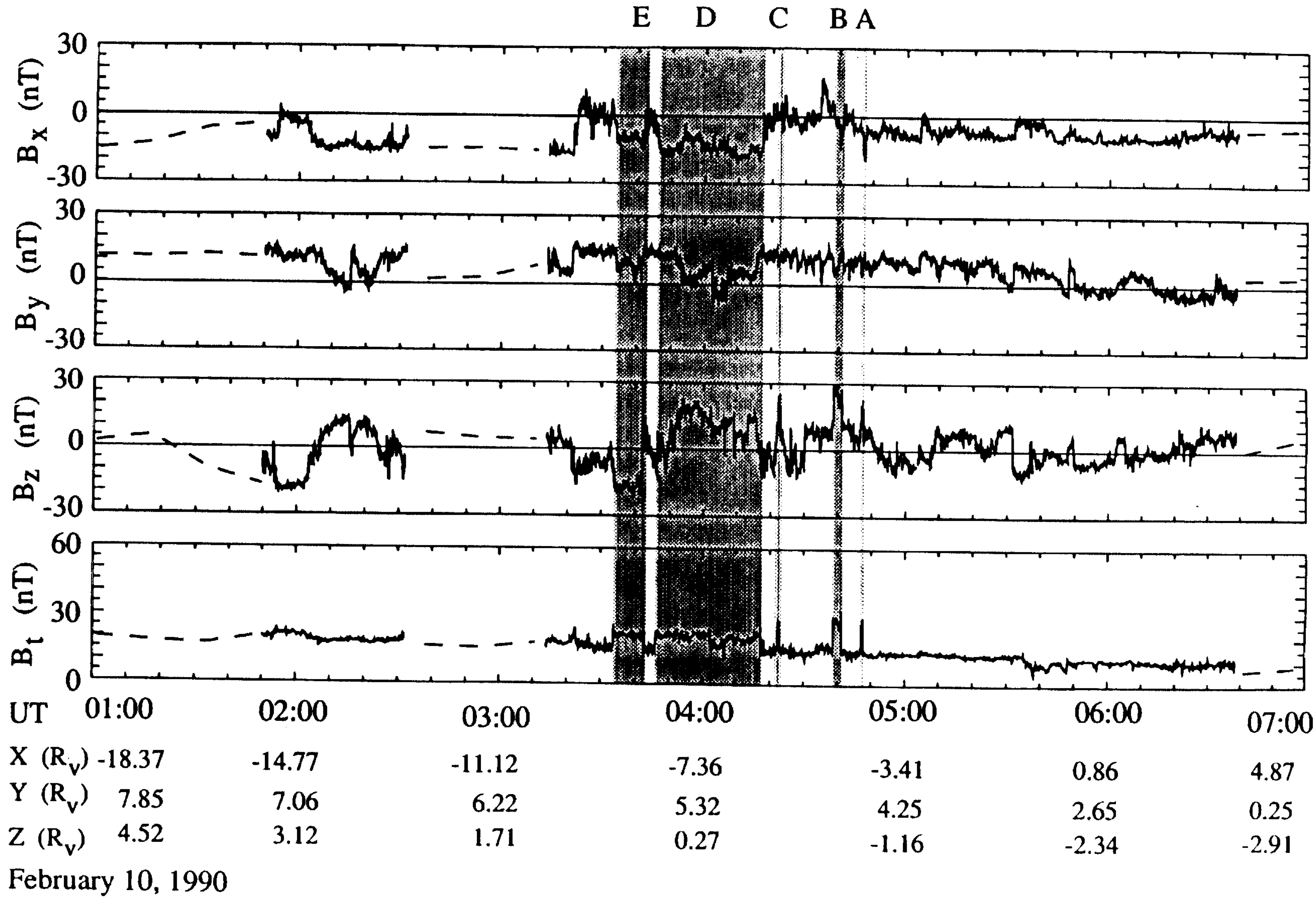

Figure 2. Magnetic field components and total field in VSO coordinates [4]. The shock crossing intervals in Figure 1 have been shaded. The gaps in the high time resolution data are filled in by using "optimal average" data taken on the spacecraft with 16 minute resolution (dashed lines).

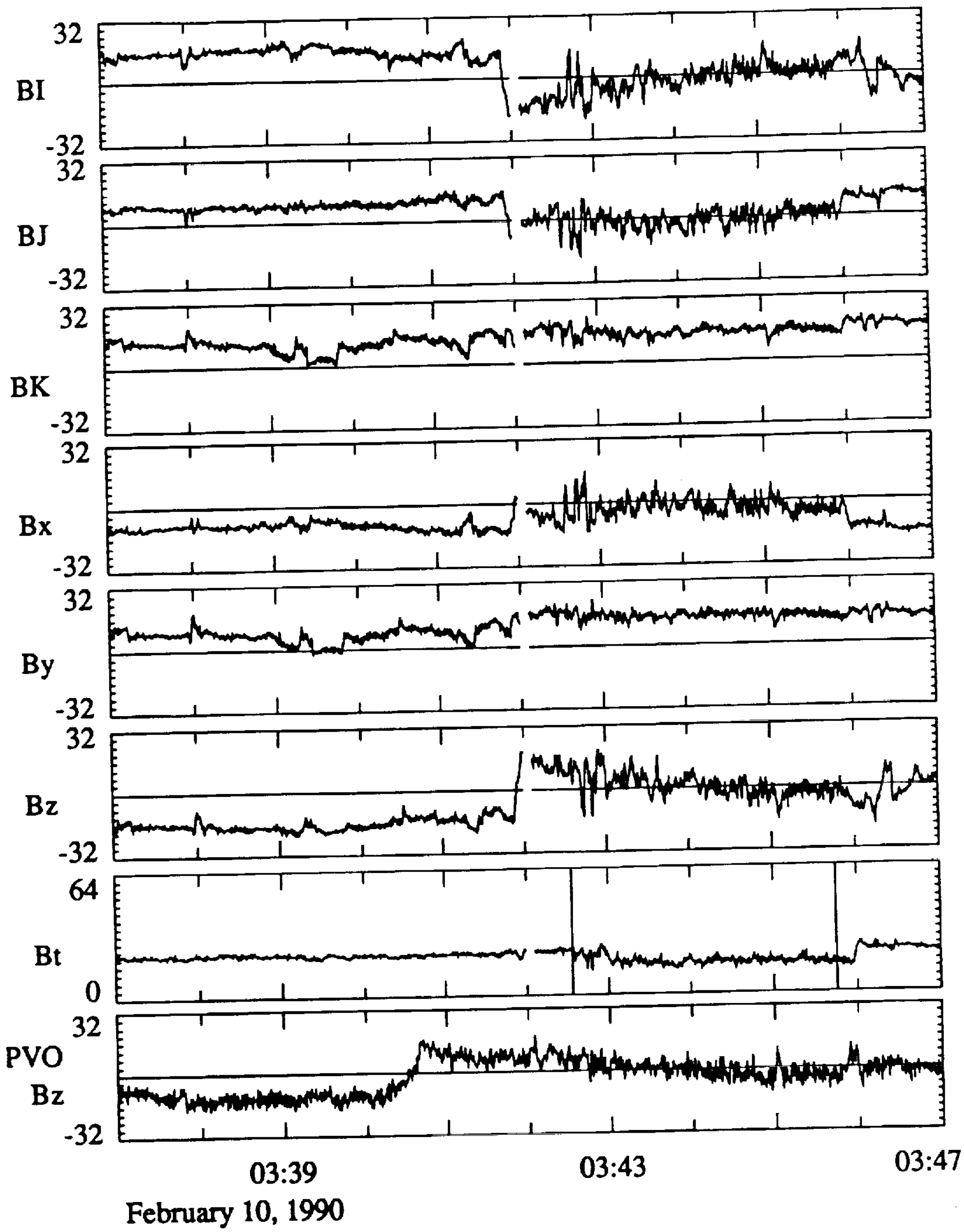

Figure 3. Magnetic field data in shock normal and VSO coordinate systems for the interval between 03:37 and 03:47 UT on February 10, 1990 [4]. The bottom panel shows the VSO B_z component observed by PVO. The interval used in the shock normal calculation is denoted by vertical lines on the B_T panel.

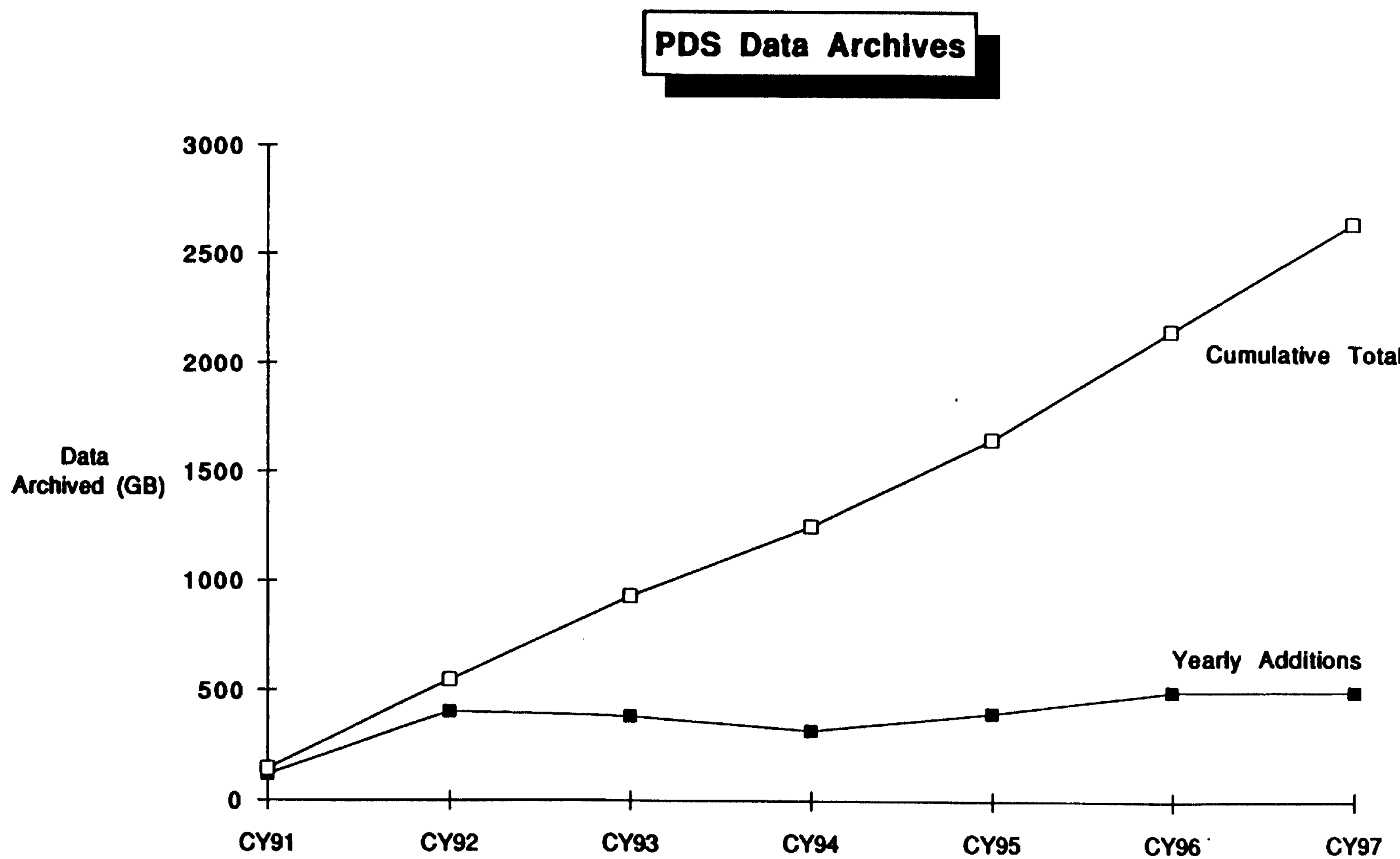

Figure 4. A projection of the data volumes to be archived by the Planetary Data System from 1991 to 1997 (courtesy of S. McMahon). The open symbols give the cumulative total while the solid symbols give the yearly additions.

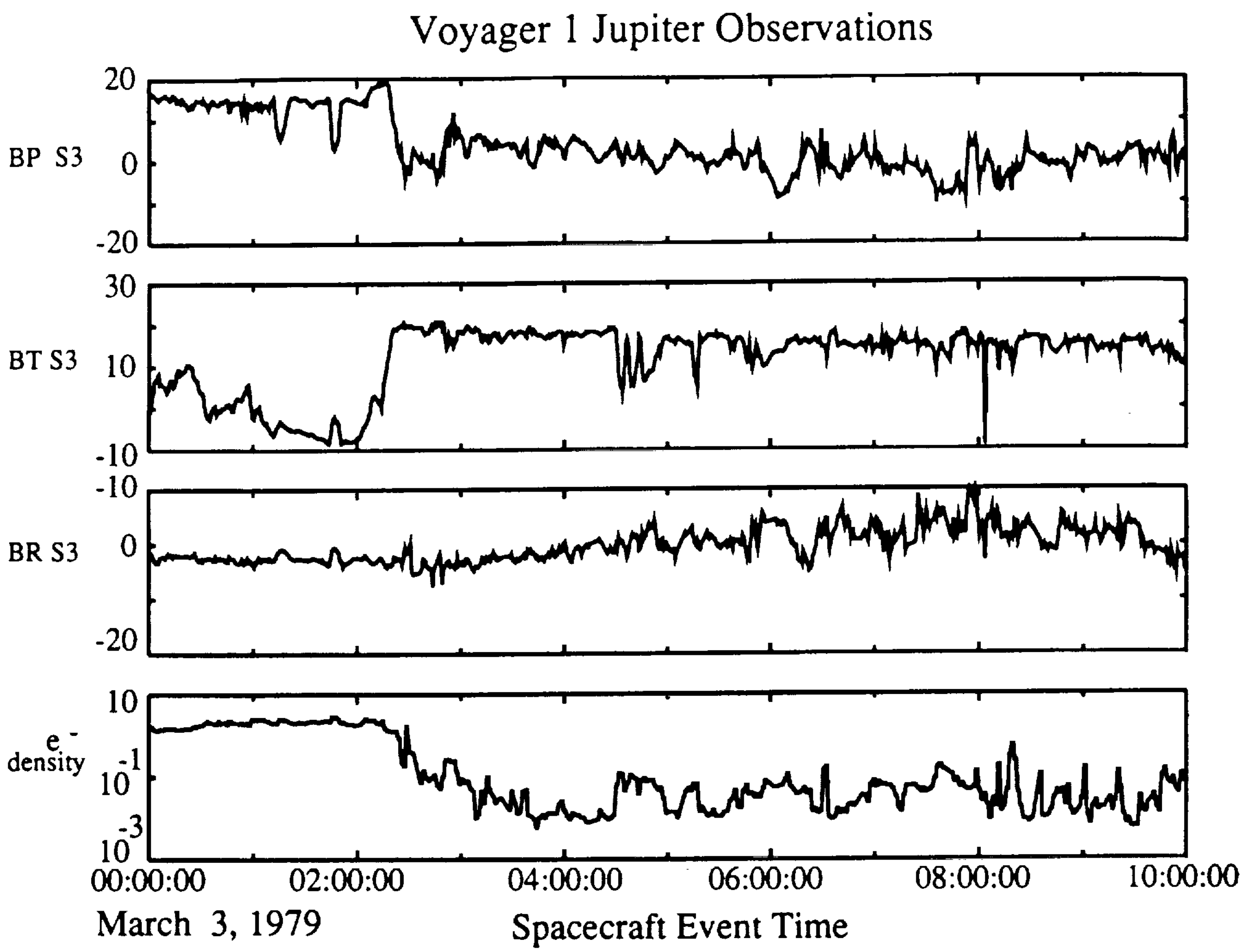

Figure 5. A typical data display from the Planetary Plasma Interactions Node Browse System. Plotted are magnetic field data in Minus System III coordinates and the electron density from the Voyager 1 encounter with Jupiter.

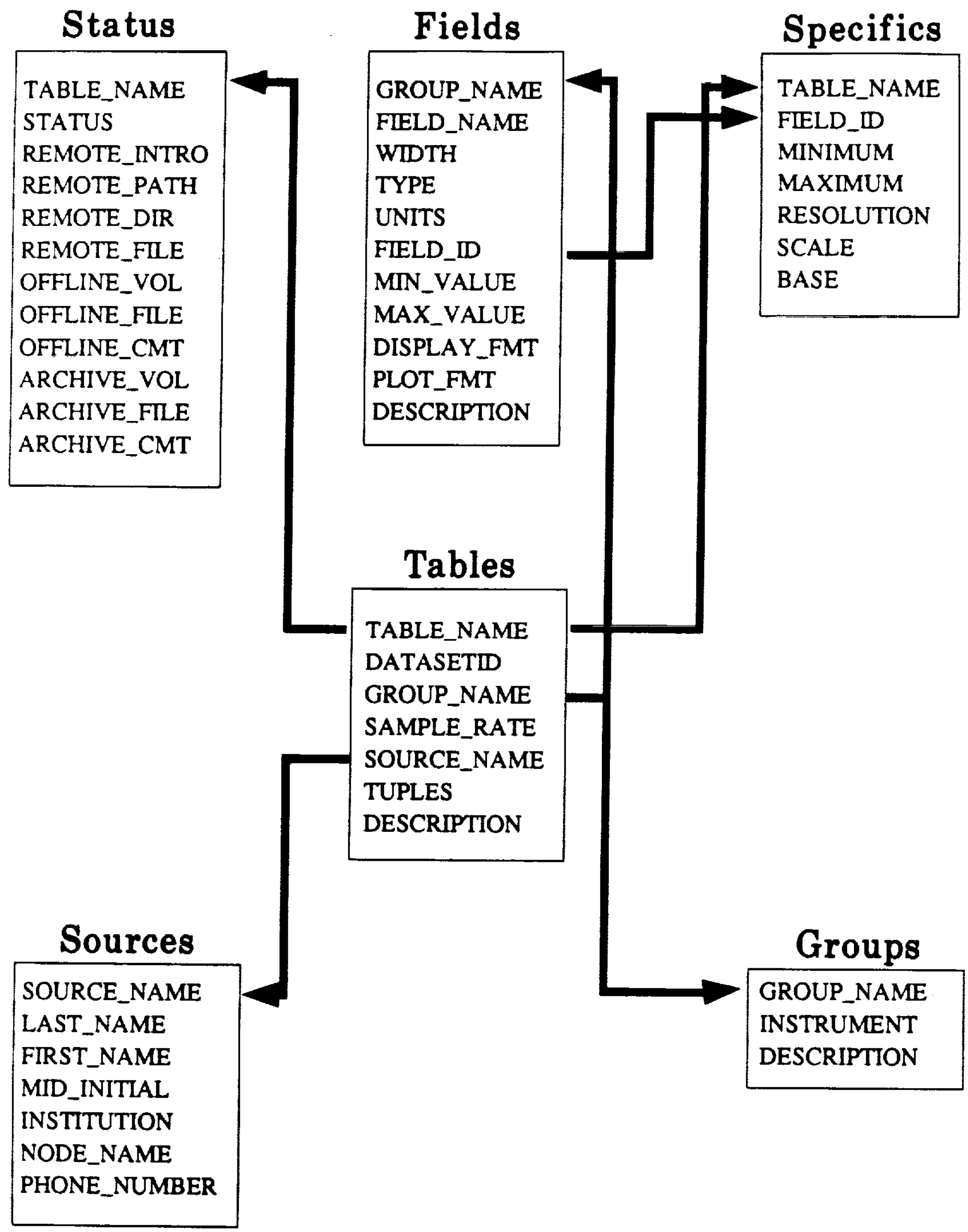

Figure 6. The file management tables used by the Planetary Plasma Interactions Node of the Planetary Data System. There are six tables (Tables, Fields, Status, Specifics, Sources, and Groups). The Tables table contains one entry for each table (data file) in the system. The Fields table contains the description for each field in a data table record. It is linked to the Tables table by the group_name field. Status contains data about the status of individual data tables controlled by the system. This includes the location of the data and whether it is on-line or off-line. The Specifics table contains information which is unique to each data table. It contains one entry for every field in every data table. The Sources table contains information about the source of the data contained in the table such as the name of the data supplier. The Groups table contains information related to data set groups. It includes a description of how the data were grouped (i.e., by spacecraft, target, etc.).