ASTROTECH 21
WORKSHOPS
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VOLUME

Workshop Proceedings: Information Systems for Space Astrophysics in the 21st Century
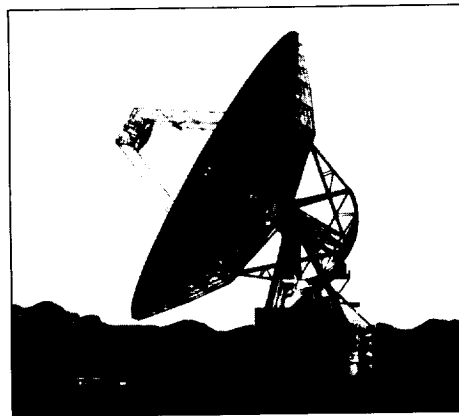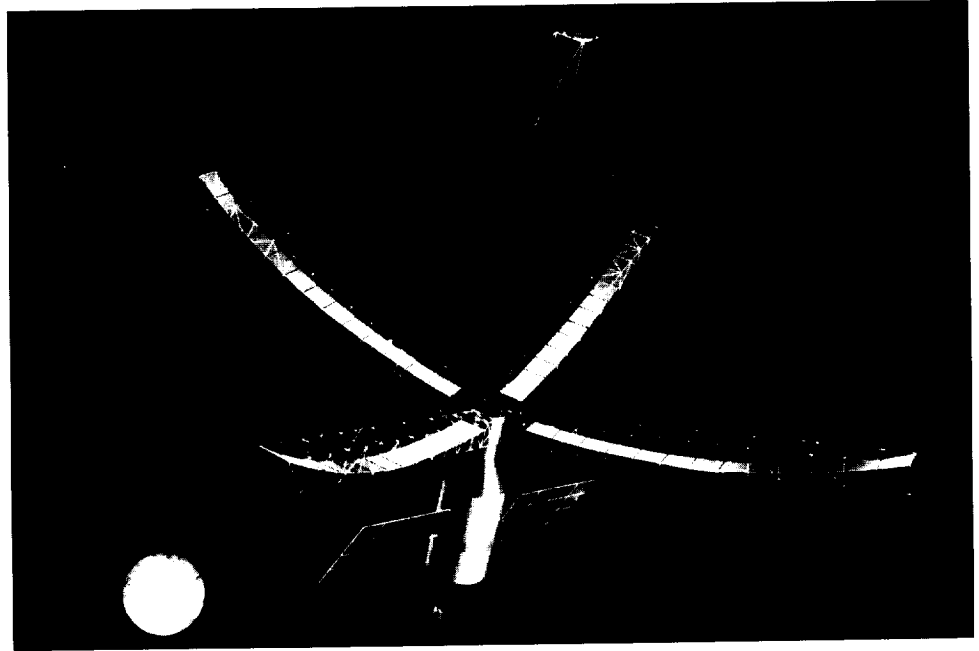
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Workshop Proceedings: Information Systems for Space Astrophysics in the 21st Century

Editors

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ABSTRACT

In 1989, the Astrophysics Division of the Office of Space Science and Applications initiated the planning of a technology development program, Astrotech 21, to develop the technological base for the Astrophysics mission developed in the period 1995 to 2015. An infusion of new technology is considered vital for achieving the advances in observational technique needed for sustained scientific progress. Astrotech 21 was developed in cooperation with the Space Directorate of the Office of Aeronautics and Space Technology, which will play a major role in its implementation. The Jet Propulsion Laboratory has led the planning of Astrotech 21 for the agency.

The Astrotech 21 plan was developed by means of three series of workshops dealing respectively with: Science Objectives and Observational Techniques; Mission Concepts and Technology Requirements; and Integrated Technology Planning. Traceability of technology plans and recommendations to mission requirements and impacts was emphasized. However, "breakthrough technologies," whose ultimate applications cannot be anticipated, were also considered. Proceedings documents are published for each workshop. A summary report has also been prepared which synthesizes the results of the planning effort.

The Astrophysical Information Systems Workshop was one of the three Integrated Technology Planning workshops. Its objectives were to develop an understanding of future mission requirements for information systems, the potential role of technology in meeting these requirements, and the areas in which NASA investment might have greatest impact. Workshop participants were briefed on the astrophysical mission set with an emphasis on those missions that drive information systems technology, the existing NASA space-science operations infrastructure, and the ongoing and planned NASA information systems technology programs.

Program plans and recommendations were prepared in five technical areas: Mission Planning and Operations; Space-Borne Data Processing; Space-to-Earth Communications; Science Data Systems; and Data Analysis, Integration and Visualization. The workshop also recommended that NASA introduce new approaches to the implementation of its future astrophysics program. These included radically improved communications and scheduling; transparent instrument and observatory operations; and a cyclical research and development methodology.

FOREWORD

A technology development program, Astrotech 21, is being proposed by NASA to enable the next generation of space astrophysical observatories which will be launched in the two decade period 1995-2015. Astrotech 21 is being planned and will ultimately be implemented jointly by the Astrophysics Division of the Office of Space Science and Applications (OSSA) and the Space Directorate of the Office of Aeronautics, Exploration and Technology (OAET). The Jet Propulsion Laboratory is assisting NASA in developing the Astrotech 21 plan.

The workshop on Astrophysical Information Systems in the Twenty-First Century forms part of the planning process for Astrotech 21.

The Astrotech 21 planning process has three phases. The first phase focussed on the fundamental science objectives and the observational techniques used to realize these objectives. In the second phase, specific mission concepts were evaluated and their technology requirements were assessed. In the third phase, the technology needs and opportunities in various areas of technology are being synthesized. This workshop was part of this third and final phase in Astrotech 21 planning. A total of 67 scientists and engineers drawn from universities, NASA centers and other government laboratories participated.

The workshop was structured to inform the participants about NASA's concepts for astrophysical missions in the period 1995-2015 and about NASA's current and planned information systems capabilities and technology programs. These briefings laid the groundwork for the activities of five panels, charged with defining technology needs and opportunities in various areas of information technology and formulating recommendations to NASA on potential areas of investment for NASA. These recommendations will be used by the agency to formulate a program plan for an FY'93 Astrotech 21 budgetary initiative.

The organizers thank the participants for their energetic efforts in preparing for the workshop, participating in the panel activities and supplying papers and reports for these proceedings. We also gratefully acknowledge the support of the JPL staff who made the local meeting arrangements and handled the publication of the proceedings.

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EXECUTIVE SUMMARY

Workshop on
Astrophysical Information Systems
for the Twenty-First Century

The Workshop was held on May 23-25 in Annapolis, Md. as part of "Astrotech 21," a study of technology needs for Astrophysics in the twenty-first century. It was a joint effort of the NASA Office of Aeronautics and Exploration Technology (Code R) and the Astrophysics Division of the NASA Office of Space Science and Applications (Code SZ). More than 65 scientists, engineers, and managers participated in this workshop.

The goal of the workshop was to identify information technology needs for Astrophysics missions for the next ten to twenty years. Most of the discussions took place in parallel meetings of five panels which were concentrating on (1) mission planning and operations, (2) space-borne data processing, (3) space-to-earth communications, (4) science data systems, and (5) data analysis, integration, and visualization.

The primary results of the workshop are fairly specific recommendations for a large number of technology developments. These recommendations range from near-term technical improvements (e.g. a self-tuning Astrophysics Data System with distributed processing; upgrades to the existing communications infrastructure) to longer-range development (e.g. high-temperature superconducting communications components; lunar/earth optical links). Several of the recommendations concern developments which are unique to Space Astrophysics or predominantly used in that discipline, e.g. correlators for interferometers, or automated multi-site scheduling systems.

Several "technology drivers" emerged, which will require accelerated development programs in order to meet the needs of future Space Astrophysics missions. These include high-speed signal processors, correlators, acousto-optical filters, development tools for systems and software, data compression, and Ka-band hardware.

Perhaps the most important results of the workshop are proposed "culture changes" or "paradigm shifts":

"Open communications": Near-continuous high-speed two-way communications allow new observations to be scheduled easily without having to undo all previously scheduled discrete events (e.g. via TDRSS), and allows data to be routed directly to multiple users via data distribution satellites (building on ACTS technology).

"Transparent instrument and observatory operations": each observatory or instrument is treated like a node on a large, NASA-wide network. This allows a common approach to ground-space communications, and opens the possibility that instruments could broadcast news of interesting events ("targets of opportunity") which could then be picked up by other instruments.

"Cyclical requirements development method": In each of the five panels, technologists, technology developers, and members of the science community emphasized that the traditional development methods will not be able to cope with future development needs. Instead, extensive simulations of instruments, spacecraft, and infrastructure should be combined with rapid prototyping as a means of delineating and corroborating requirements early in the design phase, i.e. before requirements and interfaces are set in concrete and cost too much to change.

From NASA's point of view, this workshop was a success because it initiated a dialogue between engineers/technology developers and scientists/users, and identified a wide range of information systems needs. In the longer term, we need to assure the continued involvement of both groups in the formulation of a technology program to meet these information systems needs. This program needs to be formulated at NASA centers, other federally funded research and development centers, universities, and industry. Every one of the five panels emphasized the need for user involvement in all phases of development. The joint information technology efforts should therefore encompass the setting of program objectives and prioritites, proposal reviews, and reviews of the development and test programs.

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PRESENTATIONS

Astrotech 21: A Technology Program
for Future Astrophysics Missions

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Abstract

The Astrotech 21 technology program is being formulated to enable a program of advanced astrophysical observatories in the first decade of the 21st century. This paper describes the objectives of Astrotech 21 and the process that NASA is using to plan and implement it. It also describes the future astrophysical mission concepts that have been defined for the twenty-first century and discusses some of the requirements that they will impose on information systems for space astrophysics.

I Introduction

During the 1990s, four Great Observatory missions will be launched and will probe the universe by observing radiation from gamma rays to the far infrared spectral region. But NASA is already looking beyond the Great Observatories to the first decade of the 21st century and is beginning the formulation of a New Century Astronomy program to continue the process of discovery. To make possible the New Century Astronomy Program, and thereby assure continued U.S. Leadership in space science, a substantial investment in technology will be needed during this decade. This will be provided by the Astrotech 21 technology program which is currently being defined by NASA. The purpose of this paper is to describe how NASA is carrying out the definition of Astrotech 21 and to highlight some of the features of the program that are already emerging.

II Background

In 1984, NASA requested the Space Science Board (SSB) to undertake a study to determine the principal scientific issues that the disciplines of spaces science would face from about 1995 to 2015. The study report, published in 1988 (1), outlines a scientific strategy for NASA to pursue in the early decades of the twenty-first century. The SSB's recommended program in astronomy, astrophysics and fundamental physics includes:

1)   Imaging interferometers with the ability to acquire higher angular resolution images and provide powerful new insights into planets, stars and galactic nuclei;

2)   Telescopes with great collecting area and improved spectroscopic capability with the ability to observe the farthest and faintest objects in every waveband accessible from space;

3)   A Laser Gravitational Wave Observatory in Space (LAGOS) which would use laser metrology to detect gravitational waves originating from astronomical sources with frequencies below 10 Hz; and

4)   A capability to respond to exploratory opportunities across the entire electromagnetic spectrum with small Explorer-class satellites.

It should be recognized that the SSB recommendations were not prioritized and constituted in aggregate a larger space program than might be anticipated in the period projected for the study. Nevertheless, they represent a stimulating and challenging description of opportunities in space sciences.

During early 1989, NASA's Astrophysics division began an examination of the SSB's program and began the definition of a New Century Astronomy Program embodying the SSB's recommendations. It was determined that a substantial investment in new technologies would be required. The Astrotech 21 program was conceived as the mechanism for identifying the needed technologies and for bringing them to a state of readiness. The Jet Propulsion Laboratory is assisting the agency in the definition of the Astrotech 21 program.

As part of its planning effort for Astrotech 21, NASA is also consulting the Astronomy Survey Committee (ASC) of the National Research Council which is currently undertaking its decade survey of programs in both space-based and ground-based astronomy. This survey will result in prioritization of nearer term missions and recommendations on appropriate areas for investment in technology for longer range missions.

III Approach

The two year effort to plan Astrotech 21 is now near its mid-point and consists of three major elements: the definition of scientific objectives and observational techniques; the development of mission concepts and their technology requirements; and the formulation of integrated technology plans. This workshop on Information Systems for Space Astrophysics in the Twenty First Century is one part of formulating an integrated technology plan. Although conceived by the Astrophysics Division of the Office of Space Science and Applications (OSSA) at NASA, the planning and ultimately the implementation of the Astrotech 21 program will be carried out jointly with the Office of Aeronautics, Exploration and Technology (OAET). We now describe the three major activities in the planning process:

A. Scientific Objectives and Observational Techniques

The definition of scientific objectives and the new observational techniques which Astrotech 21 will enable are being formulated by the three science branches in the Astrophysics Division: High Energy Astrophysics, Ultraviolet-Visible Astrophysics and Infrared-Radio Astrophysics. Each branch is responsible for astronomy in a segment of the electromagnetic spectrum. It should be noted that the High Energy Branch is concerned with observational programs in X-rays and Gamma-rays but not particulate cosmic radiation. However, the Ultraviolet-Visible Branch is responsible for research activities in relativity and gravitational radiation in addition to its responsibility for ultraviolet-visible observational programs.

A series of workshops involving observational astronomers and theoreticians has been organized by the branches to develop a more detailed plan in each discipline. The first workshop,

covering High Energy Astrophysics, was held in Taos, New Mexico, December 11-14, 1990 and addressed science objectives and observational techniques across the entire field of interest to the High Energy Astrophysics Branch. A second workshop, sponsored by the Ultraviolet-Visible Branch, and held at Caltech during March of 1990, also dealt with science objectives and observational techniques, but emphasized the interferometric methods that the SSB (1) had recommended for achieving a breakthrough in angular resolution.

The Astrotech 21 planning effort has also been guided by the recommendations of two advisory bodies which met during late 1989 and early 1990: the first, established by the Ultraviolet Visible Branch and chaired by Prof. Irwin Shapiro, has considered science objectives and techniques for future relativity missions; and the second, established by the Infrared Radio Branch and chaired by Prof. Thomas G. Phillips, has considered the plans for submillimeter observations from space using radiatively-cooled telescopes.

At least one further workshop covering science objectives and observational techniques is planned and will take place this fall. The subject of the workshop is submillimeter interferometry and it will include consideration of the the scientific advantages of implementing submillimeter interferometric observations from sites in orbit and on the lunar surface.

B. Mission Studies and Technology Requirements

As science objectives are defined and the observational techniques needed to address them are better understood, then these ideas can be translated into specific mission concepts. This process has great value in sharpening the understanding of technology needs. By taking a total systems view of the experiment, technology requirements can be identified for all elements of the mission. Those elements that are critical and underdeveloped can be identified and those that are not critical and underdeveloped can be removed from consideration for the program. NASA has had a procedure in place for some years for implementing this technology planning process.

Mission studies are first carried out by the Advanced Programs Branch in the Astrophysical Division. These studies begin with early conceptual investigations (Pre-Phase A) and are carried through Phases A and B to the implementation phase where the mission becomes a budgetary line item. During Pre-Phase A, the Advanced Programs Branch works closely with the Space Directorate of OAET to define the technology requirements for the future missions. The OAET funds studies that assess the state of the technology, compare this assessment with the mission and science requirements, and define those technology needs which OAET may be able to satisfy. The results of these studies are then used in planning OAET's future programs.

In the planning of Astrotech 21, we have been following this well-developed process but have attempted to accelerate the pace at which it is executed in order to arrive at a comprehensive technology plan within a period of two years. Necessarily, this means that some issues cannot be covered in depth. However, by following a methodology in which technology needs can be traced to mission requirements we do retain the capability of updating the plan as new information becomes available. We have found most useful those studies that result in a point design: a particular realization of the mission which is close to optimal given the constraints and the knowledge that is available and which can be used as a standard of comparison against which other approaches can be judged. These early point designs serve a heuristic purpose and do not necessarily represent the ultimate mission implementation mode since the developing technologies can feed back and change approaches.

To further assist the technology planning process a detailed assessment was made of the space infrastructure that the New Century Astronomy program will be able to take advantage of. This assessment includes current and projected capabilities in transportation, telecommunications, power,

servicing and telerobotics. It also includes projections of the facilities provided by Space Station Freedom and the proposed Lunar Base. Finally, it includes the most current information on the space environment and its effects on electronic components and on optical and thermal control surfaces. This information is contained in a handbook (2) which will be periodically updated.

Now we review the progress in defining missions and technologies in the four areas of emphasis identified in the SSB report (1).

1. Imaging Interferometry

In the technique of interferometry, the coherent interaction of light waves, an array of telescopes is used to obtain images of better resolution than can be achieved with the individual elements of the array. The resolution would be similar to a telescope whose diameter is comparable to the dimensions of the array. For interferometry at radio wavelengths (Fig. 1) and for wavelengths ranging down to submillimeter dimensions, heterodyned signals from individual array stations can be separately recorded and combined in a computer to generate positional and imaging information. At optical and infrared wavelengths (to approximately 30 um) heterodyning is neither technically feasible or even desirable given the quantum granularity of the faint optical signals from many astrophysical sources. As a result, the optical or infrared beams from the collector station must be conveyed to a central combining station where they interfere with one another and the interferograms are recorded on an appropriate focal plane array detector (Fig. 2). In the remainder of this paper we will refer to this technique of interferometry as optical interferometry independent of whether it is visible, infrared or ultraviolet radiation that is being observed.

a) Optical Interferometry

For combining broadband radiation and synthesizing useful images, the path differences of the signals must be accurately matched. The different approaches to optical interferometry from space reflect in part the different ways in which these path matching critieria may be satisfied. The science objectives of optical interferometry and the observational techniques were discussed at the workshop on interferometric methods.

Three broad approaches to deploying the individual collecting stations and the central combiner in space were identified at this workshop: on a large space structure, on the lunar surface, or as a constellation of individual spacecraft. The example configurations illustrated in Figure 3 are not the only ones that are possible, but they do reflect the fact that the ease of translational and rotational mobility is fundamentally different for these three kinds of deployment.

These three concepts were the subject of an Astrotech 21 workshop on "Technologies for Optical Interferometry" held at JPL on April 30 - May 2, 1990. Two of these concepts, the large space structure and the lunar surface implementations, are also the subject of more detailed analyses that are expected to continue for at least another year. The third is now viewed as a somewhat longer range possibility and will be studied after the first two are better understood.

b) Radio Interferometry

Radio interferometers are now in routine use in ground-based astronomy and provide imaging of higher angular resolution than any other technique in the radio or optical regions. Japan and the Soviet Union are also developing first-generation Orbiting Very Long Baseline Interferometer (OVLBI) missions capable of centimeter-wave observations. NASA will participate in these missions through the use of the Deep Space Network as a key element for transfer of a precision time reference to the orbiting antenna as well as elements of the interferometer array.
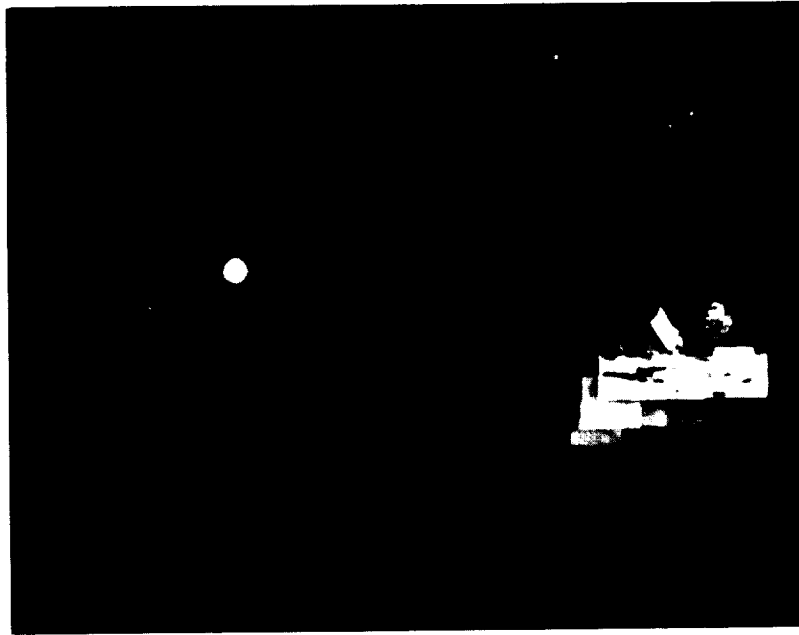
Figure 1. Imaging interferometers can provide a higher angular resolution capability than conventional imagers. One objective of an optical interferometer is to resolve planets around nearby stars.
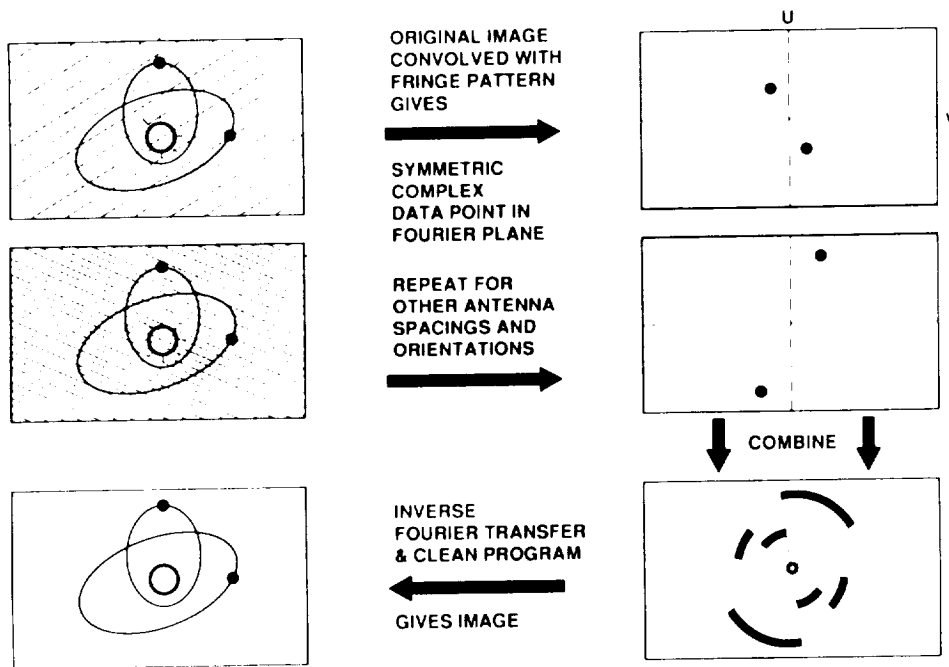
Figure 2. A high resolution image from an optical interferometer is reconstructed from a number of interferograms obtained with different telescope array orientations and spacings.

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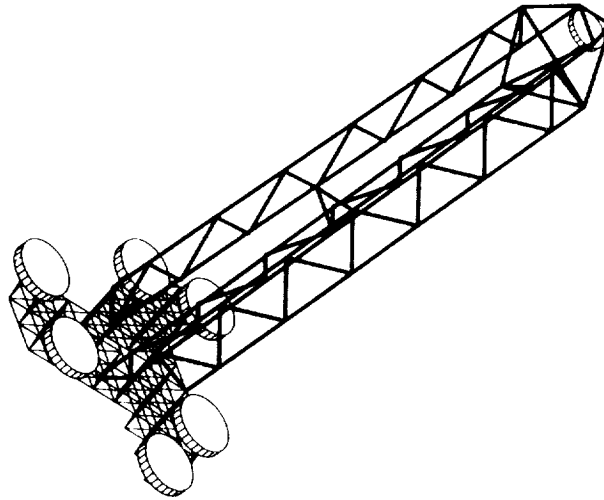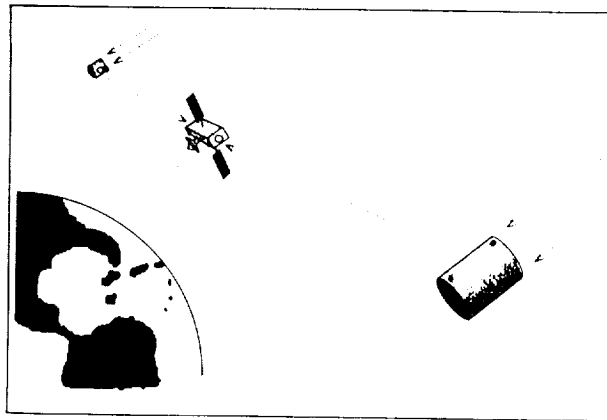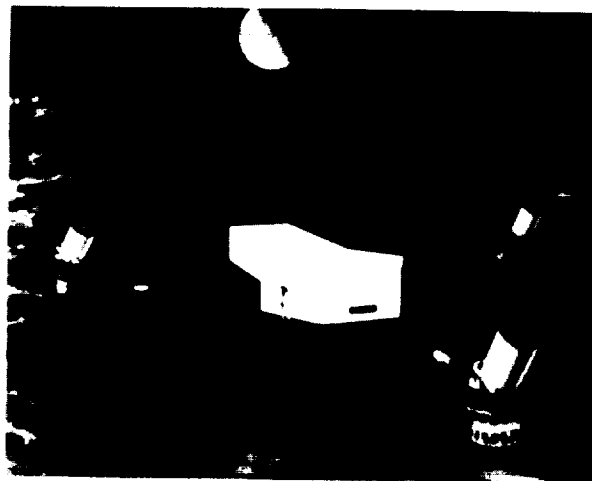
Figure 3. Alternative implementations of a space optical interferometer
a) on a large space structure; b) on multiple spacecraft; and c) on the lunar
surface.

Recently, the European Space Agency has begun a study of a second-generation OVLBI mission with a large deployed 25 m. antenna, ultra low noise receiver and a millimeter wave capability. Like the first generation Japanese and Soviet missions there would be only one antenna in space with the remainder of the antenna elements on the ground. The SSB study identified the importance of OVLBI to astrophysics but currently, there are no studies directed towards missions where NASA contributes parts of the space segment, although some of the technology being developed for submillimeter missions may be applicable. NASA has recently examined a concept for a Very Low Frequency (kilometer-wave) Interferometer deployed at the lunar outpost.

c) Submillimeter Interferometry

During the 90-day study for the Space Exploration Initiative, the concept of a submillimeter interferometer on the lunar surface was investigated. There have also been studies of a Submillimeter Interferometer on the Space Station. No further mission studies and technology assessment are currently planned, but if the findings of the fall 1990 workshop on science objectives and techniques for submillimeter interferometry are favorable, this situation may change. Submillimeter interferometry will undoubtedly enjoy a great deal of tehnological commonality with the submillimeter single telescope spectroscopic missions discussed in the next section.

2. High Throughput Missions

High throughput missions are directed at the investigation of the faintest and farthest objects using observatories with very large collecting area and ultrasensitive sensors providing high spectral resolution. They are desired in every wavelength band that is observable from space.

a) Submillimeter Missions

The development of concepts for future submillimeter missions has matured rapidly during the last year. Accordingly, it has been possible to develop a much more specific assessment of technology requirements, and to begin the definition of a targeted technology program.

For a decade, NASA has conducted studies of the Large Deployable Reflector (LDR), a 10-20m diameter radiatively-cooled space telescope (Fig. 4a) for infrared and submillimeter observations. It is characterized in the SSB report as one of the highest priority missions for the astrophysics community and, as currently conceived, would be assembled at Space Station Freedom. Motivated by the needs of LDR, OAET has carried out a number of important technology developments in: lightweight telescope mirrors and structure, low noise submillimeter heterodyne sensors and far infrared focal plane array detectors. In the light of these successful developments, the Astrophysics Division is examining options for a Submillimeter Moderate Mission (SMM) (Fig. 4b), which could open up the submillimeter region to a systematic survey much earlier than LDR, carry out important science in its own right and lay the technological and scientific groundwork for an LDR-class high-throughput spectroscopic imaging mission as well as interferometric submillimeter observatories.

The proposed start date for SMM demands that technology be ready by June 1994. Technology for LDR and any potential submillimeter interferometer will not be needed until several years after that. Accordingly, a focussed approach to the planning and implementation of technology development is called for. The Astrotech 21 planning team has been working closely with the leadership of both the SMM and the LDR study teams to critically evaluate technology requirements, to assess the state of technology in the context of those requirements and to develop a plan for a technology development program. The technology program will draw upon expertise from not only within NASA centers but also from universities (3) and industry. The plan is scheduled for completion by August 31, 1990.

a) Large Deployable Reflector (10-20 meter diameter)
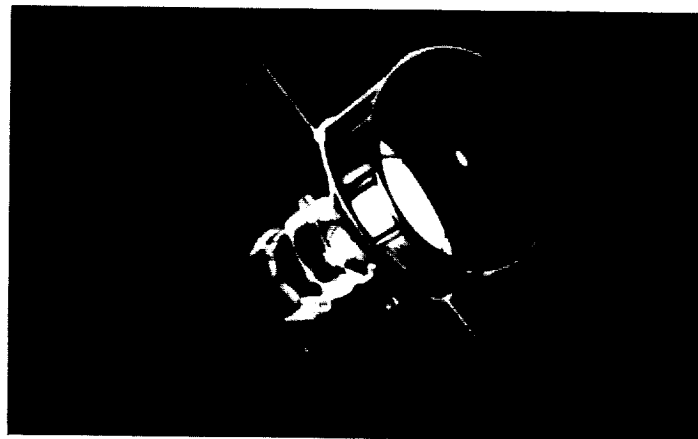
b) Submillimeter Moderate Mission (2.5 to 3.7 meter diameter)

Figure 4. Submillimeter high throughput mission: a) large deployable reflector (10-20 meter diameter); b) submillimeter moderate mission (2.5 to 3.7 meter diameter).

One result of the study activities has been some significant changes in mission concepts for LDR and SMM. Drawing on study results developed as part of the Phase A study for the Space Infrared Telescope Facility (SIRTF) mission, it was recognized that the advantages of low earth orbit (LEO) in terms of the ease of delivery of a spacecraft and potential for servicing is offset by the lack of long periods of observation in stable thermal and radiation environments. Accordingly, a 24-hour elliptical orbit and a 72-hour high earth orbit (HEO) were investigated. Although the elliptical orbit has a number of advantages, it is by far the worst of the three orbits as far as radiation environment is concerned. This may impact the performance of the detectors, the optical panels and the power systems on the spacecraft. The larger payload that can be delivered into the orbit may warrant an investment in technology to address these problems.

b) Next Generation Space Telescope

The SSB study identified an 8 to 16 m. space telescope for ultraviolet, optical and infrared wavelengths as the successor to HST. Unlike the HST which is operated at about 300K, this telescope would be radiatively cooled to about 100K for maximum infrared performance and would perform in the range of 912 angstroms to 30 micrometers complementing the coverage provided by the LDR at longer wavelengths.

In the fall of 1989, a workshop on the Next Generation Space Telescope (NGST) was held at the Space Telescope Science Institute in Baltimore, Maryland to consider scientific opportunities and technical challenges. Two concepts were examined: a 10 meter telescope in high earth orbit (Fig. 5a) and a 16-meter telescope on the moon (Fig. 5b). The workshop concluded (4) that emerging technologies have the potential for very substantial weight saving and hence cost savings. The need for further studies and the definition of critical technologies were identified.

A second workshop is being planned as part of the Astrotech planning effort to act on the recommendations of the Baltimore workshop. It is expected to take place in the late fall of 1990.

c) High Throughput-High Energy Missions

The Great Observatory Program of the 1990s includes two high energy missions: the Gamma Ray Observatory (GRO) and the Advanced X-ray Astrophysics Facility (AXAF). The Space Science Board Study (1) identified two follow-on missions: the Very High Throughput Facility (VHTF) for up to 10 KeV and the Hard X-ray Imaging Facility (HXIF) for 20 KeV to 2 MeV as major mission focal points for high energy astronomy. The Astrotech 21 workshop on High Energy Astronomy for the 21st Century endorsed the concept of missions in the HXIF/VHTF class and determined that detector and optics technology work would be important to their feasibility.

Under the oversight of the High Energy Astrophysics Management Operations Working Group (HEAMOWG), the Marshall Space Flight Center will be carrying out pre-phase A studies of these X-ray mission concepts. The importance of these studies to technology definition can be appreciated in the context of the discussions of submillimeter missions elsewhere in this paper.

The Goddard Space Flight Center has assumed the responsibility for defining a program in High Energy Detectors and X-ray Optics Technology responsive to the findings of the TAOS workshop and supportive of missions such as VHTF and HXIF. This program is being lead by Dr. Andrew Szymkowiak.

Further definition work is needed for Gamma Ray mission concepts. The SSB study identifies an Advanced Compton Telescope for spectroscopy from 0.1 to 10 MeV but no detailed concepts for this telescope have yet been developed.
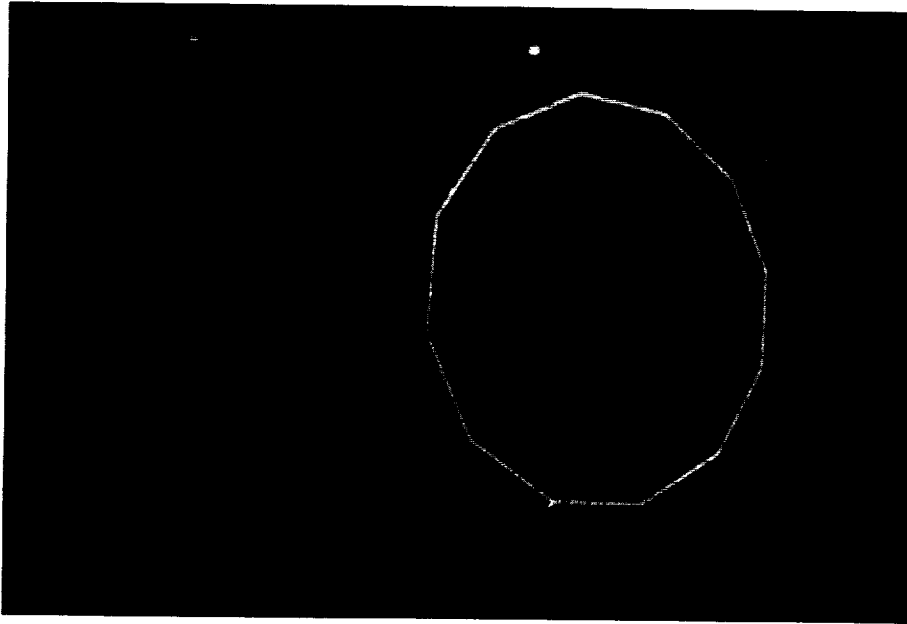
a) 10 Meter High Earth Orbit Telescope
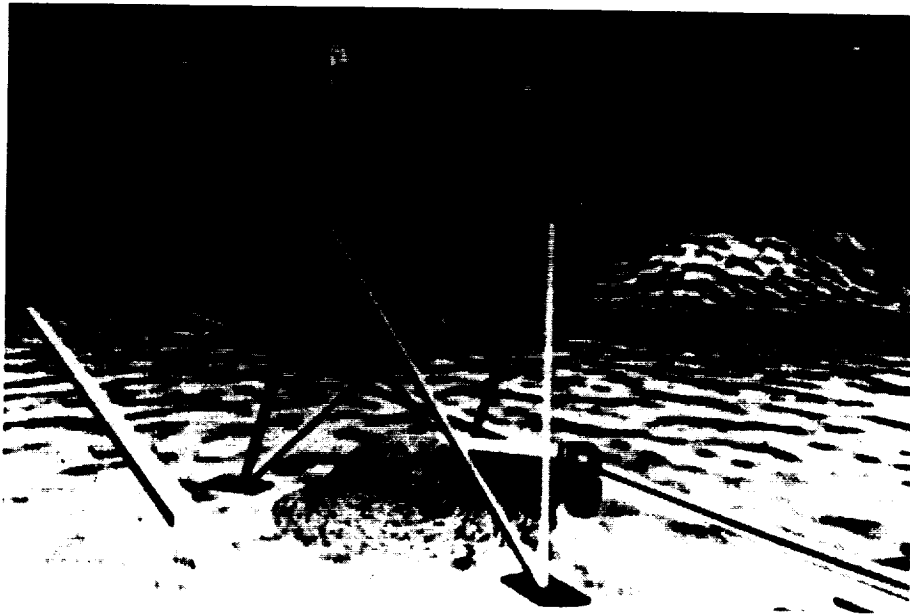
b) 16 Meter Lunar Telescope

Figure 5. Next generation space telescope: a) 10-meter high earth orbit telescope; b) 16-meter lunar telescope.

3. Laser Gravitational Wave Observatory in Space

The SSB study described a gravitational detector consisting of three spacecraft orbiting the Sun, each one a million kilometers from the next and possessing a precise system for monitoring their separation by laser ranging, which would allow the detection of gravity waves from astronomical sources with periods from 0.3 sec to 10 days. Such a detector is viewed as the best chance of directly observing the violent accelerations of matter in strong gravitational fields such as those produced by black holes. The importance of the development of the techniques for such a mission has also been affirmed more recently by NASA science advisory bodies.

Building on the pioneering work of Peter Bender of the Joint Institute for Laboratory Astrophysics, a study activity was initiated in early 1990, under the auspices of Astrotech 21 to attempt to better understand mission feasibility and technology requirements. This was followed by a workshop on technologies for the laser detection of gravitational waves from space held in Annapolis, Maryland, April 19-20, 1990. Some of the difficulties addressed in that workshop included the problem of isolating the "gravitational wave antenna" from spurious accelerations unrelated to gravitational waves, including fluctuations in the solar wind, mass perturbations in the spacecraft and the impacts of cosmic rays. This work has laid the groundwork for a joint center/university study effort directed at finding solutions for the problems identified at the workshop and performing more definitive recommendations on technology needs.

4. Small Missions

The 1980 Astronomy Survey Committee advocated that smaller and less expensive components of the space program must not be neglected. This exploratory program consists of smaller ad hoc projects that prepare the way for major thrusts of the future. Missions in the Explorer and Small Explorer class typify this kind of project.

The science community's interest in small missions continues to grow. At the Taos workshop on High Energy Astrophysics, for example, there was great interest in the role of smaller missions introducing innovative techniques for very high spatial resolution and time resolution measurements.

Other missions potentially in this category include first generation optical interferometers that would make astrometric measurements of greater accuracy than those achievable with conventional techniques.

C. Integrated Technology Planning

Because of resource limitations that every technology program confronts, it will not be possible to tackle every technology requirement identified in the Astrotech 21 program independently. Accordingly, we have established a process for identifying common needs and shared applications of technology which will lead to the definition of an integrated technology plan for Astrotech 21.

The technology integration process will take place on several different levels. The first level involves missions which use similar observational techniques but which have different performance requirements. The submillimeter missions discussed earlier are a good illustration of this since the integration process is already under way. Here the precision reflector and sensors requirements for the SMM and LDR missions are being embodied in a coordinated program which will first address the requirements for SMM and then build on these developments to satisfy the needs of LDR. Integrating the needs of a nearer term program such as SMM with immediate specific requirements, with a longer range program with more ambitious requirements, may also require a program with a mix of focussed developments of existing concepts and high risk/high payoff research into new ideas. Such an approach allows exploitation of early and intermediate technological successes.

A second level of integration involves consolidating requirements for different types of astrophysics missions. For example, the lightweight support structures under development at NASA's Langley Research Center may have equal applicability to high throughput visible and X-ray telescopes as they do to submillimeter telescopes such as SMM and LDR. Sometimes the possibilities for integrated planning are less obvious: it turns out, for example, that developments at NASA's Goddard Space Flight Center in infrared bolometer detectors have proved to be applicable as non-dispersive X-ray detectors.

The third level of integration will involve integration with the requirements of other space science disciplines. For example, some of the astrophysics needs for advanced information technologies are close to those of the earth observation programs. A few large developmental efforts aimed at these common needs may be preferable to a larger number of fragmented programs.

The integration phase of the Astrotech 21 planning effort is organized into four technology discipline areas. They are Information Systems, Optical Systems, Sensor Systems and Observatory Systems. Relevant output from the first two phases of the planning process are incorporated into the planning in the appropriate technology discipline areas. Again, the workshop approach is used for distilling this information into a set of requirements-based recommendations for technology development. These workshop recommendations will be used by the agency to develop detailed technology and advanced development plans in the respective areas of technology.

We now review the status of planning in the four technology discipline areas. We begin with Information Systems which is the subject of this meeting and also the first technology area to be examined in depth in the Astrotech 21 study. We follow with briefer descriptions for the plans for developing integrated technology plans in the three other technology areas.

1. Information Systems

As noted earlier, the needs for information systems technologies are not only similar for the different astrophysical disciplines but also display commonalities with other areas of Space Science, notably Earth Science and Applications. The needs of the Earth Science and Applications Division of NASA for information systems technology during the next 20 years were considered in 1988 in the planning of a Global Change Technology Initiative. The commonality of needs within astrophysics has been recognized by the establishment of a Science Operations Branch to establish an Astrophysics-wide program which encourages multimission panchromatic research in Space Astrophysics. This branch is responsible for development of an Astrophysics Data System (ADS) to provide the data-related ground-based infrastructure for data analysis and research. However, the scope of astrophysical needs for information systems is much broader than this and includes ground-based mission planning as well as space-based data communications, processing and storage.

The missions of the New Century Astronomy program described above will impose much greater demands on information systems than ever before. Some of the needs are reviewed briefly here.

- Science Detector Signal Processing - Future space astrophysics missions such as the Space Optical Interferometer and the NGST are projected to include very large focal plane array sensors. However, sensor data rates, which will influence the required onboard processing and/or communications capabilities are not well defined. If integrating sensors are used, the data rates are likely to be significantly less than those expected on future earth resources missions. However, if high time resolution and photon counting detectors are used in order to isolate transient events or discriminate charged particle radiation, the processing requirements will be many orders of magnitude larger.

- Heterodyne Interferometers - These instruments are likely to impose the most stressing requirements on communications and onboard processing capabilities. Preliminary studies of the lunar submillimeter interferometer have suggested that downlink capabilities of up to 10 Gbps may be needed or alternatively some form of lightweight processor for correlation on the lunar surface. The requirements for centimeter wave, millimeter wave and submillimeter wave interferometers will be investigated and quantified later in the Astrotech 21 planning activity.

- Active Optics/Active Structures - Future large telescopes and interferometers will require some degree of active control of their optical elements and underlying structures. Computational requirements for high bandwidth control of complex structures and multielement optical systems may be enormous. However, unlike science sensors, the low latency required necessitates that computation be performed on the spacecraft and not on the ground. It is possible that quite different computational approaches will be needed for active structure where the emphasis is on vibration control and active optics where well specified beam control is critical. In any case active optics/active structure requirements must be considered as part of a plan for the development of future information systems for space astrophysics.

- Panchromatic Observations - The future will involve a greater and greater emphasis on coordinated campaigns to observe objects with sensors in different wavelength bands. It may also include targets of opportunity such as transient events. These objectives could benefit from advances in capabilities for mission planning and flexible agile communication between spacecraft and ground stations.

This workshop on Information Systems for Space Astrophysics has the goal of advancing our understanding of the needs and opportunities for information systems technology in space astrophysics and to assist NASA with developing programs and strategies to meet those needs. It is jointly organized by the Science Operations Branch of the Astrophysics Division and by OAET.

The technology discipline structure of the workshop has been consciously patterned on a structure previously developed for the earth observation program, which in turn reflects the structure of OAET's program structure in Information Systems and Human Factors described in the paper by Holcomb and Erickson. Panels have been formed in five topical areas: automated mission planning; space to ground communications; space computing; ground data processing and networking; and data analysis and visualization.

2. Telescope Systems

Telescope systems are central to space astronomy. Other areas of space science such as earth science and deep space exploration use telescopes of course. But those telescopes tend to be a small part of the total flight system. In astrophysics, by contrast, the telescope is the major element of the flight systems and the spacecraft and sensing instruments are usually appendages of the telescope. Nor is it just a matter of size. The performance demands on the telescope are stringent.

Telescopes are needed to provide coverage in different parts of the electromagnetic spectrum and their performance must be maintained for an extended lifetime in space. Most important these capabilities must be provided for minimal mass and cost. These severe constraints point to a major role for new technology.

Anticipating the needs of the New Century Astronomy Program, NASA/OAET has been investing in the development of lightweight composite panel technology for submillimeter and far infrared space telescopes and in controlled structure interaction technology with applications to optical interferometers. A workshop in Fall 1990 will be addressing the further work that needs to be done in

these areas and new research efforts in areas such as integrated optical modelling, optical testing, optical metrology, lightweight visible optics and lightweight X-ray optics.

3. Sensor Systems

Sensors are critical to astronomy. Areas of clear importance include the current investment areas of infrared focal plane arrays and submillimeter heterodyne receivers. The emerging technologies in low temperature non-dispersive X-ray detectors and high-quantum-efficiency photon-counting detectors for the visible and ultraviolet are prime candidates for new programs. Radiation hardening will be an issue of increasing importance with emphasis on the needs of high earth orbit and lunar observatory locations. A workshop in March 1991 will address these issues.

4. Observatory Systems

This topic covers power and propulsion in addition to the space assembly and servicing technologies that are critical to the feasibility of high throughput observatories. The workshop on this topic is planned for late Spring of 1991. Since it will be the last workshop in the series of four, its content is expected to be significantly influenced by the earlier ones.

IV Conclusions

The field of space astronomy and astrophysics offers tremendous opportunities for progress through the introduction of new technology. NASA is formulating the plans for Astrotech 21 - a program for developing the technology enabling the New Century Program of advanced missions. Implementation of the Astrotech 21 program will provide the national space astronomy community with the range of attractive choices that assure a continuation of the nation's leadership in space science. This workshop on Information Systems for Space Astrophysics in the Twenty-First Century plays a central role in identifying the technology needs and in formulating a strategy to meet those needs.

V Acknowledgements

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Astrophysics Science Operations in the Great Observatories Era

Presentation to the
Workshop on Astrophysical Information Systems

May 23, 1990

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ABSTRACT

Plans for Astrophysics science operations during the decade of the nineties are described from the point of view of a scientist who wishes to make a space-borne astronomical observation or to use archival astronomical data. "Science Operations" include proposal preparation, observation planning and execution, data collection, data processing and analysis, and dissemination of results. For each of these areas of science operations we derive technology requirements for the next ten to twenty years. The scientist will be able to use a variety of services and infrastructure, including the "Astrophysics Data System." The current status and plans for these science operations services are described.

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INTRODUCTION TO SCIENCE OPERATIONS

Until recently, the Astrophysics community had access to data from just a few Astrophysics missions. With a small number of datasets, the use of mission-unique data and analysis tools was considered to be acceptable. With the launch of a large number of Astrophysics missions in the timespan of a few years (see Figure 1), a better approach had to be found. The NASA Astrophysics Science Operations Program was established as an Astrophysics-wide program in order to encourage multi-mission, panchromatic research in Space Astrophysics. By fostering coordination and cooperation among all mission operations and data analysis efforts in Space Astrophysics, NASA expects to maximize the scientific return from operating Astrophysics missions, as well as from existing Space Astrophysics data.

The objectives of the Science Operations Program are to maximize the scientific return from operating Astrophysics missions, to maximize the scientific return from existing Astrophysics data, and to enable multi-mission, panchromatic research in Space Astrophysics.

The term "Science Operations" includes four areas (see Figure 2):

- the **"Astrophysics Data System (ADS)"**, providing the data-related infrastructure for all of the following items,

- **research programs**, consisting of guest observations and archival research by members of the Astrophysics science community,

- **science support services**, including multi-mission archive centers and science databases, and

- management of **mission operations and data analysis**, typically carried out at a NASA field center or a mission center.

The purpose of this paper is to present

- the current status of Astrophysics Science Operations, in order to serve as reference information for Workshop participants,

- the plans for Astrophysics Science Operations for the next few years (the Workshop will, of course, focus on a more distant epoch, i. e. the next ten to twenty years), and

- the relationship between the four Science Operations functions and the "Topics for Panels in the Astrophysical Information Systems Workshop".

SCIENCE OPERATIONS: IN A STATE OF TRANSITION

The principles and day-to-day execution of Astrophysics science operations are in a state of **transition**. Although all Astrophysics missions have their unique history and future plans, they tend to evolve towards the same long-term goals.

The **character of Astrophysics missions** is changing from Principal-Investigator (PI) instruments (or even PI-type missions) to facility-class observatories, where the instruments are still built by PIs, but many Guest Observers are expected to use them. Several of these missions are also planned to be operational for sufficiently long periods of time that a significant turnover in technical and scientific personnel will take place during the active life of the mission. Furthermore, analysis methods and computing hardware will evolve through several generations during the data analysis phase of these missions.
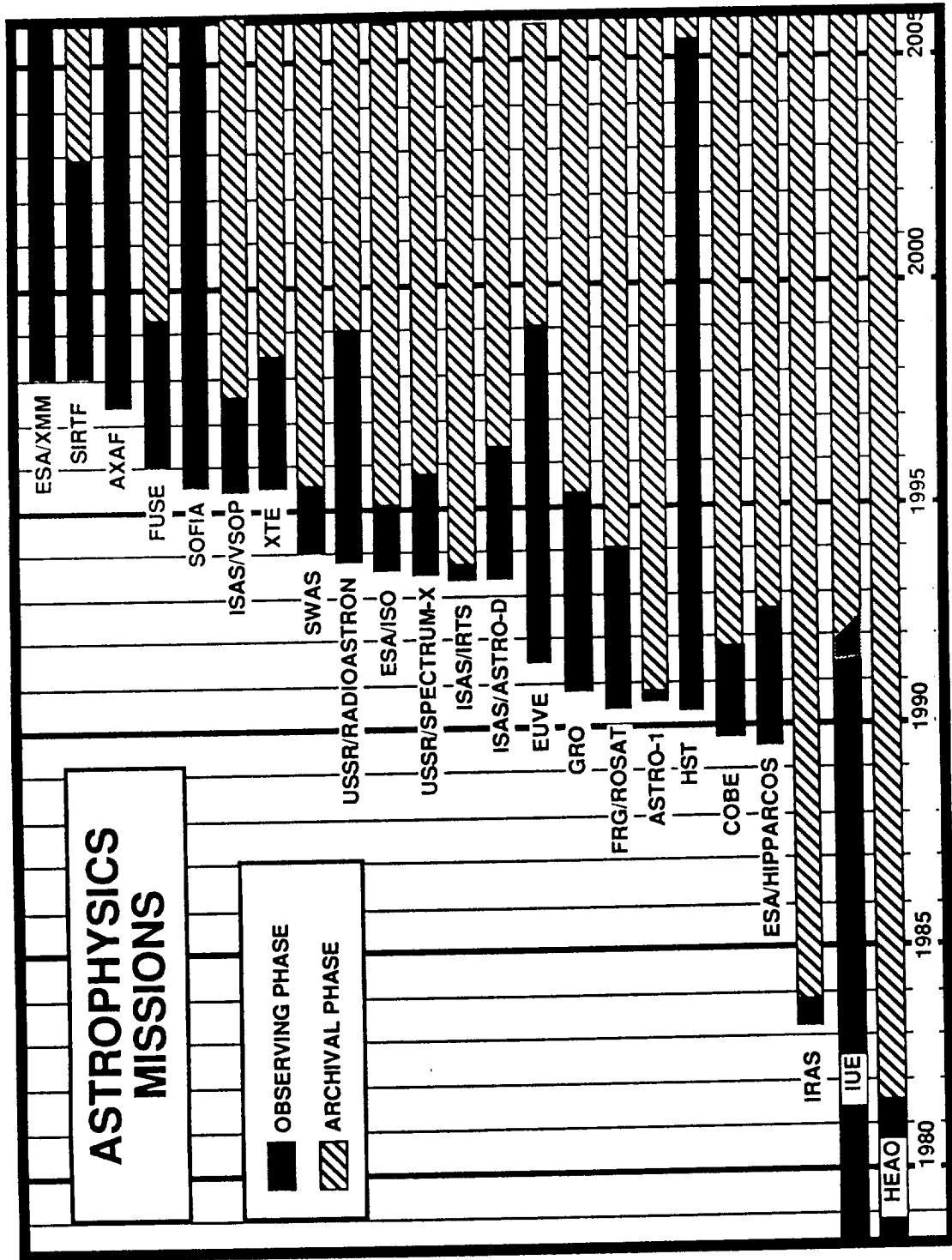
Figure 1. The active operations/observation phases and subsequent archival research phases for the major space astrophysics missions shown as a function of time.

SCIENCE OPERATIONS BRANCH

SO MOWG
- Astrophysics Data System Working Group
- Software and Research Aids Working Group
- Tech 21/SEI Working Group (ad hoc)

Astrophysics Data System
- Astrophysics Data System - Directory Service
- Media, Data Standards, FITS Office, Interoperable Catalogs
- Network coordination
- Software Environments (IRAF, IDL, AIPS, etc.)
- Development and Maintenance of Software and Research Aids
- Advanced Technology Development, Tech-21

Research Programs
- Observing programs (IUE, ROSAT, GRO, EUVE, etc.)
- Archival Analysis (Astrophysics Data Program - ADP)
- Long-Term Space Astrophysics Research Program
- Astrophysics Theory Program

Science Support Services
- Senior Review across MO&DA: balancing of science centers, observing programs, and archival research programs
- Single- and Multi-mission Data Analysis Centers (HEASARC, IPAC, etc.)
- Database Services (SIMBAD, NED) and data compilations (HEAO-1)
- Science Support Centers (Direct and Indirect Science Services incl. data analysis, data manipulation and archiving, observation planning and coordination)
- Science User Guidance to ATD/Technology 21

Mission Management
- Management of Mission MO&DA (during routine observing phase)
- IUE
- ROSAT
- COBE
- Future: GRO, EUVE, etc.
- Operations Development

Figure 2. The four major components of Astrophysics Science Operations.

20

For PI instruments, most of the data analysis was carried out by members of the PI team at the PI institution. In the future we expect to see **distributed analysis**, primarily carried out by Guest Investigators at their home institutions.

The **character of scientific research** is also expected to evolve, from single-mission or single-wavelength research to science topic-oriented, panchromatic research. For example, a recent study showed that of all the scientists who used data from the Infrared Astronomy Satellite (IRAS), only 30% considered themselves "IR Astronomers" proper, while 70% came from radio, UV/Optical, high-energy, or theoretical astrophysics. To enable panchromatic research, we require:

- the ability to execute coordinated (simultaneous or contemporaneous) observations involving space- and ground-based observatories, and

- the ability to carry out multi-mission and multi-wavelength data analysis and interpretation.

This means that Astrophysics missions must supply the necessary expertise, as well as data, data analysis tools, and other services to enable and encourage such topic-oriented research.

SCIENCE OPERATIONS NEEDS FOR A TYPICAL GUEST OBSERVATION

The table below shows steps in a typical Astrophysics investigation, and examples of the types of science operations services required at each step. Several of these services are described in more detail below.

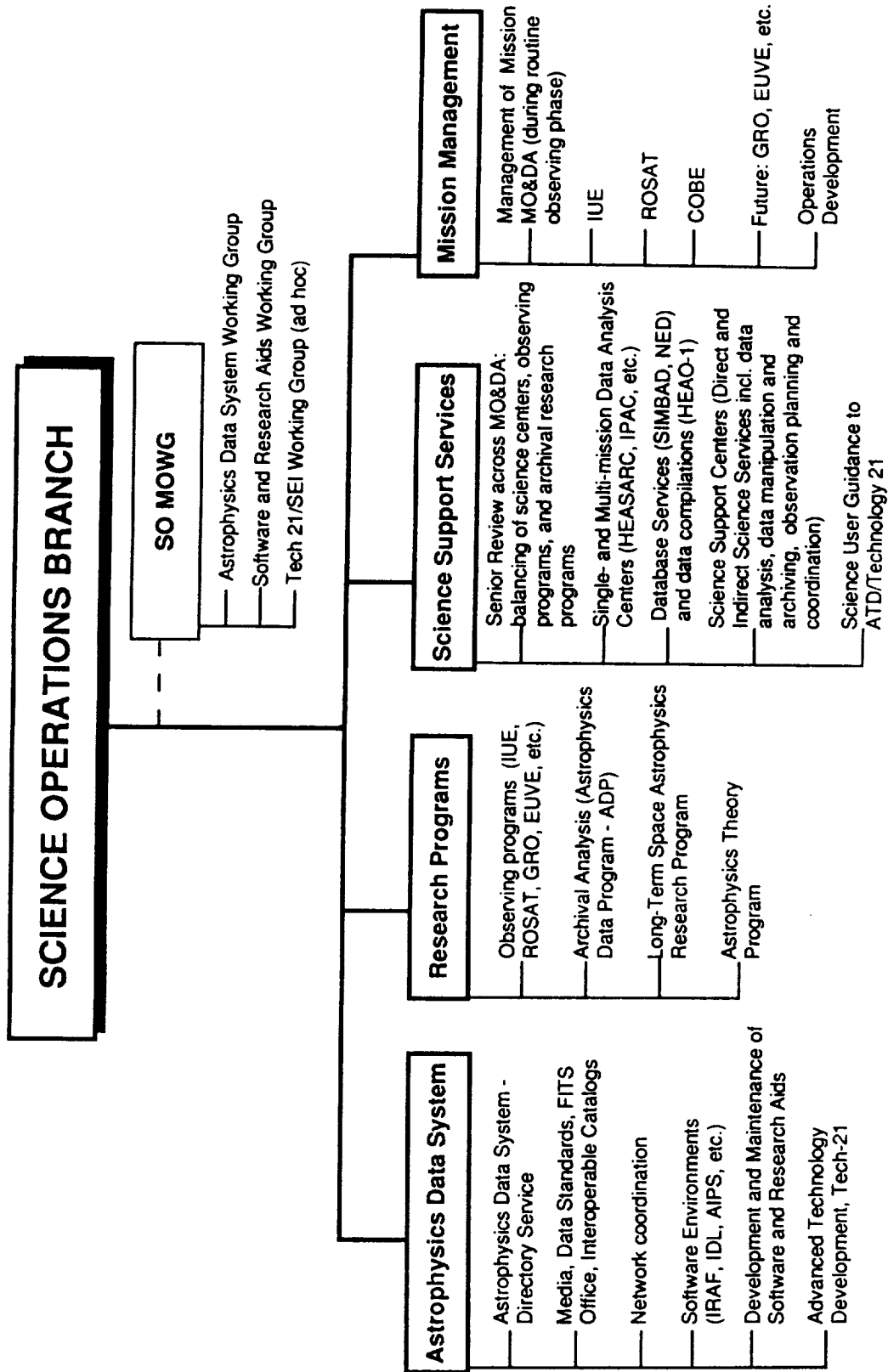| INVESTIGATION TASK	SCIENCE OPERATIONS SERVICES REQUIRED BY INVESTIGATOR
Release of the NASA Research Announcement (NRA)	Supplemental information and proposal preparation available electronically from mission science data center
Proposal writing	Obtain information about existing or approved observations through the ADS, on-line databases, database services
Proposal submission	Electronic submission, electronic peer review, publication of approved investigations (abstracts, source lists) in databases
Observation planning	Database tools for coordinated observations
Data reduction and analysis	Remote data processing and analysis, portable software, standard software packages, software interchange, ADS, data format standards, databases, discipline-specific archives

ASTROPHYSICS DATA SYSTEM (ADS)

The Astrophysics Data System provides the **infrastructure** for locating data, and for the subsequent data analysis. The ADS Project is managed at the Infrared Processing and Analysis Center (IPAC, Dr. John Good, Project Manager) in Pasadena, California. Figure 3 shows the current configuration of the ADS. It is designed to

- allow remote access by scientists at their home institution through the NASA Science Internet,

- permit scientific inquiries (e. g. "where are UV high-resolution spectra of active galactic nuclei?") to be answered simultaneously by all ADS science center nodes ,

- locate data holdings, select data (sensor, correlative, and ancillary data), browse through the data archives, and order data for electronic or mail-order transmission,

ASTROPHYSICS DATA SYSTEM
OPERATIONAL CONFIGURATION - 1991
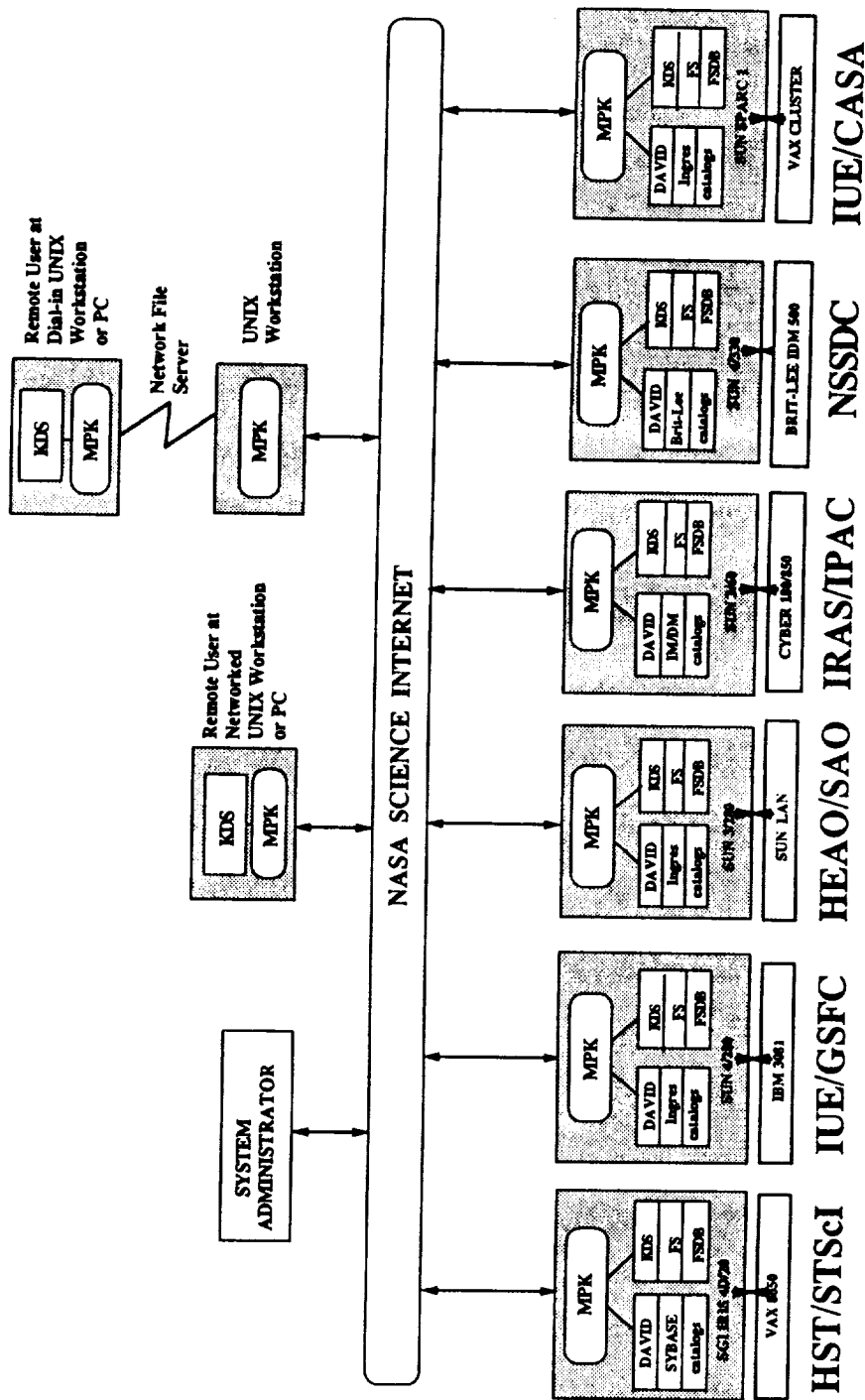
Figure 3. The Directory Service of the Astrophysics Data System (ADS): Operational configuration of the Directory Service of the Astrophysics Data System, showing the message passing kernel (MPK), the data-independent access method to databases ("DAVID"), factor space (FS), and the factor space database (FSDB) portion of the Knowledge Dictionary System (KDS). In the initial configuration (planned to be operational in 1991), the ADS nodes will include the Space Telescope Science Institute (STScI), the International Ultraviolet Explorer (IUE) at the Goddard Space Flight Center (GSFC) and the Center for Astrophysics and Space Astronomy (CASA) at the University of Colorado, the High Energy Astronomy Observatory (HEAO) Data Center at the Smithsonian Astrophysical Observatory (SAO), the Infrared Astronomy Satellite (IRAS) data center at the Infrared Processing and Analysis Center (IPAC), and the National Space Science Data Center (NSSDC) at GSFC.

- make the exact nature of the operating systems or database management systems at the various data centers (see Figure 2) transparent to the remote user.

After two years of development, the ADS is currently in the test phase, and training of new users and node managers has begun. The full ADS is expected to be operational in mid-1991.

The ADS is very similar in philosophy and design to ESA's European Space Information System (ESIS, developed by ESRIN, Frascati, Italy). Access to the ADS from outside the US will be possible through the NASA Master Directory (developed at the Goddard Space Flight Center, Greenbelt, Maryland) and via direct connection through the NASA Science Internet.

Two very important components of the infrastructure for Astrophysics science operations are **communications** and **data format standards**. As a result of the recommendation of the International Astronomical Union for the adoption of the "Flexible Image Transport System (FITS), NASA has adopted a policy for the use of FITS formats for the **exchange of data** (NOT for data files internal to reduction and analysis programs). In addition to special, mission-specific extensions, the FITS system accomodates basic images, random groups, ASCII tables, IEEE floating-point data, 3-D floating-point data, keyword hierarchies, and single-photon data. In order to assist missions and individual scientists in the use of FITS structure, a **FITS Standards Office** has been established at the Goddard Space Flight Center, Greenbelt, Maryland.

On the basis of requests from working scientists, we can identify the following requirements for future technology development:

- Media for: data transfer, medium- and long-term storage,

- Networks: higher throughput, dynamic routing/routing table changes, priority system,

- Software: tools for development, dissemination, and maintenance of analysis tools,

- Software: tools for integration of service software for on-line, networked use,

- Software environments which are highly convertible and transportable.

RESEARCH PROGRAMS

The NASA Astrophysics Division has more than ten research programs which are dedicated to astronomical observations (IUE, HST, ROSAT, GRO, etc.), archival data analysis (the Astrophysics Data Program), and longer-period research efforts (Long-Term Space Astrophysics Research Program, Astrophysics Theory Program).

On the basis of requests from proposers, peer reviewers, users' groups, and science data centers, we can identify the following requirements for future technology development:

- For proposal handling: Electronic proposal submission, tracking, acknowledgements,

- For proposal forwarding to reviewers, ingest of initial and subsequent evaluations, grading, budget assessments: Proofreading of text and numerical data from review; electronic notification of results, grades, comments, budgets; dissemination of results to science community, into databases, to contracts department; and statistical analysis, preparation or reports,

- Electronic conferencing: Voice contact and simultaneous data transmission; controlled transfer of text, numerical, and graphical data to reviewers; and controlled editing of data by chairman and peers,

- Security for all of the above: read-only transmissions; pre-set or commandable erasure of transmitted information and any copies.

SCIENCE DATABASES AND OTHER SCIENCE SUPPORT SERVICES

In response to requests from the science community, and after peer review, a number of services are either under development, or are already accessible to remote users. The "Astrophysics Software and Research Aids" Program explicitly solicits proposals for software packages, databases, operational tools, etc., and supports them after competitive science peer review. The science databases and science operations services include:

- convenient and inexpensive **access to the SIMBAD database** (developed at the Centre de Données Stellaires, Strasbourg, France)

- the **National Extragalactic Database (NED)** (developed at the Infrared Processing and Analysis Center, IPAC, Pasadena, California) containing comprehensive data on extragalactic objects, including cross-references, literature citations, and complete abstracts of referenced articles,

- **"MultiWaveLink"**, an interactive database for the coordination of multiwavelength space and ground-based observing programs (developed at Pennsylvania State University), and

- a **"Comprehensive Atomic Spectroscopy Database for Astrophysics"** (developed at the National Institute of Standards and Technology, Gaithersburg, Maryland).

As a matter of policy, NASA encourages and supports the wide dissemination of data to the astronomical community. Examples of such dissemination are the distribution, on CD-ROMs, of the HST Guide Star Catalog, of the National Space Sciences Data Center's machine-readable versions of frequently used astronomical catalogs, and of the Einstein Observatory's Imaging Proportional Counter and High Resolution Imager results.

Requirements for future technology development exist in the areas of:

- Data management: of digital, textual, and graphics data,

- Data display: visualization, animation, and

- Data analysis: analysis software, software environments.

MISSION OPERATIONS

For mission operations, technology developments are needed for:

- Planning tools: for observation and resource planning,

- Computing: on-board and ground data processors, command processors,

- Command management: software and hardware for command generation, verification, implementation,

- Autonomous scheduling tools,

- Autonomous state-of-health analysis tools: for observatory, instruments, resources,

- Autonomous analysis tools for planned and serendipitous observations, and

- Executives: to assess consequences and implement follow-on actions from all of the above.

INFORMATION TECHNOLOGIES FOR ASTROPHYSICS
CIRCA 2001

A Position Paper for the
NASA Workshop on Astrophysical Information Systems
May 23-25, 1990

by
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ABSTRACT: It is easy to extrapolate current trends to see where technologies relating to information systems in astrophysics and other disciplines will be by the end of the decade. These technologies include mineaturization, multiprocessing, software technology, networking, databases, graphics, pattern computation, and interdisciplinary studies. It is less easy to see what limits our current paradigms place on our thinking about technologies that will allow us to understand the laws governing very large systems about which we have large datasets. Three limiting paradigms are: saving all the bits collected by instruments or generated by supercomputers, obtaining technology for information compression, storage, and retrieval off the shelf, and the linear model of innovation. We must extend these paradigms to meet our goals for information technology at the end of the decade.

I have been asked to present some speculations on technologies that will be available to us in eleven years just after the turn of the century. I have even been asked to be "visionary"! I will indeed spend a few minutes telling you what I see.

Speculating is for me a pleasant and straightforward task. We can look for impressive developments in hardware, software, networking, databases, graphics, design aids, and interdisciplinary studies. A new style of computation -- pattern computing -- is emerging in the form of neural networks and associative memories that will be very helpful to us later in the decade.

What I can see is nonetheless of limited interest for me. I am far more interested in questions about what I cannot see. How do our traditional ways of thinking about our science limit the questions we ask and prevent us from seeing new approaches that will produce the innovations we require? What paradigms are we living in? What are the blind spots induced by those paradigms? What are we missing? What can we see new by stepping outside our paradigms? In short, what do we not see, and do not see that we do not see it?

It is easy for us to challenge someone else's paradigms -- and often unpleasant when someone challenges our own. The challenge often produces a startle reaction: we automatically find ourselves getting irritated, or saying "this cannot be right," or declaring "this person doesn't know what he's talking about."

I am sensitive to this. I want to challenge three of the paradigms you and I live in that affect our approach to information systems. At the same time, I want to offer some new possibilities that appear to those willing to step outside. Some of my challenges may irritate you. I ask that you say, "Oh! That's just my startle reaction," and listen on anyway.

What we can see now

By extrapolating today's trends, we can make educated guesses about eight major technologies by AD 2001.

MINIATURIZATION. We continue to refine our methods of building smaller, more power-frugal circuits. We routinely design circuits today with 100,000 transistors in the same amount of silicon as was in the first commercial transistors 25 years ago. The recent Sun SPARC RISC computer is faster and has more memory than the IBM 3033 ten years ago -- and costs under $5,000. DRAM memory chips have gone from 16K bits ten years ago to close to a million bits now and are likely to be 10 times that by the end of the decade. Look for chips of the year 2000 to offer speeds and memory comparable to today's Cray computers. Our design aids are so good that we can customize chips for special applications; look for "silicon subroutines" to be common after another ten years.

MULTIPROCESSING. Ten years ago, an advanced commercial multiprocessor was a machine with two to sixteen processing units. In one decade we have made considerable progress in mastering machines with thousands of processors. Such multicomputers are a necessity for our teraops processing goals of the mid to late 1990s. Today's Connection Machine has 65,536 ($=2^{16}$) processors; by the mid 1990s, look for one with just over 1,000,000 ($=2^{20}$) processors; by the late 1990s, look for machines of this type with over 8,000,000 processors. Look for the individual processors to have speeds beyond 100 mflops apiece. Look for considerable integration of processing, memory, and communication on each chip.

SOFTWARE TECHNOLOGY. For many years we have invested heavily in numerical software for new machines. This has paid off handsomely: since the 1940s, John Rice tells us, our PDE-solving systems have improved in speed by a

factor of 10^{12}; hardware improvements account for a factor of 10^6, algorithm improvements for the other factor of 10^6. Today's research efforts are showing us how to program the multiprocessors effectively. We are within reach of programming environments that will allow us to design highly parallel programs quickly and correctly by the mid to late 1990s.

NETWORKING. The globe is crisscrossed with communication links connecting computers, telephones, fax, radios, and televisions. I call this the phenomenon of worldnet. The distinction between a workstation and the worldwide network is blurring. In just ten years a workstation has shifted from being a personal toolkit to being a portal into the world; look for continued transformation so that by the end of the century we wear our computers, converse with them, and converse with others through them. Today's Research Internet backbone transfers data at the rate of 1.5 mbps, and NSFNET will install 45 mbps within the year. The gigabit optical fiber network should be with us by the mid 1990s. By the turn of the century our terrestrial networks will operate at 10 to 100 times that speed, depending mostly on advances in optical switch technologies and protocols. Look for the current satellite links, now running at 300 mbps, to be operating at speeds comparable with the terrestrial network. Look for networking infrastructure to reach into a sizable portion of businesses and homes in the US, Europe, And japan. Look for portable computers to be routinely connected by cellular links into the world network.

DATABASES. Mass storage systems and systems for archiving and retrieving information have been persistent problems -- our reach far exceeds our grasp. The largest direct access computational memory today is on the Cray YMP, 256 million 64-bit words. Look for this to increase significantly on multiprocessors where we can implement a uniform machine-wide virtual address space with little penalty for access between computers. Look for optical stores to become practical, replacing large disk storage "farms" with capacities of 10^{15} bits. The biggest problem will be finding information in these storage systems rather than transferring it in or out.

GRAPHICS. Look for continued improvements in resolution and function. What we today call HDTV will be the norm. Graphics libraries will permit a wide range of visualizations across many disciplines. Animations in real time will be routine. Head-mounted displays, data gloves, and other technologies associated with virtual reality will be common for scientific visualization and simulation.

PATTERN COMPUTATION. Three styles of computation are widely used today: signal processing, numeric processing, and symbolic processing. (Symbolic processing is the basis of machines that do logical inference within ai systems and languages like Prolog.) A fourth style is emerging, variously called pattern processing, associative processing, and neural processing. Its computational model -- a network of many-input threshold circuits -- is inspired by biological systems. These neural networks can store and retrieve large bit vectors that represent encoded sensory patterns. Although such systems have been the subject of speculation since the beginning of the era of electronic computing (1940s), circuit technology did not permit their construction until recently. Many new approaches to vision and speech recognition are now being tested in neural networks. Look for

this type of computing to attain maturity by the end of the century. It will not replace the other three types, but will certainly augment them. It will provide learning capabilities that are not attainable within rule-based expert systems.

INTERDISCIPLINARY STUDIES. Look for more interactions between experts in different disciplines. For example, many parallel algorithms now being developed for numerical computing will be transferred into earth sciences simulations and data analyses.

What we cannot see

Most of us here are scientists and engineers. Most of us here have worked in one discipline most of our lives. We are mostly men and mostly white. Most of us come from Judeo-Christian traditions.

These statements are facts about our common cultural background. They are neither "good" nor "bad"; they inform us about the body of shared assumptions that constitute our common wisdom about how science works, what science is important for public policy, what is innovation, what questions are worth investigating, what is true, what is good research, which data are valuable, and many similar questions. We seldom reflect on the common presuppositions given to us by our traditions. Most of the time, we are not even aware of our presuppositions. We are blind to them.

Let me give you an example. We often use the word paradigm to refer to the framework of preunderstandings in which we interpret the world. We have been taught, and we teach our students, that the great discoveries of science have happened when the discoverer challenged the current paradigm and stepped outside of it. At the same time, as recognized masters of our scientific domains, we resist changes that might leave us in less esteemed positions. Thus we have a love-hate relationship with paradigms: we like challenging the paradigms of others and we dislike others challenging our own. We especially dislike anyone suggesting that we are blind in some domain of importance to us.

Let me give you another example. As scientists we say that the scientific method consists of formulating hypotheses about the world, using them to make predictions, performing experiments to collect data, and analyzing the data for support or contradiction of the hypotheses. This method is based on a presupposition that the world is a fixed reality to be discovered. Our job is to probe the world with experiments and pass on our findings as validated models. In this preunderstanding, it is natural to say that someone discovered a new particle, discovered a new theorem, or discovered a new fact about the world; it sounds strange to say that someone invented a new particle, invented a new theorem, or invented a new fact about the world. And yet some scientists, notably chemists and molecular biologists, are engaged in a process of invention rather than discovery. The terminology of invention is natural in the paradigm of engineering. Have you ever noticed that physicists and mathematicians like to talk about the great discoveries of science while chemists and engineers like to talk about the great inventions? Because their paradigms are different, scientists and engineers often

disagree on what is "fundamental".

In his book, *Science in Action* [Harvard University Press, 1987], Bruno Latour painstakingly analyzes literature before, during, and after great discoveries and great inventions. He distinguishes between the simplified story we tell about science when looking back after the fact, and the complex web of conversations, debates, and controversies that exist before the "discovery" is accepted by the community. By tracing the literature, he demonstrates that statements are elevated to the status of "facts" only after no one has been able to mount a convincing dissent. Thus, he says, science is a process of constructing facts. Not just any statement can be accepted as fact -- a large community of people must accept the statement and must be incapable with resources and methods available to them of adducing new evidence that casts doubt on the statement.

Latour calls on the two-faced god Janus to contrast the retrospective view (an old man looking leftward, seeing "ready made science") with the in-action present view (young man looking rightward, seeing "science in the making"). See Figure 1. Examples of statements made by Latour's Janus are:

OLD: "Just get the facts straight."
YOUNG: "Get rid of the useless facts."

OLD: "Just get the most efficient machine."
YOUNG: "Decide on what efficiency should be."

OLD: "Once the machine works, people will be convinced."
YOUNG: "The machine will work when all the relevant people are convinced."

OLD: "When things are true, they hold."
YOUNG: "When things hold, they start becoming true."

OLD: "Science is not bent by the multitude of opinions."
YOUNG: "How to be stronger than the multitude of opinions?"

OLD: "Nature is the cause that allowed the controversies to be settled."
YOUNG: "Nature will be the consequence of the settlement."

It is interesting that although the young man's statements are typical of the ones we make while "doing science", we quickly adopt the old man's views as soon as the "science is done." Our research papers, for example, describe orderly, systematic investigations proceeding from problem descriptions, to experiments, to data collections and analyses, to conclusions. The description tells a story that never happened: it fits neatly inside the scientific-method paradigm while the discovery itself is made inside a network of ongoing conversations. We do this also with the history of science. We trace an idea back to its roots, giving the first articulator the full credit. (If the idea is great enough, we give its original articulator a Nobel Prize.) The complex, dynamic web of conversations and controversies disappears. I will argue shortly that this paradigm of science is
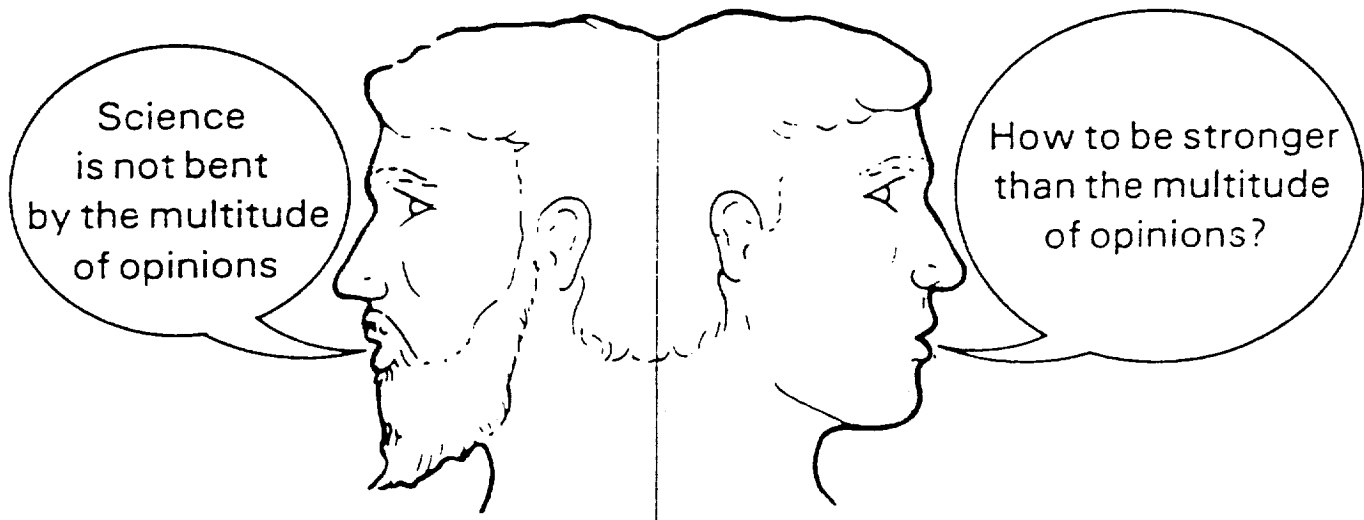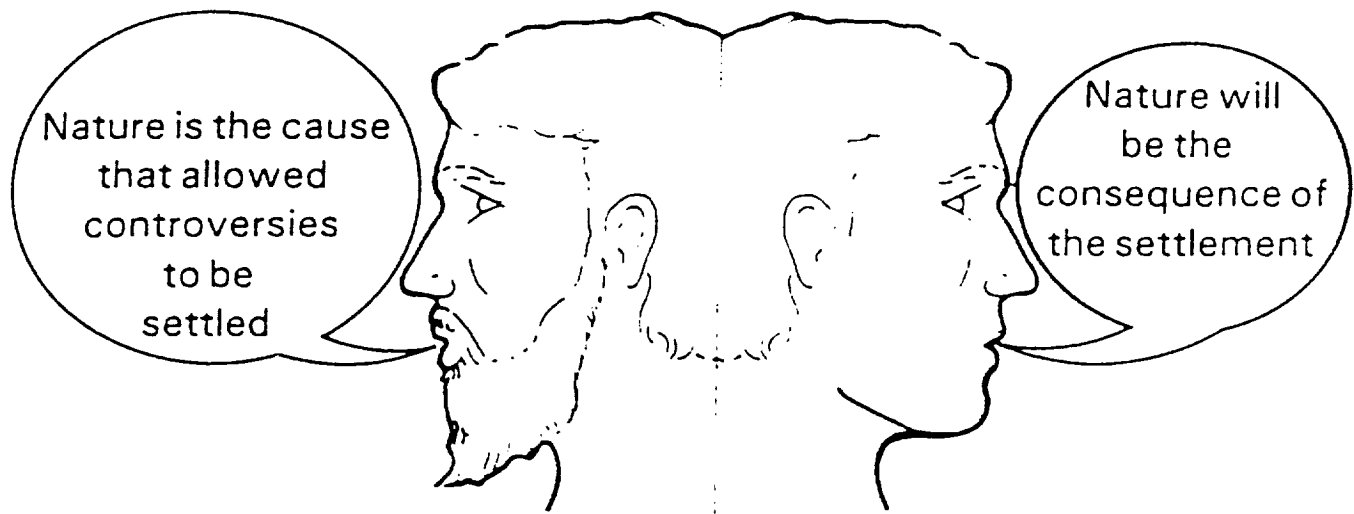
FIGURE 1. In his book, *Science in Action*, Bruno Latour illustrates the contrasts between the view of science after a statement has been accepted as fact (leftward looking face of Janus) and the view while statements are being defined and debated (rightward looking face).

linked to our nation's difficulties to compete effectively in world markets.

I see three major paradigms that shape our thinking about information systems. The first I call *saving all the bits*. Those in this paradigm argue that all bits from instruments and massive computations must be saved, either because the cost of recovering them is too high or because some important discovery might be lost forever. I will show two examples of new technologies that offer the possibility of increasing our power to make new discoveries without having to save all the bits.

The second of the three paradigms I call *obtaining technology off the shelf*. Those in this paradigm argue that NASA ought not sponsor its own research in information system technologies because research money ought to be spent on science and because the needed technology can be acquired from the commercial sector. I argue that this paradigm equates networking with connectivity and ignores networking as a way of collaborating. I argue that NASA has unique mission requirements that do not now appear in the market, and will not over the coming decade; thus I see that the commercial sector will be incapable of delivering the innovations NASA requires.

The third paradigm I call *the linear model of innovation*. Those in this paradigm argue that every innovation begins with a discovery or invention and passes successively through the stages of development, production, and marketing on the way to the customer. They see research as the noble beginning of all innovation. I argue that in reality a cyclical model is at work. Most innovation is accomplished by refinements over successive generations of a science or technology. I argue that NASA must design research programs to create and sustain cycles of innovation that involve NASA, university researchers, and commercial partners. The Numerical Aerodynamic Simulation (NAS) project is a successful instance of a cyclical model of innovation in NASA.

I will now discuss each of these paradigms in more detail.

Saving all the bits

I often hear from colleagues in earth sciences, astronomy, physics, and other disciplines that after we start up an expensive instrument or complete a massive computation, we must save all the bits generated by that instrument or computation. The arguments for this are first, the cost of the instrument or computation is so great that we cannot afford the loss of the information produced, and second, some rare event may be recorded in those bits and their loss would be a great loss for science. I have heard debates in which these points are made with such vehemence that I am left with the impression that saving the bits is not merely a question of cost, it is a moral imperative.

Those in this paradigm are perforce limited to questions about saving and moving bits. How shall we build a network with sufficient bandwidth to bring all the bits from instruments to us? How shall we build storage devices to hold them? How shall we build retrieval mechanisms that allow us to access them from around

the world? Data compression is of interest only if it is "lossless", i.e., it is a reversible mapping from the original data to the compressed data. "Smart instruments" that detect patterns in the data and inform us of those patterns are of little interest -- it is claimed, for example, that such "on-board processing" delayed the discovery of the ozone hole for several years.

As we speak, the Hubble Space Telescope is in limited operation, sending us on the order of 300 mbps via the TDRSS satellite link network to Goddard. This will be joined shortly with the ACT (advanced communications technology) satellite and, in a few years, the network of satellites making up the EOS (earth observing system). These are just a few of the growing number of advanced instruments we have put into space, any one of which can produce data streams at the rate of hundreds of mbps.

Let us do some simple arithmetic with the EOS alone. This system is expected to produce between 10^{12} and 10^{13} bits per day. (This is an enormous number. If we had one ant carrying each of those bits, a day's transmission would make a chain of ants stretching all the way from earth to sun.) It would take 2,500 CDs (compact optical disks) at about 4 gigabits capacity each to hold one day's data. Increases in optical storage density may allow this number to be reduced by a factor of 10 or 100 by the time EOS is on line. Where will all this storage be? Is Goddard going to be responsible for recording 2,500 disks daily? Even the national gigabit network will be inadequate to divert all those streams to other sites for recording elsewhere. And if we succeed in recording all the bits, how is anyone going to access them? How do I as a scientist ask for the records that might contain evidence of a particular event of interest? I am asking for a search of 2,500 disks representing one day's observations, 0.9 million disks for a year's, or 9 million disks if I want to examine trends over a ten-year period.

This scenario doesn't mention the data fusion problem that arises when an investigator requests to study several different data sources simultaneously for correlations. I have heard it said that advanced graphics will allow the investigator to visualize all the bits and see the correlations. But this statement is too glib: it hides the limitations on bandwidth of networks, speeds of graphics devices, methods of storing and retrieving the data, and algorithms for performing the correlations.

In short, the paradigm of saving all the bits forces us into an impossible situation: the rate and volume of the bits overwhelm our networks, storage devices, retrieval systems, and human capacities of comprehension.

Suppose we step outside the paradigm and say that there are important cases in which we do not need all the bits. What machines can we build that will monitor the data stream of an instrument, or sift through a database of recordings, and propose for us a statistical summary of what's there?

Let me give an example under test jointly by RIACS and the Artificial Intelligence Branch at NASA-Ames. Peter Cheeseman has developed a program called Autoclass that uses Bayesian inference to automatically discover the smallest set of statistically distinguishable classes of objects present in a database. In 1987 Autoclass was applied to the 5,425 records of spectra observed by the

Infrared Astronomical Satellite (IRAS) in 1983 and 1984. Each record contained two celestial coordinates and 94 intensities at preselected frequences in the range of wavelengths 7 to 23 microns. Autoclass reported most of the classes previously observed by astronomers, and most of the differences were acknowledged by astronomers as clearly representing unknown physical phenomena. NASA reissued the star catalog for the IRAS objects based on Autoclass's results.

One of these discoveries is shown in the accompanying Figure 2. Previous analyses had identified a set of 297 objects with strong silicate spectra. Autoclass partitioned this set into two parts. The class on the top left (171 objects) has a peak at 9.7 microns and the class on the top right (126 objects) has a peak at 10.0 microns. When the objects are plotted on a star map by their celestial coordinates (bottom), the right set shows a marked tendency to cluster around the galactic plane, confirming that the classification represents real differences between the classes of objects. Astronomers are studying this phenomenon to determine the cause.

There is nothing magic about Autoclass. It is a machine that can take a large set of records and group them into similarity classes using Bayesian inference. It is thus an instrument that permits finer resolution than is possible with the unaided human eye. It does not need to know anything about the discipline in which the data were collected; it does its work directly on the raw data.

The important point illustrated by Autoclass is that a machine can isolate a pattern that otherwise would have escaped notice by human observers. The machine enabled new discoveries, otherwise impossible.

Cheeseman suggests that an Autoclass analyzer could be attached to an instrument, where it would monitor the data stream and form its own assay of the distinguishable classes. It would transmit the class descriptions to human observers on the ground at significant reductions in bandwidth. If the human observer wanted to see all the details of specific objects, he could send a command instructing the analyzer to pipe all the bits straight through.

Let me give a second example. Also at RIACS we have a project studying an associative memory architecture called SDM (sparse distributed memory). See Figure 3. In the SDM each memory cell contains a name field (a vector of bits) and a data field (a vector of counters). When an address pattern (a bit vector) is presented, address decoders at all the cells simultaneously determine whether the given address and their own names are close by some measure such as Hamming distance; all the cells for which this is true participate in the read or write operation requested relative to the given address. Writing is accomplished by adding an image of the data vector to these counters, reading by statistically reconstructing a bit vector from these counters. We have a simulator running on the Connection Machine; it simulates a memory of 100,000 cells with bit vector lengths of 256, and it cycles 10 times a second.

In one experiment David Rogers sought to learn if a variant of SDM could learn the correlations between measurements and desired results. He fed SDM a stream of approximately 58,000 records of weather data from a station in Australia. Each record contained 12 measurements and a bit indicating whether rain fell in the
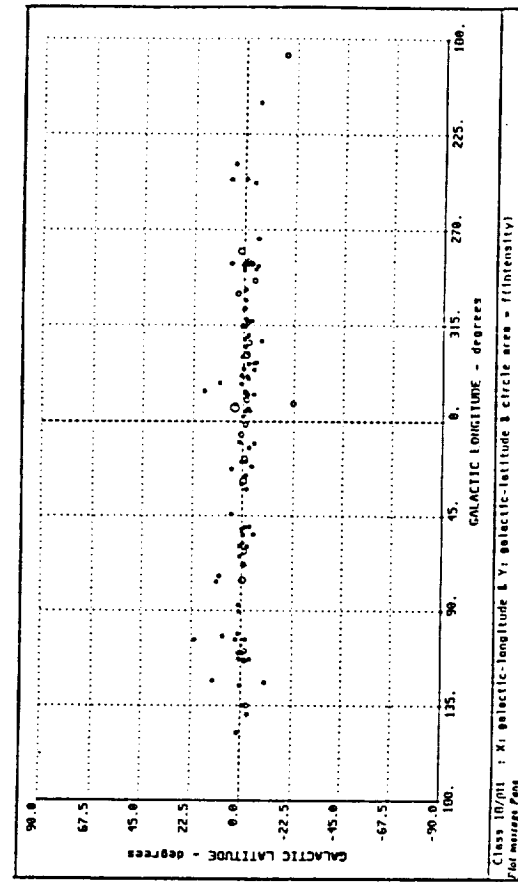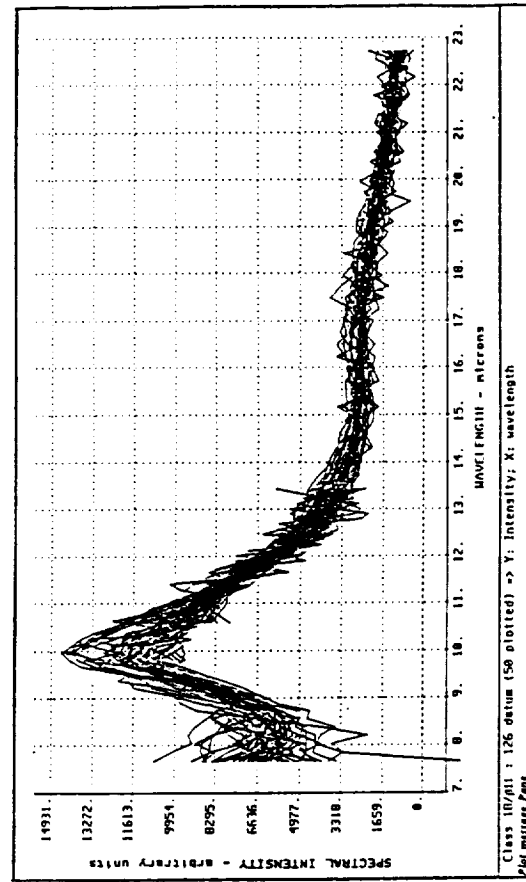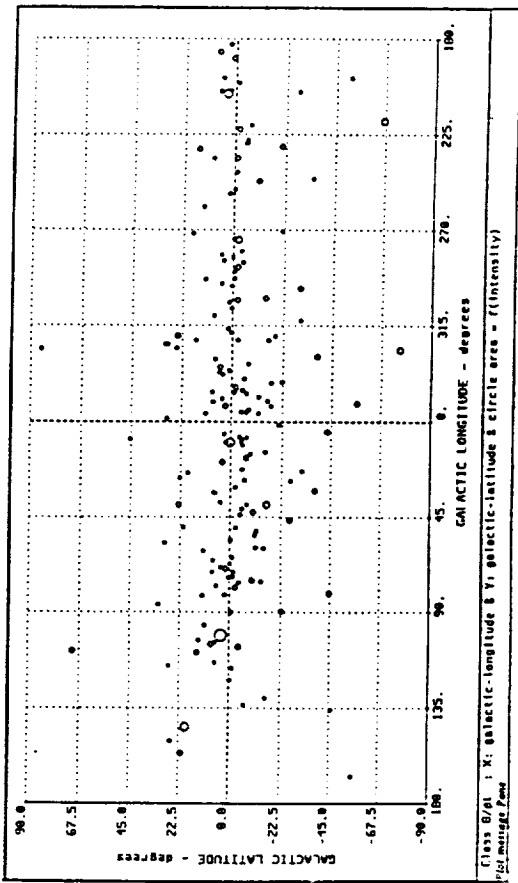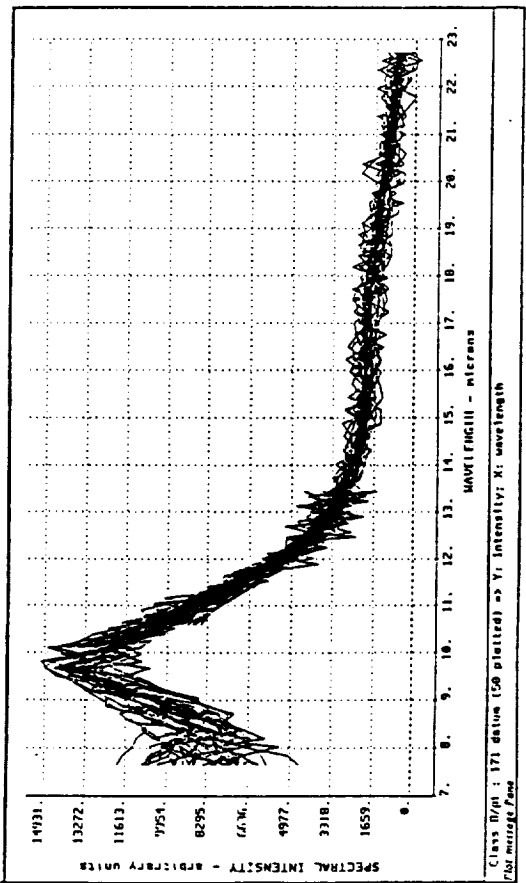
FIGURE 2. In 1983 and 1984, the Infrared Astronomical Satellite (IRAS) detected 5,425 stellar objects and measured their infrared spectra. A program called AUTOCLASS used Bayesian inference methods to discover the classes present in the data and determine the most probable class of each object. It discovered some classes that were significantly different from those previously known to astronomers. One such discovery is illustrated in the accompanying picture. Previous analysis had identified a set of 297 objects with strong silicate spectra. AUTOCLASS partitioned this set into two parts (top). The class on the left (171 objects) has a peak at 9.7 microns and the class on the right (126 objects) a peak at 10.0 microns. When the objects are plotted on a star map by their celestial coordinates (bottom), the right set shows a marked tendency to cluster around the galactic plane, confirming that the classification represents real differences between the classes of objects. AUTOCLASS did not use the celestial coordinates in its estimates of classes. Astronomers are studying the phenomenon further to determine the cause.

34

110110011101101101...   (17)
1010101010111111111...   (512) ◄── Good selection
00000111100 1000001...   (222)
00110110010110 1100...   (32)
10111011000010110 1...   (87)
001010111111101000...   (156)
110110110110110110...   (302) ◄── Good selection
01000001000000000...   (3)
011010100100001000...   (1) ◄── Bad selection
10110101100111001 1...   (55)
11000101110101010 1...   (216)
...etc...   (. . .)

Population of Binary strings Fitness scores

1 0 1 0 1 0 1 0 0 1 1 1 1 1 1 1 1 0 1 0 1 0   First parent

1 1 0 1 1 0 1 1 0 1 1 0 1 1 0 1 1 0...   Second parent

↓

1 0 1 0 1 0 1 0 1 1 0 1 1 0 1 0 1 1 1...   New member
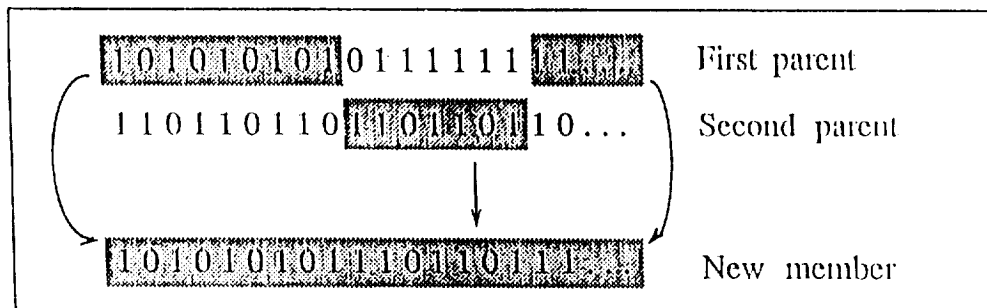
FIGURE 3. The genetic sparse distributed memory is an associative memory system whose addresses are dynamically modified during training so that they collectively evolve toward a set that is capable of best prediction of a future data element. The idea of address modification is based on Holland's genetic algorithm.

measurement period. The measurements were encoded into a 256-bit vector, and the rain bit of the next period was used as data. Just before the actual next-period rain bit was stored, the SDM was asked to retrieve its version of the bit. If the retrieved bit agreed with the bit about to be written, each selected cell had 1 added to its "success count". At intervals the two highest scoring cells were cross-bred by combining pieces of their names; the new name thus created replaced the name in the lowest- scoring cell. This is the principle used in genetic algorithms, and Rogers calls his variant the genetic memory.

At the end of the experiment, Rogers found that the memory gave accurate predictions of rain. By examining the name fields of all memory cells, he was able to determine which subset of the measurements were the most correlated with the occurrence of rain in the next measurement period.

The genetic memory is a machine that can be fed a stream of data. It organizes itself to become a consistent predictor of a specified pattern.

Both these examples show that it is possible to build machines that can recognize or predict patterns in data without knowing the "meaning" of the patterns. Such machines may eventually be fast enough to deal with large data streams in real time. By the end of the decade they may be well enough advanced that they can serve on space probes and space-borne instruments, where they can monitor streams that would be incomprehensible to us directly. With these machines, we can significantly reduce the number of bits that must be saved, and we can increase the likelihood that we will not lose latent discoveries by burying them forever in a large database. The same machines can also pore through databases looking for patterns and forming class descriptions for all the bits we've already saved.

I am not alone in this conclusion. In *Science*, 11 May 1990, journalist Mitchell Waldrop documents the rising concern in the science community about the volumes of data that will be generated by supercomputers and by instruments. He likens the coming situation with drinking from a fire hose: "Instant access to far-flung databases could soon be a reality, but how will we swallow a trillion bytes a day?" He is drawn to a proposal by Robert Kahn and Vinton Cerf to create surrogate processes that would roam the networks looking for data of a particular kind, returning home with their findings. Called knowbots (short for knowledge robots), these processes would resemble benign viruses in their operation. The article ends without saying how knowbots might work. What do you suppose would go inside? Machines that perform automatic discovery, pattern matching, and prediction.

Technology off the shelf

Over the past decade I've repeatedly heard representatives of scientific disciplines giving testimony to NSF, NASA, ONR, advising those agencies against engaging in research on networking. They have argued that the research dollars should be spent on science, that networking is technology, not science, and that the government can acquire the technology it needs "off the shelf" from the

commercial sector. This way of thinking has stopped NASA from engaging in research on its networking needs, and it nearly stopped the NSFnet from being formed. The high performance computing initiative plan departs only slightly from this way of thinking by specifying a technology project to produce a gigabit network by 1995 that will be taken over by the commercial sector. This paradigm does not distinguish networking as connectivity from networking as a way of collaborating.

I'm not challenging the statement that we must build an infrastructure of networks and databases that will allow data to be stored, shared, and analyzed in the scientific community. Many of the components of such an infrastructure are (or will be) available in the commercial market. In those cases, it is appropriate for the government to acquire the needed technologies "off the shelf."

I am challenging the notion that all NASA's networking needs can (or will) be satisfiable commercially. I am specifically challenging the notion that NASA needs no research efforts of its own that treat problems arising in the context of large networks of computers, databases, instruments -- and scientists collaborating over large distances.

NASA is the only organization on earth with the data needs of the magnitudes outlined earlier. No commercial organization has such needs. No commerical customers demand products that would cope with such bandwidths or volumes of data. NASA has defined a unique set of requirements. We are simply not going to cope with all the data with our current ways of thinking: we need wholly new ways of thinking about and handling data. This is true for each major NASA scientific community. NASA earth scientists, I say, must organize their own research program to study data collection, recording, retrieval, fusion, analysis, and understanding in their disciplines. No one else is looking at these questions.

Linear model of innovation

Many innovations will be needed to achieve the goals for information systems by the turn of the century. Most of us think about how to bring those innovations about within the confines of a "linear model" of innovation. (See Figure 4.) This is the familiar model that says every innovation begins with a discovery or invention (usually by some individual or at some institution) and passes successively through the stages of development, production, and marketing on the way to the customer. We use the term research to refer to institutional activities that systematically seek to spawn new discoveries that feed the pipeline. We see research as the noble beginning of all innovation.

In my discussion of Latour, I noted that this model seems to fit what we see when we look back from the present to the past moment when the idea was first articulated. That retrospective history seems to contain the stages noted above.

But the retrospective model is limiting because it hides the intricate webs of conversation, false starts, controversies, and iterations that take place while we seek to make a technology usable by many people.

RESEARCH

$\downarrow$

- - - - - - - - - - - - - - - - - -

DEVELOPMENT

$\downarrow$

- - - - - - - - - - - - - - - - - -

PRODUCTION

$\downarrow$

- - - - - - - - - - - - - - - - - -
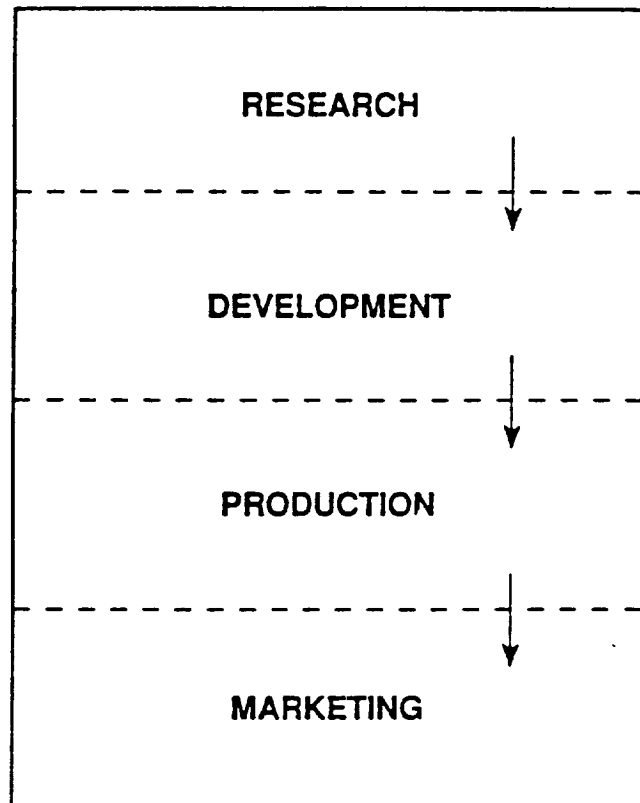
MARKETING

FIGURE 4. Steve Kline, among others, has challenged the linear model of innovation, which holds that ideas are generated during research and then flow through a pipeline of development, production, and marketing on the way to customers. He depicts the model as shown here.

Stephen Jay Kline published a report called "Innovation Styles in Japan and the United States [Stanford University, Department of Mechanical Engineering, Report INN-3, December 1989]. He analyzed in some detail how the actual process of innovation differs markedly from the linear model given to us by our cultural paradigm. Kline reprints a figure compiled by Christopher Hill of the Library of Congress in 1986 showing an inverse relation between Nobel Prizes and growth of GNP, just the opposite of what one would expect if innovation took place according to the linear model. (See Figure 5.) Kline shows that an accurate model consists of many feedback cycles among the various stages of development of a technology: research permeates and sustains all the stages.

Writing in *Scientific American* in June 1990, Ralph Gomory also criticizes the linear model and says that a cyclical model is actually at work in most cases of innovation. While some innovations have been introduced by a linear model, most occur by successive refinements over a series of generations of a product.

Why is this relevant to NASA? As we lay our plans for research in during the 1990s, we must not fall into the trap of thinking that NASA earth scientists will be the original source of many future discoveries that will benefit all of earth science and then eventually all of society. We must instead design our research programs to create and sustain cycles of innovation that involve NASA, university researchers, and commercial partners. We are much more likely to reach our goals of 2001 AD by engaging in cycles of innovation than by setting ourselves up to be either the source of new ideas or the recipient of new ideas generated by others.

The Numerical Aerodynamic Simulation (NAS) facility at Ames illustrates the approach. A major component of the work needed to achieve the national goal of complete simulation of an aircraft inside a computer is technological: namely the acquisition of supercomputers. The planners of the NAS, however, recognized that the architectures of supercomputers such as the Cray-1 and Cyber 205 could not be extended to deliver the needed teraflops computational rates. They argued that the requirement for such speeds was unique to NASA, and thus NASA would have to work closely with commercial partners to foster the development of supercomputers with thousands of processors. They argued that a research component was also needed to develop entirely new kinds of algorithms to exploit the machines and assist the aircraft companies to use the NAS. The NAS they designed has many cycles of activity in it including partnerships with industry, aircraft companies, other supercomputing centers, and universities; it also has a research group on site supporting all these activities. This facility embodies a cyclical model of innovation. It is of obvious value to the US aircraft industry and the nation. It is a smashing success.

Conclusions

We live in three paradigms that can impose severe limitations on what NASA can accomplish in an information systems program during the 1990s. It is not necessary to give up these paradigms; they have been useful in the past. It is, however, necessary to avoid being limited by them.
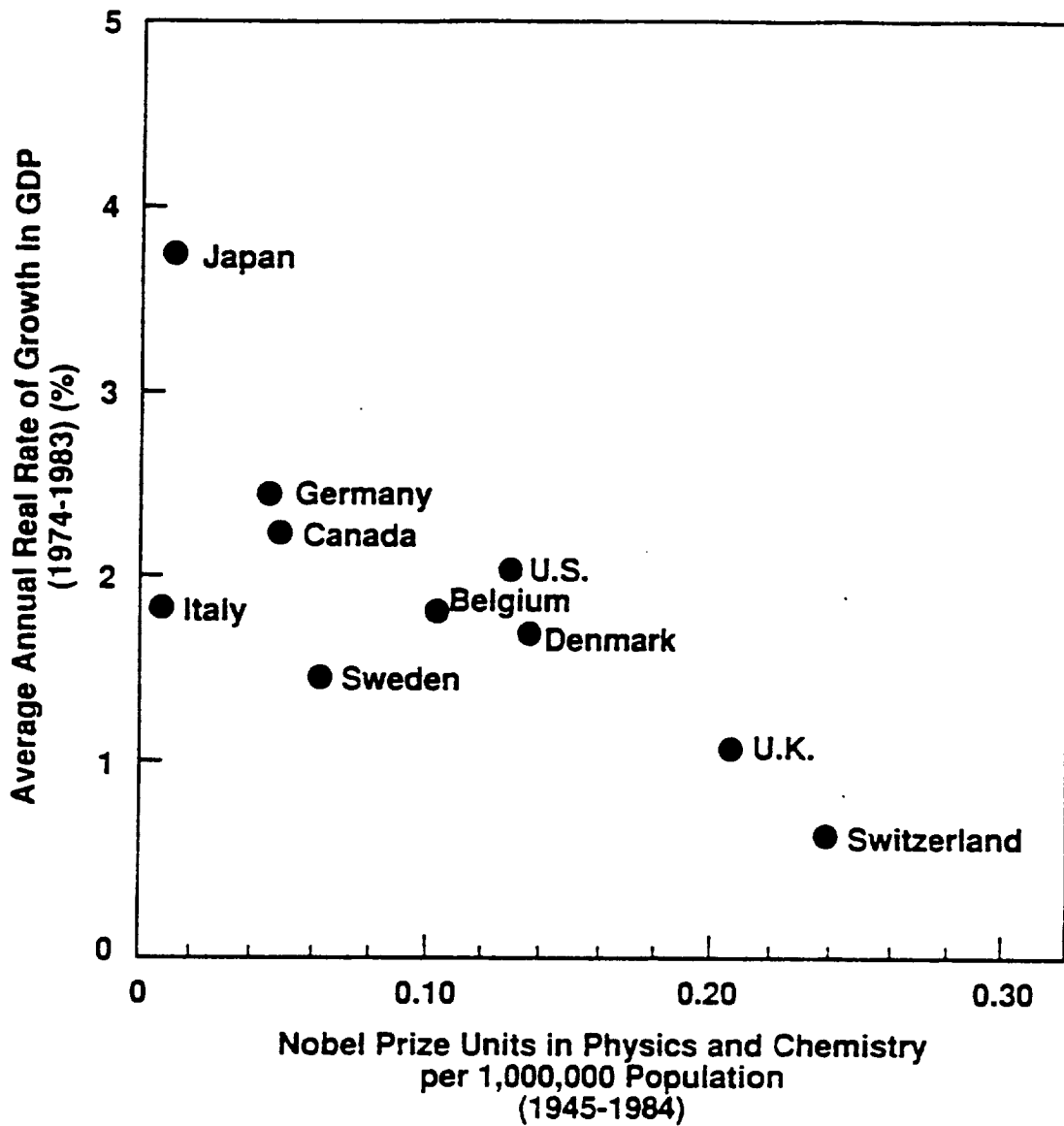
FIGURE 5. Kline cites a Congressional study by Hill in 1986 as striking evidence against the linear model. Hill found inverse correlation between the number of Nobel Prizes and the annual growth of a country's economy.

* C. Hill, Congressional Research Service Study, April 16, 1986.

To go beyond the save-all-the-bits way of thinking, I recommend that NASA include research on machines that can perform automatic discovery, pattern identification, prediction, correlation, and fusion. Such machines would allow us to make more discoveries without having to store all the bits generated by instruments. They could be part of the instrument itself, and could be shut off during intervals when all the bits are needed.

To go beyond the technology-off-the-shelf way of thinking, I recommend that NASA declare that most of its requirements in information management are unique to the agency because of the magnitude of the needed bandwidths and storage and the size of the participating scientific community. I recommend that NASA undertake research programs that will assure the presence of technology needed for the NASA missions.

To go beyond the linear-model-of-innovation way of thinking, I recommend that NASA position itself as a sustainer of the cycles of innovation that will be needed to produce the technologies required for NASA missions in earth sciences during the late 1990s.

Editor's Note:

Peter Denning was the Director of RIACS at the time this paper was written. RIACS is an institute of the Universities Space Research Association at the NASA Ames Research Center. RIACS works to assist Ames in fulfilling its missions by engaging computing researchers from the universities with Ames in parallel computation, learning systems, and networking. Denning has a Ph.D. in electrical engineering from MIT. He served 15 years in computer science departments at Princeton and then at Purdue. He has written extensively and, since coming to Ames in 1983, he has focused on interfaces between research in computing and in other disciplines.

NASA'S INFORMATION TECHNOLOGY ACTIVITIES FOR THE 90'S

Lee Holcomb[1] and Dan Erickson[2]

INTRODUCTION

I would like to discuss briefly NASA's plans in information systems technologies for the 1990's. Let me begin by outlining the approach and philosophy which the Office of Aeronautics, Exploration and Technology (OAET) uses in deciding what technologies to address and how far to take these technologies. I would then like to describe the current and planned research and technology development programs in informations systems and close with some thought on what I feel are the key information technology problems for astrophysical missions in the twenty-first century.

NASA, over the years, has adopted a standard model for technology maturity, rating developing technologies on a readiness scale from one to seven. While the definitions are sometimes difficult to apply, they do give a good starting point for coordinated planning between technology developers and technology users. OAET generally develops technologies through readiness level five which is the demonstration of components or breadboards in the relevant environment.

In recent years, OAET has engaged in a number of processes to try to insure that we are developing the right technologies, and that we are developing them right. Our technology development resources are scarce. We want to develop those technologies which will be most beneficial to NASA missions and support requirements and that our advanced development addresses the key risk issues which would otherwise tend to preclude the technology's use.

CURRENT AND PROPOSED OAET PROGRAM

OAET is just completing an extensive assessment of its nearly five hundred million dollars of proposed space technology development work. The budget is divided into four segments which I will describe later when I talk about the current program. Let me first describe the thrust areas which we have been using to sort our way through this assessment from a user's perspective. The areas are Exploration, Transportation, Space Station, Space Sciences and Basic Research. The thrust area that has received the most attention lately is the exploration thrust. Into this category, we have put most of the technologies which are designed to contribute to fulfilling the President's vision of returning to the moon, this time to stay, and proceeding to Mars in the second decade of the next century. We have separated out space station and transportation technologies. Transportation technologies would include rovers as well as launch vehicle technologies, for example. Space Science which includes technologies for Earth Science, Astrophysics, Space Physics, and Planetary Science is our second largest thrust area. Finally, we have a small number of efforts in high risk, high payoff breakthrough technologies which, if successful, could contribute significantly in many of NASA's application areas.

In addition to the NASA in-house technologies development, we also take advantage of technologies that can be done better by others. We guide independent industry research and

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[1] Lee Holcomb is the Director of the Information Sciences and Human Factors Division of NASA's Office of Aeronautics, Exploration, and Technology and is the author of this paper.

[2] Dan Erickson is Manager of the Information Systems Technologies Subprogram at the Jet Propulsion Laboratory/California Institute of Technology.

development through participation in reviews, exchange of information with colleagues through workshops, symposia and conferences, engaging in active joint planning with other agencies through activities such as the NASA-Air Force Space Technology Interdependency Group, and stimulating private industry by using Small Business Innovative Research grants.

It is not part of OAET's mission to work on technologies which are needed for very near term applications. The major emphasis of our program is on technologies for medium term missions, say three to ten years away.

Enough of the generalities; let us get down to the specifics of the information systems technology programs and plans. I mentioned that the OAET space budget is divided into four segments. One of those segments, in-space technology experiments, has little information systems technology at this time. On the other hand, the High Performance Computing Initiative (HPCI), which is in the aeronautics budget, may have a significant impact on space missions, so I would like to describe that to you along with the space program elements. I will discuss the goals and technology areas of each of four programs. As I do so, I will give some examples of specific efforts in these areas.

THE BASE RESEARCH AND TECHNOLOGY PROGRAM

This program is the foundation of our technology developments. It provides fundamental technologies with broad applicability. It generally is concerned with demonstrating concepts and feasibility. I shall cite a few examples relevant to this Workshop. For example, we are currently conducting work in Information Management, Neural Networks, and Space to Earth communications. One of our tasks, called Distributed Access View Integrated Database or DAVID, is building an intermediate interface to give users a coherent view of data access across multiple remote data bases. Typically, data from science instruments are stored at the principal investigation's home site in a format and with an access method chosen by the instrument team based on their experience and need. Multidisciplinary investigators have been faced with the problem of learning a different access method to obtain data from each instrument of interest. DAVID can alleviate that problem, giving the investigators more time to concentrate on their science.

THE CIVIL SPACE TECHNOLOGY INITIATIVE (CSTI)

This initiative began in 1988 and is focused on technology development for application in medium term missions such as the Eos platforms. In this program, the emphasis is on breadboard and engineering module demonstrations. Developments are proceeding on a Spaceflight Optical Disk Recorder, an Advanced Image Processor, a Configurable High Rate Processing System, Spaceborne Multi-Computers, and Automated Mission Planning and Operations.

The Spaceflight Optical Disk Recorder effort has delivered a prototype Gallium Arsenide 10-element laser array and a prototype 14-inch formatted magneto-optical disc platter. It has developed a system design which will allow terabyte systems composed of several drive units, each with two counter-rotating platters. Unlike tape drives, such systems will be capable of block access and simultaneous read and write.

The Configurable High Rate Processing System (CHRPS) is an architectural approach for connecting processors, mass storage, high data rate instruments and telemetry channels on board a spacecraft. The CHIRPS architecture would allow sharing of storage and processing resources among instruments producing data at up to gigabit rates. Test bed implementations of this architecture will be demonstrated with other data systems technologies such as the Advanced Image Processor and the Spaceflight Optical Disk Recorder.

Automated mission planning and operations have the potential to reduce operations costs, enable more complex missions, reduce planning errors, and allow speedier recovery from anomalies. The Real Time Data System (RTDS) Project has been demonstrating automation in

parallel with the existing Mission Control Center in Houston. Many of the operations concepts demonstrated by the RTDS have been converted to production status.

Automation is also helping science analysis. By applying cluster analysis on Infrared Astronomical Satellite (IRAS) data, the AutoClass system has distinguished two subgroups of stars previously thought to be one.

EXPLORATION TECHNOLOGY PROGRAM (ETP)

This program focuses on the technologies needed for a lunar base, lunar based science and an eventual manned mission to Mars. These missions would benefit greatly from a family of evolvable flight computer systems and from high-rate communications. In 1989, the General Accounting Office recommended to Congress that NASA seek ways to shorten the development cycle for space qualified computers. In response, the Spacecraft Computer Technology Subcommittee of the Space Science and Technology Advisory Committee studied the spacecraft computer development environment. They recommended an ongoing computer development actively making maximum use of industry standards. They also noted that the spacecraft environment and the critical applications of flight computers would be key drivers for any such program. We hope to begin a program in Fiscal Year 1992.

HIGH PERFORMANCE COMPUTING INITIATIVE (HPCI)

This is a new program targeted for a start in Fiscal Year 1992. The HPCI is NASA's portion of the federal High Performance Computing Program. The federal program aims to retain the United States' lead in supercomputing by developing the technologies to effectively use highly parallel computing, scalable to teraflops (flop = a floating point operation) performance. The NASA program is driven by Grand Challenge applications in three areas of interest, Computational Aerosciences, Earth and Space Sciences, and Remote Exploration and Experimentation. By developing testbeds of massively parallel, scalable architectures and demonstrating algorithms and applications which could scale up to full performance, NASA will accelerate the development and application of high performance computing.

The national High Performance Computing Program involves many agencies. The four largest participants are NASA, DOD, NSF, and DOE. The President's Office of Science and Technology Policy has put a high priority on this program for a Fiscal 1992 budget start. An interagency task team, coordinated by the Federal Coordinating Council for Science, Engineering and Technology (FCCSET) is developing a "terms of reference" document for the Office of Management and Budget. NASA has been given the lead role in coordinating the software tools and algorithms efforts among the agencies and developing visualization and data management approaches.

Earth and Space Sciences applications include several of interest to the Astrophysics community. These include stellar dynamics, fluid dynamics, and inversion problems. The first two areas involve models with increased resolution, precision, and scope over those which can be run on today's supercomputers. Inversion problems involve the determination of physical parameters from high volumes of observable data.

Remote Exploration and Experimentation applications include space, lunar and planetary high performance computing for data reduction and automation. These applications also require three orders of magnitude performance increases, but since flight computers start from a lower base, this will bring us to gigaflops performance in space in the same era that we hope to achieve teraflops performance on the ground.

UNIQUE ASTROPHYSICS NEEDS

Now let us look more specifically at the key technology areas for Astrotech 21. Many of the ongoing and planned efforts in our current information systems programs will contribute solutions to anticipated astrophysics technology challenges. The attached chart sorts elements from our on-going development programs into five key technology areas for Astrotech 21. We should

continue to identify and clarify Information System Technology needs for New Century Astronomy. We have the opportunity to bolster and guide on-going programs, and to initiate new efforts which will address key Astrotech 21 challenges.

The Astrophysics program shares with the other Space Science programs a challenging information explosion. By the turn of the century, we will have the capability to take more space-based data bits per day than would be required to store all of the text in the Library of Congress. Furthermore, we will have many scientists accessing multi-instrument data, whereas our old information systems were designed around a single PI per instrument model. We are in danger of having modern instruments which are under utilized because we cannot access, process, and correlate the data.

By the late 1990's, we can develop some pretty impressive capabilities. If we proceed along our current course we will have flight qualified computers which perform at 10-30 megaflops. Laboratory models of flight computers will ingest data at a gigabit per-second and process it at gigaflops speed. Flight qualified onboard optical disk storage will give block access to a terabyte of data. On the ground, teraflop computers with petabyte staging memories will begin to become available commercially. A 45 megabit per second National Research Network will be in place along with a small gigabit per second network being demonstrated. Ka-Band space communications will give us space communication rates of a gigabit per second with experimental optical links operating up to 5 gigabits. Operations will be more complex, but will be assisted by automation on the ground. Onboard automation capability will have been demonstrated.

While these goals may seem ambitious, I am convinced that they are achievable. It will be more difficult to balance priorities and to assure that the new technologies are configured for the greatest benefit to the users than it will be to accomplish the technical goals. That is where workshops such as this one contribute. We all need to project our needs in the future, with as much precision as we can, and to continue to do so as the need date for the new technologies approaches. In this way, we can maximize the benefit from our scarce technology development resources.

ASTROTECH 21
KEY TECHNOLOGY AREAS

CODE RC PROGRAMS	AUTOMATION IN MISSION PLANNING & OPERATIONS	SPACE-BORNE DATA PROCESSING	SPACE-TO-EARTH COMM.	DATA PROCESSING, TRANSPORT, & ARCHIVING	DATA ANALYSIS, INTEGRATION, & VISUALIZATION
BASE R&T		PHOTONICS	OPTICAL COMM. Ka BAND	DAVID INTELLIGENT DATA MANAGEMENT	- CESDIS - AUTONOMOUS EXPLORATION - OPT. PATTERN RECOGNITION
CSTI	ARTIFICAL INTELLIGENCE —SHARP —RTDS	HIGH RATE/ CAPACITY DATA SYSTEMS —MAX —CHRPS —VMS —SODR			
EXPLORATION		—ADV FLIGHT COMP & ARCH —NEURAL PROCESSING —STORAGE DEV	OPTICAL COMM. AND Ka BAND FOR DEEP SPACE		
HPCI		REMOTE EXPLORATION AND EXPERIMENT-ATION		EARTH & SPACE SCIENCE COMPUTING NREN	COMPUTATIONAL AEROSCIENCES

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WHITE PAPER
on
SCIENCE OPERATIONS

incorporating inputs from the

Science Operations MOWG

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SCIENCE OPERATIONS WHITE PAPER

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1. INTRODUCTION

Major changes are taking place in the way astronomy gets done. There are continuing advances in observational capabilities across the frequency spectrum, involving both ground-based and space-based facilities. There is also very rapid evolution of relevant computing and data management technologies. However, although the new technologies are filtering in to the astronomy community, and astronomers are looking at their computing needs in new ways, there is little coordination or coherent policy. Furthermore, although there is great awareness of the evolving technologies in the arena of operations, much of the existing operations infrastructure is ill-suited to take advantage of them. Astronomy, especially space astronomy, has often been at the cutting edge of computer use in data reduction and image analysis, but has been somewhat removed from advanced applications in operations, which have tended to be implemented by industry rather than by the end user scientists.

It is likely that technology developments will continue to take place far more rapidly than most individual astronomers and new facilities will be able to take advantage of them, and increased attention to this problem is necessary. The challenge will be to provide new methodologies and infrastructures commensurate with the new technologies. It is likely that the impact which technological developments will have on astronomy over the next decade will be dominated by management and policy issues, and not by the technology itself. Furthermore, current procurement policies within the government introduce considerable time lags between the introduction of new technologies and their availability to the astronomy community. These policies, which were more appropriate to the era of infrequent main-frame procurements, are not suitable for the rapidly evolving world of personal workstations and mini-supercomputers. They must be reviewed and modified.

The purpose of this paper is threefold. First, we briefly review the background and general status of astronomy-related computing in Section 2. Second, we make recommendations in 3 areas: we summarize recommendations in the areas of data analysis in Section 3; operations in Section 4 (directed primarily to NASA-related activities); and issues of management and policy in Section 5, believing that these must be addressed to enable technological progress and to proceed through the next decade. Finally, we recommend specific NASA-related work as part of the Astrotech-21 plans, to enable better science operations in the operations of the Great Observatories and in the lunar outpost era.

2. BACKGROUND

Traditionally, astronomers (with exceptions) tended to be somewhat behind the other physical science disciplines in utilizing state-of-the-art computing technology. This situation has changed greatly over the last two decades, due largely to the fact that the type of astronomical problems being studied began demanding observations and analysis of data at many wavelengths, decreasing the separation between different sub-disciplines of astronomy. Thus, radio and x-ray astronomers, originally coming into the field with physics backgrounds and more familiar with computing technology, have become better integrated into "main-stream" astronomy. Optical astronomers have started using x-ray and radio facilities as well as data from the "near-optical" space facilities such as IUE and IRAS. Optical astronomy itself has had to face the task of processing high-volume digital data from CCDs and preparing in a major way for space astronomy with HST. The paucity of new space astronomy missions has made utilization of archival data more desirable. Theoretical modelers have gained access to supercomputers which allowed them to generate meaningful simulations and compare them with observational data in the various wavelength bands.

The process of cross-fertilization between the different astronomy disciplines has been accelerated by the computer networks which very recently began to make serious inroads into the astronomy community, even if underfunded and often uncoordinated by the primary astronomy funding agencies and centers. Astronomers thus became exposed, often reluctantly and inefficiently, to a variety of computing environments and they have been forced to think about more powerful and cost-effective types of computing hardware, data storage, networking, and even improved software development methodologies. It is thus not surprising that a growing number of astronomers started looking at computing and data management problems in a broader way, recognizing the existence of common problems, the possibility of common solutions, and above all, the need for better coordination and more funding.

The developing new outlook on data systems and computation in the astronomy community over the last decade has been manifested in several ways. First, individual astronomers and groups with enough support began to experiment with the newly introduced hardware, including workstations, PCs, mini-supercomputers, and supercomputers. They discovered ways to connect with existing networks. They started studying the use of optical disks for archiving large amounts of data. Sharing of software became more common, as the larger groups began to move away from "one-of-a-kind" solutions to computation problems, and by the early 1980s, the second-generation user-oriented data analysis systems (e.g. AIPS, IRAF, MIDAS) were conceptualized and/or under development. However, these were more-or-less grass-roots efforts carried out at the major user facilities, and there was only minimal funding and little effort toward cross-disciplinary coordination.

In recognition of the lack of adequate attention to the situation, the Committee On Data Management and Computation (CODMAC) was established in the late 1970s under the auspices of the Space Science Board. In several reports CODMAC assessed the magnitude of the computing and data problems facing the space science community, and made numerous observations and recommendations concerning the advantages of portable software, remotely accessible archives and wide-area networking, pointing the way toward distributed data analysis systems. But foremost among the findings were the conclusions that the problems standing in the way of qualitative improvements were mostly with management, not computing technology, and that user involvement in all stages of data system development was key to the achievement of usable capabilities. Although CODMAC findings were often given lip-service, for several years there was little true management attention to these latter problems.

A major positive step was taken by NASA in 1987 when the Astrophysics Division convened an Astrophysics Data System Study. This study, chaired by Gayle Squibb, and incorporating wide community participation, issued a report containing numerous recommendations for both specific activities and general guidelines to be followed, similar to those of CODMAC. Also included was a suggested architecture for an overall astronomy data system. The Astrophysics Division has started implementing several of the recommendations, via a dedicated Science Operations Branch, and with community interaction via a Science Operations Management Operations Working Group (SOMOWG). Key among the actions have been the establishment of an Astrophysics Data System pilot project and a peer-reviewed Software and Research Aids Program to support community efforts in astrophysics-related computing technologies. Increased attention has also been given to network links between different astronomy sites.

On the NSF side, there has been little new activity in astronomy-specific computing. Although some of the most substantial work toward community-wide data analysis systems was started at NSF-funded national centers (the FITS data interchange standard and the AIPS development at NRAO, and the IRAF development at NOAO), the redirection of NSF funding away from astronomy has limited these efforts, and, in fact, NASA is now helping to subsidize IRAF maintenance and development, and the FITS data standards. On the other hand, NSF's supercomputer centers and the related networking efforts have been very beneficial to astronomers. In fact, between the new NSF links, the existing ARPAnet, and NASA's SPAN and TCP/IP connections, there has been a dynamic qualitative improvement in connectivity in the astronomy community over the last few years.

Many individual astronomers and groups not only have taken advantage of the new capabilities but have recognized the advantages of moving toward general shared facilities. When the STScI was deliberating on a data analysis system for HST, it decided to build its data analysis software within the IRAF environment developed at NOAO, recognizing the advantages to the astronomer of not having to learn an unending stream of new data analysis systems. Similarly, when the ROSAT project also decided to use IRAF, it extended this philosophy to what had previously been an entirely separate sub-discipline of astronomy. The relevant groups have chosen to coordinate further developments with NASA's endorsement. In a related development, when HST needed to develop an optical disk archive capability, a facilty was designed which could be used by multiple institutions, and was, in fact, developed by the STScI with substantial support by the ST-ECF at ESO and the Dominion Astrophysical Observatory in Victoria.

Despite the improvements over the last decade, much work remains to be done. The continuously evolving new technology must continue to be exploited, not only in small projects and in science computing, but more difficultly, in major facilities and in operations systems. It has become clear that large programs have a qualitatively harder job adopting new technologies and the new methodologies needed to exploit them, due most probably to the increased separation between the users and developers of systems as well as the usual management problems of large projects. This is particularly true in operations, which are handled on a mission by mission basis, and where for the most part there has been little grass roots effort to apply the lessons being learned in the data processing and analysis area. It is equally clear that improvement is still needed in the same areas identified by CODMAC a decade ago, including primarily user involvement in all stages of the development of data systems.

3. RECOMMENDATIONS IN DATA ANALYSIS AND COMPUTING

3.1 Data Access

- There should be easy remote access to digital data located at distributed data centers. Centers should provide documentation and expertise in the use of the data, software, and databases via active researchers at these centers.

- There should be access to processed data and software tools from not only the great observatories, but also from other space-based missions and ground-based surveys. This will involve new policies for ground-based observatories.

- There should be recognition of the need for data analysis to take place at astronomers' home institutions, with electronic or physical distribution of data as appropriate, and direct receipt of data from active missions a possibility

- There should be support for maintenance of catalogs and databases, and the necessary software and expertise.

- Proprietary rights policies and related international agreements should be reviewed, with the goal of making data more rapidly and widely available to a broader community including amateurs, educators, etc.

- There is great benefit to be derived from adequate descriptive material as well as the data itself. This material should include definitions, descriptions of processing, etc. which often get lost in the archiving process but which are essential to the proper scientific use of the data; this is an essential element of the ADS concept.

- Users should be protected from being forced to learn a multitude of user interfaces. We should promote a philosophy which includes minimizing the number of independent analysis systems and encouraging software portability, on-line help, standard command structures, etc.

3.2 Software Support

- There should be ongoing software maintenance support.

- Calibration software should be portable and included in the analysis systems.

- There should be support of advanced software developments and expert systems for data analysis. These should emphasize utility to a broad multi-disciplinary community and include cross-mission capabilities.

3.3 Workstation Support and Access

- The broad need for workstations as part of a distributed computing environment should be acknowledged

- The obsolescence factor should be recognized. Project plans should include replacement of equipment in a finite amount of time

3.4 Supercomputing Support and Access

- There is need for access/coordination between NASA users and NSF centers.

- There should be support for the development of supercomputer algorithms and other advanced computing strategies in image processing and data analysis

- Mini-supercomputers should be made available at major user facilities.

3.5 Network Support, Access and Coordination

- NASA should take a more active role in Internet coordination across agencies.

- NASA should take a more active role in connecting data centers to the Internet and to the ADS activity.

- There should be better connection/coordination of the science networks with operations activities in NASA.

3.6 Electronic Publishing -- Data, Abstracts

- There should be a means for making "published" data computer accessible.

- Abstracts should be made available on-line.

- Electronic proposal submission and perhaps review via e-mail should be encouraged.

4. RECOMMENDATIONS IN OPERATIONS

- NASA should support the development of portable, distributed, user-friendly, transparent observation planning tools. These should be consistent with the telescience concepts of remote mission planning and operations.

- There should be adequate bandwidth and minimal communications restrictions for remote observations and data communications, be it on the ground, in orbit, or from a lunar base. The concept of "INTERNET to the moon" should be encouraged.

- NASA must modernize its mission operations and communications infrastructure, including distributed operations concepts and direct reception of data.

- There should be more attention to Operations within the Science Operations Branch.

- There must be better coordination of operations development with instrument and spacecraft h/w development. There should be direct, frequent interaction between end-users, designers, developers and managers in the implementation of new operations capabilities.

- There should be user involvement in the development of a second generation TDRSS or its equivalent for non-low earth orbit missions.

- The potential for direct operation of small missions or experiments should be studied. This would allow more efficient interaction between the user and the facility, and could reduce costs.

5. MANAGEMENT AND POLICY

Management and policy problems far outweigh technical issues.

- NASA Operations Infrastructure should be made compatible with a distributed service-oriented operations concept.

- There should be increased emphasis on small, rapid-turnaround inexpensive missions. Benefits include lower launch costs and more continuity in research programs.

- Science goals can be better met by taking a bottom-line approach to what is truly needed, and not artificially linking the science missions to other NASA goals.

  e.g. tying astrophysics to the manned program, with its safety and communications overheads, is regarded as very deleterious to science.

  e.g. TDRSS support to science is inadequate, given the low priority relative to manned and DOD missions.

- The end-user must be involved in all phases of project development, and there should be more accountability within NASA in developing science missions.

- The procurement procedures used in large NASA missions is often incompatible with attaining the desired science goals:

  - existing talent in the astronomy and advanced technology communities should be utilized and not neglected.

  - the extended procurement cycle for many systems (e.g. computers) which almost assures obsolescence on delivery must be changed.

  - development contractors are not responsible for long-term operability and maintainability and do not adequately plan for these parts of the life cycle.

  - software development methodolgy must change to better involve end-users in all stages. Rapid prototyping must replace conventional adversarial development schemes.

- Multiwavelength capabilities should be encouraged in NASA programs, both in instrument complement (e.g. via addition of monitors) and in operations concepts.

- NASA should become more involved in astronomy education, and should encourage active involvement of amateur astronomers in NASA astronomy programs. Libraries should be modernized.

6. PLAN FOR SPECIFIC NASA-RELATED ACTIVITIES

6.1 General

NASA has recently formulated the Astrotech 21 Program, with the general goal of developing the technology base for a "new century astronomy program", including astrophysics missions of the 21st Century, and with a specific goal of preparing for lunar-based astronomy. In the sections below, we discuss specific activities which NASA should carry out in the context of Astrotech 21. However, these

same technologies would also be relevant for non-lunar sitings, where remote and/or unattended operations and communications constraints exist. The requirements of a lunar outpost for these science operations capabilities will be stronger, but not unique. This should be regarded as an advantage, since the capabilities can thus be usefully prototyped in advance, in realistic but perhaps less extreme applications. For astrophysics operations, there will be unique opportunities to maximize the utility of the proposed prototyping by making use of existing and planned astrophysics missions as testbeds for lunar outpost concepts. This is consistent with the need to set up the data and science operations infrastructure for supporting lunar-based telescopes *before* sending telescopes to the moon. The infrastructure to be developed must include capabilities for automated mission planning and scheduling, autonomous monitoring of both science and engineering data, including dynamic command management and autonomous response (both protective and for unique scientific actions), and intelligent data compression and distribution mechanisms.

There have been very strong recommendations that the operations capabilities be developed with continuing and direct user involvement, since many of the capabilities will be specific to astrophysics applications. It will thus be clearly advantageous to carry out prototyping within OSSA in applications which are closely related to candidate lunar outpost missions. In particular, many of the concepts could be tried out in the context of the currently planned Great Observatories.

6.2 Data Analysis Support

The traditional data analysis and data processing model for NASA space missions has been a series of "levels" of processing that gradually homogenize the data and remove artifacts of the source of the data. In a rough sense, the "Level 0" process cleans up the data with regard to data drop-outs, formatting, compression, and timing related to the transmission from the satellite to the ground. "Level 1" processing encompasses the reorganization of data, application of calibrations, and routine algorithms such as attitude corrections to place the data in "scientifically useful" form. These functions, Level 0 and Level 1, are usually done at the data capture facility and/or within mission data centers. The "Level 2" processing is the scientific data analysis which is done by the scientist, often with the assistance of the mission which provides the algorithms, software, facilities for this activity.

The lines that distinguish these levels of data processing and analysis are becoming blurred at present, particularly between "Level 1" and "Level 2". On the one hand, increases in the computer power available to individual scientists and institutions have reduced the need for centralized processing of data. On the other hand, the mix of users and the levels of sophistication an/or familiarity with the data requires that services such as standard processing of data continue to be available. The trend, then, must be to allow a broader spectrum of user services. This will require missions to provide not only standard processed data, but also data processing and analysis tools in portable and interoperable forms and unprocessed data to those who desire the less digested form of the data.

The need to develop interface specifications to allow such portability and interoperability must become a high priority of the scientific community so that current and future missions will be able to function in a highly integrated environment. This is true for data, catalogs, databases, and for software. The framework for supporting the prototyping of advanced software and astronomy information handling techniques already exists within the Astrophysics Division's Software and Research Aids Program and in the Astrophysics Data System. These programs should be encouraged and augmented.

6.3 Operations Concept Studies

Studies of operating modes and requirements, including scheduling, command generation, coordination with discipline facilities, etc. are needed. These will include the study of existing technologies for applicability to generic astrophysics-related requirements, and participation in the candidate mission studies. It is important to have visibility into the missions which are being considered, to make sure that operations-oriented considerations are included, and to feed requirements back into the operations prototyping activities discussed below. Thus, the specific missions being planned in the post-Great-Observatories era, and especially for the proposed lunar outpost, should be reviewed and studied to better define the required operations capabilities.

6.4 Operations Technology Prototyping

6.4.1 Data Compression (both noiseless, with 100% retrievability and no compromise in accuracy, and with dynamically determined accuracy).

Data compression is the process of encoding ("compressing") a body of data into a smaller body of data. It must be possible for the compressed data to be decoded back to the original data or some acceptable approximation of the original data. Data compression is a tool that data system designers can use in overcoming communications bandwidth and storage limitations which would otherwise make it impossible or difficult to satisfy science users needs. The use of this tool must be traded off against added computational loads for decompression, increased data link Bit Error Rate performance, and the potential of losing some scientific information.

In the case of future astronomy missions, data compression might be used within the flight segment (orbiting or lunar-based) to acquire more data than the data buffers or space-ground link would be able to accomodate, either temporally averaged or for high rate data bursts. Large volumes of image data on the ground must be stored, archived and browsed. Data compression can be a tool in reducing media costs, and can in some cases enable electronic transfer of science data for primary distribution or for interactive browsing.

Remote operations of instruments, such as may be required for a lunar observatory, will likely involve visual aids. These visual aids will present imagery to "tele-operators," providing feedback on the status and configuration of equipment as well as the general health and state of the observational data and communications links. Such purposes often do not require high fidelity reproduction at the receiving end -- only that the image "look" like the original.

Data compression techniques can be described as being either lossless, in which case the original data can be fully recovered, or lossy, in which case data (although perhaps no information) are lost. Lossless compression techniques will typically produce compression ratios of 2:1 or 3:1. In most cases, lossless techniques will be used for the transmission or storage of the science data. Lossy techniques can produce compression ratios as high as 1:100, and with significant processing overhead can even go as high as 1:1000. These techniques are more appropriately applied to transmission of browse products and to visual feedback aids for remote operations. However, even for the actual science data, it is possible that astronomers will be faced with a trade-off between the use of a lossy data compression scheme and no data at all. In that case, the lossy scheme is obviously the choice, provided that it is information-preserving with respect to the scientific purpose.

Significant progress has been made in the past several decades in the development of data compression algorithms and implementation of those algorithms in high speed hardware. In fact many internationally recognized standards now exist for the compression of video and text data. However, continued efforts are necessary in order to meet the particular requirements of the space science community. A NASA Workshop on Scientific Data Compression, held in 1988, recommended that it was of foremost importance to develop metrics of information quality and content for lossy compression schemes that would allow scientists to make intelligent choices regarding data compression vs. data loss. The same workshop also recommended that NASA continue the development of high-performance, high throughput flight-qualified data compression hardware that can be used on future missions. This latter recommendation was reiterated by the CODMAC in their 1988 report on Selected Issues in Space Science Data Mangement and Computation in endorsing data compression as an important component in an overall strategy addressing the management of high data rates and data volumes.

It is important to make astronomers familiar with the advantages and disadvantages of data compression, since they have not historically had to use it. Data compression techniques should be encouraged in NASA astrophysiscs flight projects, and prototypingof astronomy-specific techniques should be supported via the Software and Research Aids Program. Compression techniques should be considered for data within instruments, in temporary and permanent archives, and in transmission. The assumption is that astronomical instruments generate very high volumes of image data, and data transmissions from a Lunar outpost will most likely be extremely limited and/or schedule constrained. Thus there need to be

capabilities of decreasing the volume of data both within the instrument, when possible, and in data storage and forward.

The option of staged transmission should be considered, whereby low-volume "quick look" data is transmitted routinely, intermediate-volume data is transmitted periodically, and high-volume data is transmitted occasionally or on request.

The ramifications of archiving compressed data (either loss-less or with variable information content) on the query and retrieval process should also be addressed.

6.4.2 Automated Planning and Scheduling Tools

There is a need for proposal preparation aids and proposal management systems for missions. These must guide the users through the proposal process, provide information on expected performance and allow calculation of required input parameters for an observation. It would be desirable to see such generation aids integrated over missions so that there are common interface and basic functions. Similarly the management of the proposals, tracking their evaluation, notifying the proposers, and coordinating proposals could be broadly based. It should be possible to examine the observational program of several facilities to see what is being planned and to review what has already been done.

There are existing examples of "expert" planning and scheduling tools, including SPIKE, which was developed at STScI for long term HST planning and is being studied for EUVE and other missions; KDS, which is being studied for the ISO mission, and possibly the ROSAT system. Support should be given for studying these and other approaches and ascertaining how generalized they could become.

A Lunar Observatory will likely operate unattended for extended periods. Flexible, autonomous control systems are needed to ensure efficient utilization of scientific instruments and Observatory resources during these long periods. A central component of an autonomous control system is a planning and scheduling system for managing Observatory resources. The planning and scheduling of Lunar Observatory instrument and system resources is complicated by a number of factors which require automated systems for solution. These factors include complex and dynamically changing operational constraints due to scientific tasking, system health and status, and configuration of support resources. Each of these is discussed in turn in the following paragraphs.

Scientific tasking introduces several types of constraints on the planning and scheduling of Lunar Observatory resources. The first is oversubscription of system resources. Historically, requests for resources for science observations on space platforms have far oversubscribed system capacity. The process of scheduling space science activities in the past has primarily been done by hand and involved work-decades of effort even for relatively short observation periods such as planetary encounters. It is likely that high demand for space science resources from the science community will continue and be a severe constraint on the planning and scheduling of those systems. New automated tools are required which can assist Earth or Lunar-based scientists in managing initial resource allocation where requests vastly oversubscribe system capacity. Some computer-based tools have been developed to meet this type of need on other space projects. However, those tools are either obsolete, or tailored to specific missions or hardware. Existing tools (cf. the ST ScI SPIKE system for long-range planning) should be examined for possible generalization or adaptation. Autonomous scheduling systems are also required for managing those scarce resources at the Lunar Observatory to avoid overloading capacity when the system is forced to respond autonomously to dynamic situations, as described in the paragraphs below.

The second type of constraint introduced by scientific tasking is the need for a Lunar Observatory to respond quickly, efficiently, and autonomously to transient or emerging science opportunities and events. Once such an opportunity or event is detected and the desire to respond to it established, Lunar Observatory systems must be reconfigured dynamically, being careful to avoid oversubscription of system resources. Autonomous replanning which impacts the availability or configuration of resources must be accomplished with minimal disruption to existing schedules to avoid compromise of previously planned science activities. This calls for automated scheduling systems with a host of rescheduling strategies which can be chosen according to the response time available and other dynamic constraints of the situation at hand.

An autonomous planning and scheduling system is also required in order to respond quickly and efficiently to diminished capability due to failure or degradation of Lunar Observatory resources. An automated replanning system must reconfigure and reallocate Observatory resources in an attempt to recover and resume any activities which are disrupted by transient or permanent failures. An automated replanning system should also minimize the impact of reduced capability on future scheduled science activities.

Finally, the interaction of an unattended Lunar Observatory with external systems and support resources must be managed. This will require the planning and scheduling of data storage and data transmission facilities at the Observatory itself and throughout the data system on the Moon, on communications spacecraft, and on the Earth. Autonomous or semi-autonomous scheduling systems must be able to coordinate their actions to make efficient use of all resources.

6.4.3 Intelligent Tools to Assist in Data Analysis

Related to the need for autonomous operation and data compression is the desirability of developing intelligent systems to support the detection and analysis of interesting features in images, spectra, and temporal phenomena. One of the greatest challenges for automation in support of an unattended Lunar Observatory is the ability to recognize interesting and possibly transient science opportunities, and to respond to them through changes in observing strategy, configuration of Observatory resources, and coordination with other observatories. An additional challenge to Lunar science operations is to maximize the productivity of both resident Lunar Observatory scientists and scientists remotely operating or receiving data from the Observatory.

These challenges entail the ability to rapidly analyze the large volumes of scientific data which will be received from Observatory instruments. Currently, only a fraction of the data returned from space science missions is processed and analyzed in real or even near-real time (within days of acquisition). There are archives of science data from previous missions which have never been analyzed. Since the time of resident scientists will be a scarce resource and since the detection and analysis of interesting data may redirect observations or subsequent analyses, it is desirable that an automated science analysis system, as part of science operations, direct the scientists attention and effort towards "interesting" data and facilitate its interpretation.

In support of these requirements, an intelligent science analysis computing environment should be developed and should be tightly integrated with other Lunar science operations systems. Such an environment would include a variety of intelligent systems, data manipulation, and graphical visualization capabilities which serve as an "automated research assistant." They would facilitate rapid analysis of interesting science data, in the areas of preliminary review of data, suggested analysis methods, and cross-referenced information. The intelligent systems would incorporate both low-level pattern recognition algorithms for detection of interesting features in images, spectra, and temporal phenomena, and higher-level strategies and heuristics for performing preliminary analyses on interesting data. These systems must include abstraction and filtering capabilities to enable rapid evaluation of unusual data.

The results of automated detection and analysis of interesting data should be forwarded as "alerts" to an autonomous scheduling system in the Lunar Observatory for planning additional observations as well as to other scientific facilities or observatories for further evaluation and response.

These requirements can be addressed by recent developments in the fields of artificial intelligence, graphics, and data management. Some work has also been done in the astronomy community, in the areas of automated classification schemes and rule-based calibration procedures. To date, these technologies have not been integrated or widely applied to space science problems, and this must be a major focus of prototyping efforts. These considerations should not be taken as substituting for an individual researchers freedom to analyze data in unique and independent ways.

6.4.4 Instrument and Experiment Self-Monitoring Tools

Self-monitoring and diagnosis capabilities are absolutely necessary to ensure the continuous, reliable, safe, and productive function of an unattended Lunar Observatory. Automated self-monitoring systems for instruments and experiments should be developed which provide the primary functions of detection and characterization of faults, initiation of safeing actions, and communication of system health and status information to resident operations personnel and/or to external controllers in space or on the Earth.

An automated monitoring system is required in order to detect and respond to long and short-term trends in operational characteristics or parameters. The system should provide capabilities for automated troubleshooting throughout the end-to-end instrument, experiment, and support facility systems. An autonomous monitoring system must include accurate limit-checking, particularly when the limits are dynamic due to changing system configurations and loading. This capability in turn requires access to instrument simulations and specialized diagnostic analyses tailored to specific Lunar systems.

Information from autonomous monitoring systems should also be routed to automated scheduling systems at the Lunar Observatory to initiate replanning around lost or reduced capability in an instrument or subsystem when a backup system is not available. This illustrates also the overall requirement to systematically integrate a variety of intelligent systems in an encompassing automated Lunar Observatory operations control system.

Intelligent systems for telemetry monitoring and health analysis of multiple spacecraft subsystems have already been proven in space operations environments and are rapidly moving into mission operations as flight critical software in both the manned and unmanned planetary exploration programs. In most cases, these systems are very specialized for the particular monitoring applications. These systems should be generalized and extended to accommodate the requirements of automated monitoring of scientific instruments and experiments in the context of a Lunar Observatory operations control system.

6.4.5 Integrated Lunar Observatory Control System Testbed

The autonomous operation of a Lunar Observatory over long, unattended periods will require a variety of intelligent systems which must interact and coordinate their activities. To summarize: An automated planning and scheduling system is required which will manage Observatory resources and respond to dynamic, changing constraints issuing from the other automated systems as well as from external systems including humans. An automated data analysis system is required which will detect sudden, transient events of scientific interest and direct the automated planning and scheduling system with new tasking based on these scientific opportunities. An automated experiment and instrument self-monitoring system is required which will ensure the reliability of space operations systems by monitoring system health and status, and which will instruct the automated planning and scheduling system to reconfigure Observatory systems to avoid or recover from faults or degradation of capability.

A testbed is required for the purpose of integrating these and other required science operations systems for the Lunar Observatory. There is very little system design and engineering experience anywhere with control systems that include these types of automated systems. The development of an operations testbed will permit investigation of alternative autonomous operations systems designs, and will ensure autonomous subsystem interoperability and compatibility.

6.4.6 Standardized Instrument Command Structures

The existence of long-lived observatories on the moon will require a higher level of standardized instrument command structures than has been necessary in the past. A standard structure which is applicable to astrophysics instruments, and compatible with astronomical observatory operations will be necessary. This will require the development of systematic architectural models for the components of astrophysics information systems. Protocols must be defined for component interaction that reflects astrophysics domain-specific needs. The entire cycle, including mission planning, instrument control, instrument monitoring, and data analysis must be considered. The projection of these systems onto the computing domain, including the facets of communications, execution control, numerical processing, data management, and user interfaces must be taken into account in the development of these models and

protocols. It is essential that a framework be established in which standard and custom components can be mixed and matched to produce distributed, heterogeneous, evolvable systems.

REPORTS OF SCIENCE AND TECHNOLOGY PANELS

PANEL 1

MISSION PLANNING AND OPERATIONS

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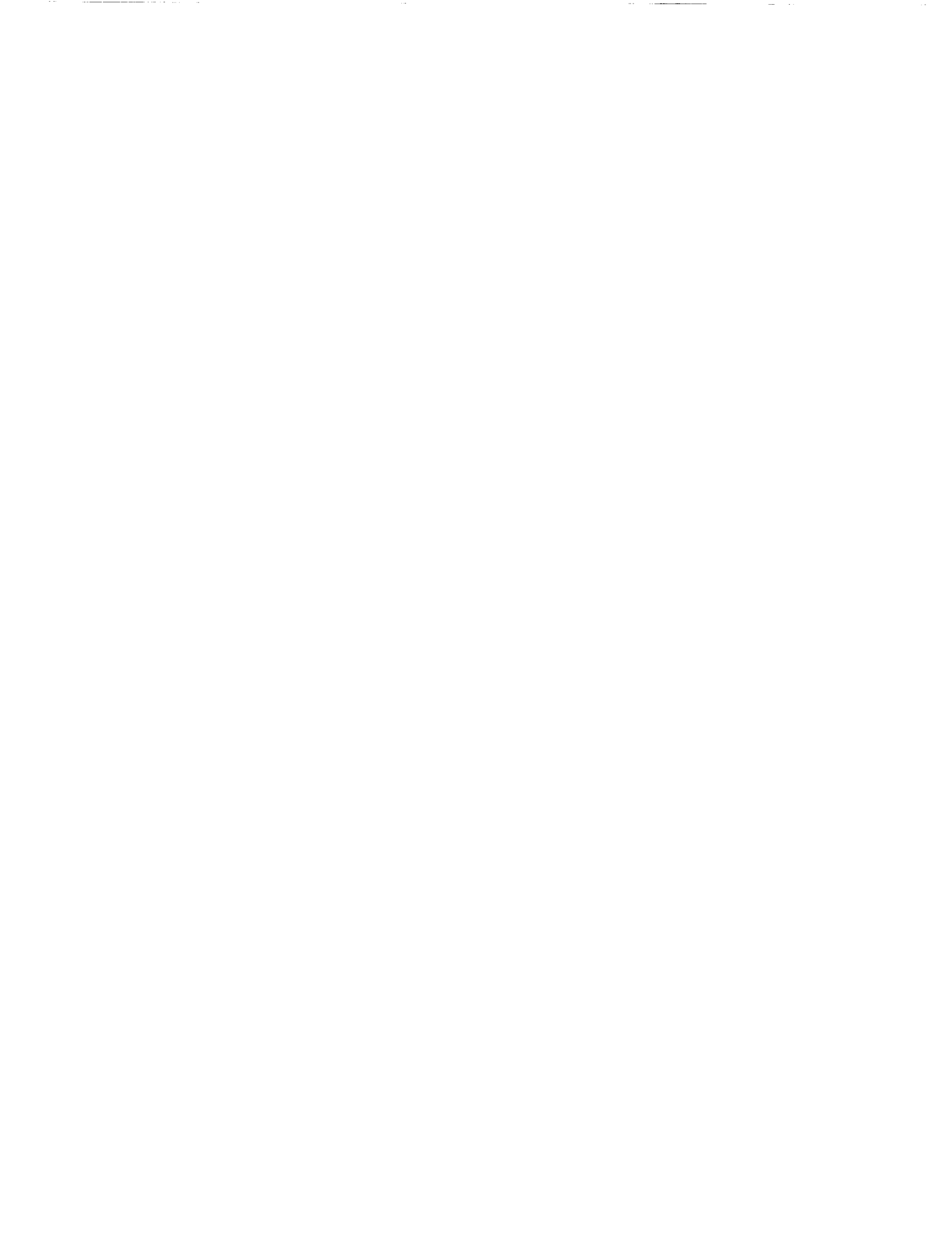Mark Johnston; Space Telescope Science Institute; Baltimore, MD

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PANEL 1 REPORT: MISSION PLANNING AND OPERATIONS

A.   INTRODUCTION

This Panel was charged to examine the future technology needs in mission planning and science operations. The topics provided to the Panel include: multimission observation coordination, real-time monitoring and control, multi-sensor operations, multi-platform operations, scheduling and planning tools, real-time first order data reduction and analysis, and automated instrument coordination and control. It should be noted here that this theme is also considered in the papers by G. Riegler and E. Schreier (in these Proceedings).

B.   MISSION REQUIREMENTS

The issues relating to mission operations and planning are often more related to the site than to the objective of the specific mission. The kinds of sites that were considered to have a bearing on long-term projections for the future of mission operations are: ground-based observatories; suborbital flights; low earth orbit (LEO), which can involve instruments attached to the shuttle or space station or to free flying spacecraft; high earth orbit (HEO); geosynchronous; lunar-based observatories; and deep space missions. All of these sites can be used for astrophysical observations and all are subject to particular problems regarding mission operations that must be addressed in the coming decades.

Current ground-space bandwidth and latency restrict the potential scientific returns at many types of sites, most especially lunar-based observatories and observing from deep space probes. Some considerations of this panel are closely linked to future advances in communications bandwidth but some of the pressure may be relieved somewhat by increasing the autonomy of remote observatories. Thus developments in areas studied by the other panels at this workshop affect the range of potential scientific studies because of the indirect impact on mission operations.

Finally, it should be pointed out that the recommendations given below share many needs and interact with each other, indicating that an integrated approach must be taken to solving the problems that come up in future missions.

C.   INFRASTRUCTURE AND TECHNOLOGY ASSESSMENT

This Panel is specifically mindful of some technology studies and planning already carried out within NASA, not necessarily in the context of astrophysics. One such study, by Hansen, Ludwig, Davis and Jouchoux, under the auspices of the Information Systems Strategic Planning Project (ISSPP), contributed to a portion of the ISSPP Report Section II.2, that specifically addresses missions operations.

The Report refers to some general trends of the research infrastructure that are relevant to the themes in this Panel:

*   Higher data rates will result from the increased number and capabilities of instruments on future free-flying spacecrafts.

* These higher data rates combined with longer mission lifetimes will result in greater data volumes to be processed.

* There is a general trend towards aggregation of data processing and archiving to the discipline level, as opposed to the previous mode of operations by individual projects.

* There will be a general distribution of nonroutine and interactive data processing and user databases to investigator sites.

* The management of science operations will provide for a cooperation of centralized management of resources with a hierarchical distribution of experiment/instrument planning, scheduling and operations.

* There will be increased reliance on distributed supercomputing.

* Security issues are increasing in importance as information systems users become more distributed, and as the number of international collaborators expands.

This same Report also cited some technology trends that are relevant to this Panel's discussions, viz.,

* increasing availability in computing resources;

* increasing cost-effectiveness in computing resources;

* expanding roles of telecommunications;

* new generation of space-qualified processor technology;

* technological advances in high-performance subsystems based on VLSI-components;

* advances in artificial intelligence, including expert systems and neural networks.

D. RECOMMENDATIONS

1. NEAR-TERM TECHNICAL IMPROVEMENTS

NASA should implement a number of near-term technical improvements that have been under study for some time and have been recommended in other workshops, such as the Information Systems Strategic Planning Project (ISSPP), sponsored by the NASA Office of Space Science and Applications.

In particular, in the ISSPP Report, section II.2 addresses issues related to this theme. Another document with recommendations generally endorsed by this panel was the white paper on science operations by Ethan Schreier, in these Proceedings. Examples from Schreier's paper that were embraced were suggestions to

* foster development of distributable planning tools,

* improve link bandwidth and instrument access,

* allow for distributed operations and data dissemination,

* develop improvements to TDRSS, and

* allow for direct communication to small experiments.

A related issue is the connection to existing technology development in other disciplines with astrophysics applications. There were several examples of projects funded by NASA that were generally unfamiliar, but potentially useful, to astrophysics missions: e.g. the Spacecraft Health Automation Research Prototype (SHARP), the Real Time Data System (RTDS), and the Space Station Operations Mission Planner (STOMP).

2. AN AUTOMATED, PORTABLE, MULTI-SITE SCHEDULING SYSTEM

NASA should support the devlopment of an advanced automated scheduling system for multi-site applications.

The motivations are clear. First, there is a common need for scheduling in most missions due to the precious nature of the hardware involved, usually limited lifetimes, and the large user community that places considerable demand on NASA facilities. Constraints, tasks and heuristics may vary, but the basic problem is the same. Second, there is an increased demand for coordinated observations between Great Observatories and other missions that must be handled by linking scheduling/systems. Certain scientific investigations can only be satisfied with simultaneous data collection by different instruments. Ground-based observatories could participate in coordinated observations. Third, such a system would allow coordination with planetary missions.

2(a). Required Features

To permit effective use of scheduling knowledge from mission to mission, a common framework should be defined that can be used for more than one mission. This system should not be tied to any specific hardware for maximum usability among the different computer systems used on different NASA missions. It should be extensible so that custom features of specific missions should be easily added. Developing such a system may require developing a language for defining constraints and knowledge representation. The results should be usable during monitoring and diagnosis of instrument health (see also below) because one requires knowledge of what was expected as well as what is currently happening. Finally, proposal processing should be included to simplify the development of timelines.

2(b). Design Issues

There are a number of design issues that should be examined and solved before such a scheduling system could be developed. One problem is when and

how to distribute subschedule tasks. The solution may require an approach based on distributed AI. Whatever the answer, it was deemed important that the user(s) be involved in deciding tradeoffs due to conflicting constraints, which involves coordinating subschedule task results, because the users have the best understanding of the science goals and the relevant tradeoffs. Schedule generation then becomes an interactive process with a wide community.

Another problem is that the user needs observation planning tools to evaluate parameter effects. This implies that an instrument simulator is required (see below) as well as a dynamic knowledge base of data relevant to the schedule constraints. A way of dealing with this issue may require application of "fuzzy logic" to use results in system, because some parameters do not have sharp acceptance criteria. A knowledge data base is especially important for guest observer programs where expert knowledge is limited, and an effective multi-site scheduling system should be capable of rescheduling a "constellation of satellites" in order to respond to targets of opportunity (TOOs). Studies of "reactive" scheduling could provide a workable approach to this problem, which gets complex when a given site may have limited resources. Another approach is to encourage autonomous rescheduling for specific sites (e.g. lunar, deep space). Means for dividing the scheduling between ground and flight systems should be investigated. An in-flight system could be studied and implemented in a testbed astrophysics mission.

The ability of the scheduling system to learn by observing the actions of human schedulers offers important performance and efficiency improvements, so studies should be undertaken to develop realistic learning mechanisms. One approach is to learn from successful procedures while an alternative, Bayesian approach would be based on examples and is data, not process, intensive. It is not clear at this time which approach is best. A recording feature would be beneficial to either approach, so that one may document the process that led to a successful schedule. Current performance is based on computation speed and algorithm efficiency, so there are ways to improve the turnaround time. One would be to develop techniques based on parallel processing. Another approach would be to improve strategies; for example, the system could switch algorithms based on resource availability. Finally, it may be possible to develop custom processors for simple or in-flight schedulers.The efficiency of any scheduler depends also on choice of user interface. At present, developing a schedule is practically an art. New data display techniques should be examined as well as approaches to displaying the schedule "possibility space" so that the user can be fully aware of the available options. Some effort should be directed toward developing an effective schedule control panel design as well.

3.   INSTRUMENT MODELING AND HEALTH EVALUATION TECHNIQUES

NASA should place more emphasis on developing high fidelity instrument models for its missions, as well as relevant modeling techniques.

There are many factors that drive us to this recommendation. Such modeling is not uncommon today but the universal need indicates that steps could be taken to make it more convenient for developing such models. Instrument models are useful during instrument design, test, calibration, integration and flight -- all phases of a normal mission. Some missions will have very long lifetimes, both in their development phase and during operations; maintaining instrument models throughout the instrument life captures and retains the expertise of the instrument developers. Because there is a

significant use of experiments by users who are not at the physical location of the center of expertise, an instrument model can be used for testing the impact of a multitude of instrument parameters on potential observations. An instrument model can be used to evaluate potential impacts on instrument performance; e.g. to determine the scientific benefits of a given design upgrade. Such a model could even be useful for developing and validating instrument commands, which are extremely important as future instruments are developed with greater flexibility in configuration, data acquisition and larger available command sets.

3(a). Required Features

Because each mission involves a unique combination of hardware and software, this problem comes down to the development of a tool kit of model-building software that can be used in various configurations for many different types of missions. The model components should have several levels of abstraction, e.g. one may examine ADC or system output. Furthermore, models should include software in processors, a very difficult task.

3(b). Design Issues

In order to be applicable to instrument state evaluation, the toolkit may require a real-time system that accepts engineering data so that a flying instrument can be successfully emulated continuously on the ground. This task requires knowledge of time line or handling of executed commands as well, thus relating the problem to the development of schedules. It is not clear that such an emulator can be developed with sufficient processing speed to keep pace with changing instrument states. A good instrument model could be of use in flight S/W validation and new S/W development. Unfortunately, the task is tremendously difficult; micro-processors have too many states to completely test. No approach was identified that would completely satisfy skeptics of software design. The potential benefits are large; after all it is often observed that simple software problems are not found that are potentially debilitating to an instrument. The current system of software testing and review could well benefit from studies of microprocessor modeling. One approach that may work is to use limited sensor data for health checking. It may be possible to send down part of data that represent state changes. Studies could be performed to determine the knowledge set needed to characterize state changes. One might consider an approach using onboard processing to make decisions based on the last state.

4. REAL-TIME INSTRUMENT OR OBSERVATORY OPERATIONS

NASA should support technology development that will allow future real time operations of instruments and space-based observatories by the users.

Practically all ground-based observations are interactive. An astronomer is aware of the instrument health during the observation and can modify the observing program according to changes in instrument performance or target behavior. Because the user is the best judge of complex, unforeseen circumstances, real-time operations of NASA astrophysics missions will often be requested.

4(a).   Required Features

There are several features that would be expected in any system that would be used to operate observatories interactively. Such a system would start remote processes on instrument(s) through an operations interface. A simple user display would show instrument states and allow the user to change states; OASIS is an existing system that can be used this way. The system would also return and display instrument data, as well as starting data analysis.

4(b).   Design Issues

Naturally, low-latency links are needed for most practical applications. Application to Low-Earth Orbit (LEO) missions depends on a new communications net. The applicability of a transaction management paradigm must be studied for potential use in space operations. The need for near real-time verification of commands brings up serious issues regarding high-speed command validation. Here again is a potential use for high fidelity platform modeling software (see above). An observatory operating system would require that resource data be displayed in real-time in order to evaluate possible configuration changes. This problem ties into the scheduling system user interface.

5.   TRANSPARENT INSTRUMENT AND OBSERVATORY OPERATIONS

NASA should develop capabilities to allow future users to operate instruments and remote-observatories in a "transparent" mode.

"Transparent" in this context means that the instruments are operated as though one didn't know that there is a ground-space communications system in between the user and the instrument. One paradigm that addresses the need is "INTERNET to the Moon" (Schreier, E. "White Paper on Science Operations", in these Proceedings). Each observatory and/or instrument is then considered to be a "node" on a large, NASA-wide network. The practical motivations are several. First, instrument interfaces are consistent during mission development, saving software development effort and training. Second, the instrument itself has a simpler interface to the system receiving its data, making it easy to ship data back to the observer. Third, such a network would make real-time operations more straightforward and would provide an infra-structure that can be used for automating observatory responses to TOOs.

5(a).   Required Features

For this approach to succeed, space communication centers need a common approach to ground-space communications and this approach must be consistent with lab-based instrument communication. Another feature that would be extremely beneficial to scientists is the possibility that instruments could broadcast news of interesting events which could then be picked up by other instruments that are available for observing a TOO. This approach may also be used so that instruments can read data from other instruments (even on other platforms), which may actually be necessary for certain observatories. (For example, a spectrometer may require an

accurate target position before acquiring a requested target and this position may be measurable only using a parallel imaging telescope.)

5(b). Design Issues

The first problem that one always runs into when using networks is the adequacy of security against command errors and unauthorized use of valuable instruments. This problem, however, is a general network problem and is NOT a NASA-specific issue. It will either be solved or not by other interested parties that have more to spend resolving the issue. A second problem that came up was that "INTERNET to the moon" may not be a valid paradigm. A major difference is that INTERNET has no actuators to monitor and no resources to control, unlike a platform that may have several instruments. Such resources include: power, position (motion), temperature, attitude, consumables (water, O2, N2 etc.), and pyrotechnics. Instruments on the same (or an adjacent) platform may be affected by the actions that are requested. To this end, new approaches may be needed so that a system can be controlled transparently in resource-limited environments. Another issue is defining the response of an instrument to broadcasts, if action is required. Some instruments may ignore all alerts, while there are others whose purpose is to listen for broadcasts of celestial news. In such cases, autonomous re-scheduling would be needed (see above). Finally, commands must be prechecked so that the health of the instruments is maintained. This checking introduces a (potentially undesirable) latency unless mission simulators can be developed to verify command effects in near real-time.

PANEL 2

SPACE-BORNE DATA PROCESSING

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PANEL 2 : SPACE-BORNE DATA PROCESSING

A. INTRODUCTION

The Space-Borne Data Processing panel was tasked to identify the space-borne data system technology needed to support the astronomy missions of the 21st century. We were concerned with the space-borne needs to gather, buffer, process and transport data and commands.

B. MISSION REQUIREMENTS

In order to identify all of the critical technology needs the panel identified a representative set of missions. The missions included the Lunar Burst Observatory (LBO), Large Deployable Reflector (LDR), Submillimeter Interferometer-Lunar (SIL) a.k.a. Synthesis Array for Lunar Submillimeter Astronomy (SALSA), Space Imaging Interferometer (SII) and X-ray Large Scale Array (XLA). LDR was chosen for its high continuous data rates. XLA and LBO were examples of missions producing high burst rate data. SII and LDR push the state of the art in structure and figure control. LBO and SIL are examples of missions which have large general and special purpose processing requirements.

C. INFRASTRUCTURE AND TECHNOLOGY ASSESSMENT

The technology development programs currently planned by NASA are covered in the paper by Holcomb. We have identified future technology issues in three areas: space hardware, systems and development methodology.

SPACE HARDWARE

1. DIGITAL CORRELATORS AND AUTOCORRELATORS

In missions such as the SIL, the data rates at the sensor are of the order of 10-100 Gbps. Communicating this data to earth for processing is unreasonable. By providing the correlation in space the raw signal stream can be reduced to, approximately, 1-10 Mbps. Thus low power, flight qualified, 10 Gbps correlators are essential. Since these correlators are specific to astronomy, being a special function, specific to space astrophysics needs, NASA must invest in the technology development to bring low power correlators from the existing 100 Mbps to the needed 10-100 Gbps.

For high throughput heterodyne spectroscopic missions such as LDR, the data rate at the sensor is of the order of 1 Tbps. Digital autocorrelators can reduce these data rates down into the Mbps range. Continuation of the development of digital autocorrelators from the 250 Mbps range to the 10 Gbps range is needed.

2. ACOUSTO-OPTICAL FILTERS

An alternative approach to the digital processing of submillimeter interferometric and spectrosopic data (SIL and LDR), is the use of analog Acousto-

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optical devices. Acousto-optical filters have the potential of handling raw data rates in the 100 Gbps to 1 Tbps range and reducing them to the 1-10 Mpbs range. Acousto-optical devices and system architectures with Gbps band widths are needed.

3.   HIGH SPEED PROCESSORS

In the astronomy missions there is a broad set of computing functions required. In some cases such as the correlators and autocorrelators proposed for the SIL and LDR type missions the rates are so high and the function is small grained and highly repetitive that application specific hardware is the primary choice. In other applications: processing of photon counting detectors, active structure and figure control and the detection of temporal changes, the amount of computation and the algorithm structure lend themselves to array processing types of processors. For spacecraft health, control and target of opportunity tasks general purpose processing may be the optimal solution.

For any one mission, such as LDR, there will be functions from each class required. In order to meet the missions needs, development in all three of the processing categories will be needed. Also, in order to reduce mass, power, volume and cost while providing the longevity and fault tolerance, heterogeneous systems will be required.

Providing the means of gathering large amounts of data and disseminating it to the computing, buffering and telecommunications resources, for the heterogeneous systems, is a great challenge. The tools to help in the design, simulation and test of these networking systems are needed. Also advancements in network hardware and control software are required.

There are many trains of thought in answering the computing needs. What can be said is that we will need general purpose, adaptable special purpose and application specific processing resources that can meet missions with needs such as the 20 Gips signal processing for burst detection and Gflops of structure/figure/attitude control processing.

4.   DATA STORAGE

Due to the lack of maturity of the mission designs most of the data storage requirements could not be defined. The data buffering requirements are directly affected by the downlink bandwidth and availability. These capabilities are not known at this time. In the case of high speed image processing it was identified that there is a need for systems to have approximately 4 Gbytes high speed buffer memory.

SYSTEMS

5.   SYSTEM DEVELOPMENT TOOLS

Many space astronomy missions will have a multitude of instruments and supporting subsystems with extremely demanding processing and control needs. The anticipated methods to meet the instrument signal processing, data buffering, data networking and structure/figure/attitude control of missions such as LDR are very sophisticated. To handle the life expectancy and fault tolerance requirements the systems

will have to address issues such as providing for functional spares and allowing for graceful degradation.

Designing and developing systems of this complexity will require tools which will allow for the early characterization and simulation of the end to end systems. These tools will have to handle the coarseness associated with the conceptual stage while allowing for the increase in fidelity of elements in the design, development and test phase. Rapid prototype, womb to tomb, system development tools are necessary if we are to develop these systems in reasonable time frames.

6. SOFTWARE DEVELOPMENT TOOLS

As pointed out earlier, the processing systems of the future astronomy missions will be far more complicated than today's systems. Multi-processor, heterogeneous computing systems capable of multi levels of fault tolerance will require software development tools far beyond the existing capabilities. In order to keep the software cost and system development schedules to a palatable level these software development tools will have to provide more automation in developing code and compatibility with the system and hardware development tools thus allowing for concurrent hardware and software development.

7. MULTILEVEL HARDWARE AND SOFTWARE QUALIFICATION

Some functions such as spacecraft attitude control are mission critical. Some functions such as coherent interferometry correlation are very tolerant to certain kinds of errors in their processing. In the future data systems, a mixture of critical tasks will reside with non-critical tasks in the same system. If we are to follow the very time consuming and expensive procedures required to guarantee all the hardware and the software in the systems are designed, developed and tested as mission critical, we will drastically limit the capabilities of the future systems. What is needed are methods to generate requirements, design, develop and test hardware and software which allow for multilevels of reliability in a common system but will guarantee mission critical functions will perform as required.

DEVELOPMENT METHODOLOGY

8. SIMULATION AND RAPID PROTOTYPING

A common feeling amongst the panel members was the need to move away from the water fall method of system design and into the spiral requirements development methods. Included in this idea is the need to utilize simulation and rapid prototyping as a means of flushing out requirements early in the design phase before things are set in concrete and cost too much to change. Associated with the rapid prototyping concept is the suggestion that MicroSats and QuickSats be used to fly new technologies in representative environments to build confidence in the technology so that it can be injected into missions sooner.

Related to the spiral requirements approach is an idea expressed that technologists, technology developers, and the science community need to foster an iterative communication process. This communication is intended to make technologies in their conceptual and infancy development stages visible to the science community so that the scientist can develop new ideas and methods of gathering and processing data in time to influence and advocate the enabling technology development.

D.   RECOMMENDATIONS

In summary, the panel has identified the need for advances in space hardware and systems to meet the needs of astrophysics missions of the 21st century. New development methodologies will also be needed. Specific recommendations are:

1.   DIGITAL CORRELATORS AND AUTOCORRELATORS

Low power correlators and autocorrelators will be needed with bandwidths of 10-100 Gbps. Current technologies are capable of 100 to 250 Mbps operation.

2.   ACOUSTO-OPTIC FILTERS

Low power analog correlators and autocorrelators are needed with overall bandwidths of 1 Tbps. This will require new processor architectures and acousto-optic devices that are less temperature sensitive than present devices.

3.   HIGH SPEED PROCESSORS

General purpose, adaptable special purpose and application specific processors are needed that can meet needs for sensor processing, active structure and figure control, and burst detection in the 1-20 Gips range.

4.   DATA STORAGE

For high speed image processing, there is a need for systems with approximatley 4 Gbytes of high speed buffer memory. Because of immaturity of mission designs data other storage requirements could not be specified.

5.   SYSTEM DEVELOPMENT TOOLS

New tools are needed to characterize and simulate end-to-end systems. These tools will have to encompass the conceptual, design, development and test phases. A rapid prototyping approach to the development of these tools is required.

6.   SOFTWARE DEVELOPMENT TOOLS

New software development tools must accommodate multi-processor, heterogeneous computing systems capable of multilevels of fault tolerance. To keep cost

and schedule within bounds, these tools must incorporate more automation than current tools and permit concurrent hardware and software development.

7. MULTILEVEL HARDWARE AND SOFTWARE VALIDATION

In future systems, a mixture of critical tasks will reside with non-critical tasks in the same system. Methods are needed for design, development and test which allow for multilevels of reliability in a common system.

8. DEVELOPMENT METHODOLOGY

The requirement for future complex systems cannot be effectively defined by unidirectional top-down methods. Spiral requirements approaches are needed. The adoption of simulation and rapid prototyping is needed in order to flush out requirements early in the design phase of systems.

Of the technology needs identified above, only three involve needs unique to astronomy missions: correlators with 10 Gbps to 1 Tbps bandwidth (1 and 2), and processors for the structure/figure/attitude control (3). All the other technologies have been identified as common to future initiatives in global change monitoring. In the case of correlators, Astrotech 21 should take the lead in developing the needed technologies. For the other technologies, CSTI, HPCI and the Code R base program are working the issues. For these technologies Astrotech 21 should take a proactive stance and advocate their continued development. In the cases where the astronomy missions have unique requirements extra effort must be made to influence the technology development to guarantee they will have the technologies they need when they need them.

PANEL 3

SPACE-TO-EARTH COMMUNICATIONS

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PANEL 3: SPACE-TO-EARTH COMMUNICATIONS

A.   INTRODUCTION

The space-to-earth communications panel was assigned the task of defining the needed technologies for communicating data from spacecraft in low earth orbit, high earth orbit and on the lunar surface to the earth. The emphasis was on efficient communications to the ultimate user of the data, and the need for direct RF links was explicitly addressed. The need for development of various communications technologies including solid state MMIC phase array transmitters and optical communications technologies were assessed. The potential of high temperature superconductors in communications was also considered. The space-to-Earth communications panel identified technology requirements, conceptualized system configurations, assessed existing technologies and developed recommendations for both new systems capabilities and technology development.

B.   MISSION REQUIREMENTS AND ASSUMPTIONS

A baseline was established by taking a cross section of anticipated astrophysics missions. The science requirements stem from a wide variety of infrared, ultraviolet, and high-energy observatories. The following list summarizes those science instruments and systems that were considered. Where applicable, data rates were estimated according to $R = N \times b \times r \times b$, where R is the data rate, N is the number of antennas, b is the bandwidth, r is the number of polarizations, and b is the number of bits.

Table 3.1.   Data Rates for Future Astrophysics Missions

High Energy (e.g. X-Ray Large-Scale Array)	<100 Mbps (bursted)
Imaging Spectroscopy (1024 X 1024 X 128 large format, in Earth orbit or on Lunar Surface)	10 - 100 Mbps
Orbiting VLBI (continuous, direct transmission)	1000 Mbps
Submillimeter Interferometer Array (with correlation)	10 Mbps
Low Radio Frequency (Lunar, near side)	800 Mbps
Low Radio Frequency (Lunar, far side)	2000 Mbps

Beyond contending with large volumes of data, there are unusual and unique monitoring and distribution requirements. For example, there is a need to be able to

react to transient phenomena, such as gamma ray bursts. Analysis of these short duration, high priority events requires that the scientists have the capability to locate and observe (or record) the occurrence as soon after it happens as possible. Such an ultrafast mobilization process is currently unavailable. An additional capability likely to be required is direct wide geographic coverage. The traditional method of scheduling time slots (access) in series, via TDRS for example, will be unacceptable for various users. Real-time control of the instruments by principal investigators was perceived as a need, not just a want. A tremendous desire was expressed for immediate and direct multipoint links. Considering both the nature of the information and the prospect of sifting through terabits-per-day of archived information, direct data distribution is a logical solution. Dedicated coverage to support the multiple simultaneous missions will require an intensive developmental effort. This transparent connection between users and instruments was probably the most sought after feature discussed at the workshop.

In addition, virtually "error-free" communications ($<$ 10-6 BER) was stressed as an important parameter. This is consistent with the reluctance to accept "lossy" data compression as a technique for alleviating the pressure on the communications links and storage media to handle massive amounts of data. Every bit of scientific information is considered valuable, and perhaps irreplaceable.

C. INFRASTRUCTURE AND TECHNOLOGY ASSESSMENT

The anticipated near-Earth and lunar based astrophysics mission needs beyond the turn of the century present the next evolutionary challenges to the technology of free-space communications. In particular, the staggering amounts of data to be generated by numerous, close proximity, highly sophisticated science instruments require us to reexamine traditional thinking and customary architectures.

1. INFRASTRUCTURE

Historically, from a NASA perspective, the technology has been driven primarily by commercial satellite communications. The components and systems developed under this program (antennas, traveling wave tubes, baseband processors, error correction, etc.) have significantly advanced civil and military communications. However, the impetus has been relatively modest data rate voice and video. A second major thrust has been deep-space communications. Remote space probe communications is governed by limited spacecraft power and large spreading loss. (Data rates essentially scale as the inverse square of the propagation range for a fixed radiated power.) To compensate for the extremely small received power levels, NASA has invested heavily in the ground segment. The Deep-space Network (DSN) consists of three global multi-station complexes designed to produce an aggregate signal with acceptable bit error rate characteristics for deep-space missions. More recently, NASA's communications network has been enhanced with the addition of a constellation of tracking and data relay satellites (TDRS). This network provides 90 percent temporal connectivity for near-Earth spacecraft. Despite all of these developments and the intricate network of communications satellites and ground stations, it must be emphasized that the infrastructure was never intended to support the type of science operations projected for the 21st century.

Unfortunately, the planned upgrades to the existing infrastructure are not responsive to the anticipated growth in communications traffic. Currently, the DSN's

absolute data rate is 2.2 Mbps. The long range plan, out to the year 2020, calls for a 150 Mbps downlink and a 0.5 Gbps optical link. Furthermore, the DSN uplink is now limited to less than 10 Kbps. Advanced TDRS (ATDRS) will function only as a "bent pipe" relay, offering little in terms of the data distribution capability mentioned earlier. Today's TDRS provides an S-band phased array for multiple access to as many as twenty user satellites, but at data rates less than 50 Kbps. Single access S- and Ku-band relay links provide data rates up to 300 Mbps. ATDRS is expected to have a 650 Mbps single access Ka-band link and twenty 3 Mbps multiple access channels.

The ACTS is pioneering a number of technologies that could be used for future DDS type satellites. ACTS will be equipped with a multiple spot beam antenna system which enables frequency reuse. A time division multiple access architecture is used to permit Earth stations to time share the same frequencies. Fixed and electronically hopped spot beams can respond to the varying demands of numerous geographically separated users. A switching system on board the satellite will route the traffic directly to the users. In addition, ACTS developed the necessary Ka-band technology to permit data rates up to 220 Mbps.

2. ACCOMMODATING ASTROPHYSICS NEEDS

It is clear that both optical and microwave technology should have important roles to play in the astrophysics missions of the twenty-first century. Microwave technology is more developed and in most situations it is completely responsive to the science needs. Optical communications inherently provide extremely high theoretical power and bandwidth advantages.

Accommodating the identified data rates of 10^6 to greater than 10^9 bits per second per instrument will require considerable development of Ka-band (or higher frequency RF) technology and a profound investment in optical communications. In principle, a Ka-band channel with about two percent bandwidth employing today's modulation schemes has the capacity for gigabit per second rates. Links from far-side lunar, inter-geostationary/lunar, eccentric orbit, and geosynchronous platforms need to be considered. Higher data rates to support the science instruments will obviously be a technology driver, but the greatest challenges will most likely be related to the rapid acquisition and dissemination of the information. Management of this information explosion will ultimately govern the direction of technology and systems architectures.

Lunar far-side communications to Earth will require, as a minimum, one relay satellite in orbit about the L2 libration point. Presumably, whether for outposts or in support of astrophysics missions, a near-side relay satellite will eventually be required. An option to interconnect near- and far-side operations using optical fiber cables was also considered. (There certainly appears to be a trend on Earth to supplant satellite communications with optic fiber links, at least for densely populated areas.) Although implementation might at first appear farfetched, closer inspection suggests that the merits of such an optimal network (wide bandwidth, high reliability, minimal or zero maintenance) might compensate for the added inconvenience and cost. Ultimately, a scenario could be developed which would obviate the necessity of twin satellites. Weight and volume are probably the foremost concerns. Assuming that the cable would cover about one-fourth of the Moon's circumference, a two-fiber multimode cable with a rugged jacket would weigh about 100,000 pounds! A typical satellite (e.g. TDRS) weighs about 5,000 pounds, plus another 35,000 pounds or so for the rockets to hurl it from the shuttle payload bay to geostationary orbit.

A most attractive solution for facilitating the management of the large (an understatement) amounts of raw information is a data distribution satellite (DDS) system. A DDS would serve as the hub of a sophisticated network which would receive data from multiple sources and provide the necessary onboard switching to route the information directly to multiple users. The system would require the agility of multiple scanning spot beam phased array antennas and intelligent onboard processing. One possible configuration consists of an optical lunar-geostationary link which is then sorted by the DDS and retransmitted directly to user very small aperture terminals (VSATs) over multiple Ka-band channels. The technology being developed by the Advanced Communications Technology Satellite (ACTS) is prefatory to such a system. ACTS basic ground terminals operating at about 200 Mbps and utilizing 2.4 meter antennas are expected to cost about $1 million each. Alternatively, direct optical links to ground necessitate significant site diversity for optimal connectivity (i.e. near 100%). Tradeoff studies between ground-based site diversity and Earth relay (DDS) satellites as well as optical and RF links for the various segments need to be conducted.

3.   COMPONENT TECHNOLOGIES

Trends in component technology are equally important. Monolithic Microwave Integrated Circuit (MMIC) amplifiers and phase shifters will be required to enable agile phased array antennas for DDS type satellites. Traveling wave tubes (TWTs) could provide the necessary power levels for high data rate Moon-to Earth links. It is likely that optical communications will eventually be required for the high capacity channels. Advanced modems and more bandwidth efficient modulation schemes can expand the information throughput and provide the necessary growth in channel capacity.

TWTs have a proven track record and have been the mainstay of civil and military space communications. Although the technology is considered mature in many circles, substantial advancements are still occurring, especially with regard to efficiency and reliability. Emphasis has been placed on long-life cathodes, low secondary electron emission materials, multistage depressed collectors, and novel slow wave structure designs. There is little competition from other technologies in terms of output power and efficiency from a single aperture. ACTS will employ a 46 watt, 22 % efficient TWT amplifier. A 32 GHz, 7 watt, 35 % efficient TWT amplifier is scheduled for demonstration in October, 1990 for potential application to the Cassini mission.

Phased array antennas enable high efficiency spatial power combining and enhance reliability because of graceful degradation (due to multiple radiators). Most importantly, since mechanical inertia is eliminated, rapid (microsecond) beam steering is possible. The key components are low noise and high power amplifiers and low loss phase shifters. NASA developed Ka-band amplifiers have demonstrated output powers in excess of 300 mW with greater than 25 % power added efficiency. Ka-band phase shifters have demonstrated 2 dB per bit insertion loss. Although chip reproducibility is still an issue, prototype arrays have been built. Device model integrity and processing repeatability will require considerable development. Cost effectiveness is often quoted as a major benefit of MMICs. Because of high performance, small volume requirements, cost may not be an incentive for space applications.

Lunar/Earth optical links at the specified data rates will require laser transmitters with output powers greater than 500 mW and significant improvements in receiver technology. Furthermore, state-of-the-art pointing accuracies of about 10 microradians require at least an order of magnitude improvement. Q-switched Nd-YAG lasers with 100

mW of average power and a pulse width of 20 nsec at a repetition rate of 25 kHz have been demonstrated. A 50 Mbps direct detection APD optical receiver has been completed with near theoretical BER performance at a sensitivity of 48 photons per bit. Frequency stability and lifetime are major concerns. Prototype optical transceivers need validation in the space environment at the earliest possible opportunity. A Space Station attached laser communications transceiver experiment is under development and is expected to be launched in the mid-to-late 1990s.

Practical high-data-rate, bandwidth- and power-efficient modems need to be developed in conjunction with the RF and optical technology. Theoretically, advanced modems could double or perhaps triple the capacity of existing links through advanced octal phase shift keying or 16 phase continuous phase frequency shift keying. Novel modulation and coding techniques need to be developed which will optimize bandwidth efficiency and bit error rate performance. In addition, data compression algorithms need to be investigated as a practical matter. In particular, viable techniques for managing immense volumes of image data will be required. A compromise between realistic data throughput and acceptable amounts of data sacrificed through lossy compression is inevitable.

Another technology which could potentially revolutionize communications and data systems is superconductivity, specifically high temperature superconductivity (HTS). Although discussed only peripherally during the workshop, mainly due to time constraints, HTS promises to enhance and enable components and systems for science, power transmission and storage, and spacecraft propulsion as well. The recently discovered ceramic superconductors operate at temperatures near 100 K. Commercial applications are thought to be somewhat far-term due in part to the expense and inconvenience of cryogenic cooling. Space applications, however, are extremely intriguing. The space environment offers a natural setting. Theoretically, passive (radiative) cooling on the dark side of the moon to 70 or 80 K for small heat loads is possible! Furthermore, deep-space observation platforms could provide a reasonable heat sink for some applications. Even if mechanical cooling is required, it is not unattractive due to the ambient environment. In the area of communications and data, major benefits to analog and digital systems have been identified. HTS exhibits about twenty times lower loss than copper at 10 GHz and 77K. Hence, much more efficient communications components can be designed. Much further off are applications in digital systems: superconducting Josephson junction gates provide a three-to-four orders of magnitude improvement in the delay-power product compared to CMOS and GaAs ECL! High speed computation and data storage beckons for the development of this technology.

D. RECOMMENDATIONS

It is unreasonable to believe that we have considered or even anticipated all of the requirements for future astrophysics missions. It is also unrealistic to believe that we have outlined the best and the only solutions. However, the following list of recommendations provides initial guidelines for a technology plan which we believe addresses most of the critical technology needs for astrophysics and those that are largely unique to astrophysics. While communications technology has traditionally been motivated by voice and video and low data rate remote space probes, it is clear that the milestones of the next century will be driven by highly sophisticated "local" science missions.

1.   OPTICAL COMMUNICATIONS TECHNOLOGY

Accelerate development and deployment of optical communications technology to enable practical high data rate systems for space applications. The astrophysics community, which is often not consulted on such issues, needs to advocate early experiments and demonstrations to validate technology readiness.

2.   Ka-BAND AGILE MULTIACCESS COMMUNICATIONS SYSTEMS

Develop the necessary Ka-band hardware (MMICs, TWTs, antennas, arrays, modems, etc.) to improve the agility, versatility, and reliability of multiple access communications systems. Component design will, in many cases, need to be specific to the astrophysics mission requirements, although considerable leverage of existing programs will occur.

3.   COMMUNICATIONS NETWORKING BASED ON ATDRSS AND ACTS

Expand the DSN/ATDRSS infrastructure to provide dedicated support to multiple simultaneous missions and to accommodate the anticipated data rates. Encourage the investigation of an "ACTS-like" data distribution satellite architecture for networking instruments and users.

4.   DATA COMPRESSION AND MODULATOR/DEMODULATOR TECHNOLOGY

Develop data compression techniques and modulator/demodulator technology to supplement wider bandwidths through improved spectral utilization.

5.   HIGH TEMPERATURE SUPERCONDUCTING DEVICES

Initiate a focused technology program in high-temperature superconductivity to explore new and potentially revolutionary communications, data processing, and data storage devices and systems.

PANEL 4

SCIENCE DATA SYSTEMS

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PANEL 4: SCIENCE DATA SYSTEMS

A. INTRODUCTION

This Panel was assigned the responsibility for determining technology needs and architectural enhancements required for the future analysis and archival data systems in astrophysics science operations. Riegler's paper in these Proceedings describes the NASA vision and plans for the Astrophysics Data System (ADS) in the Great Observatories Era. This Panel takes off from there and attempts to project the technology needs beyond that Era. The topics covered include high performance computing; distributed processing; science networking; data systems architecture; information standards; data storage and retrieval technology; database, data structure, and data compression for science analysis; and data distribution. The scope of this Panel's charge is for ground-based systems, thus complementing Panel 2's charge for space-borne data processing. Some of the topics covered in this Panel overlap those of Panel 5, which, however, put primary emphasis on scientific investigators' "desktop power" for data analysis and visualization.

B. REQUIREMENTS

Astronomy data systems for the next millennium will require advances in many areas of technology, improvements in users' abilities to access these technologies, and improvements in the methodologies for developing these technologies. Some of the technologies are required by many disciplines in science and engineering, and we assume that these will be generally available (e.g. data storage, distribution media) or supplied as national infrastructures (e.g. networks, supercomputing). However, NASA will have to participate in the development of these infrastructures so as to make them useful to its users in general and to the astronomy community specifically, and to ensure that this community of users has access to the resources. In other areas, we believe that NASA will have to develop technologies of specialized use to astrophysical information systems. The technology needs are driven by the anticipated astrophysics data rates, which range from tens of megabits per second to tens or hundreds of gigabits per second.

C. INFRASTRUCTURE AND TECHNOLOGY ASSESSMENT

In a number of technology arenas, such as those listed in this Section, NASA is primarily a user and participant in some larger national efforts involving several government agencies and industry. In these areas NASA should either take the posture of a smart user or a proactive advocate for certain technology to be developed, and OSSA should provide the proper infrastructure for cost-effective multi-discipline applications of these technologies.

1. NETWORKING

It is essential that a widely distributed national network be developed, and that all major astronomy groups and data centers have access to it. Based on the megabit to gigabit/sec individual astronomy missions planned for the next decade, and the multi-terabyte archives being accumulated over this decade, we believe that a gigabit/sec national network backbone will be needed before the turn of the century. This is consistent with the National High Performance Computing Initiative.

NASA will have to support the connecting of its data centers and its users to this network, with tail circuits in the megabit/sec class. The NASA Science Internet Program should monitor the needs in this area and participate in the National Research and Education Network (NREN) planning. An interagency astronomy coordinating group should be established to coordinate and facilitate use of the net.

2. SUPERCOMPUTERS

The need of astrophysical theory for computing is essentially unlimited, in the sense that faster computers generally give more results with less human time required to improve algorithmic efficiency. There is a large supply of theoretical questions (e.g. "Simulate the Universe...") beyond any reasonable limit of computer capability, and always plenty of problems near the limit of current feasibility. In addition, image processing requires significant amounts of computer time. The appropriate level of support for supercomputer technology development, both hardware and software, therefore, becomes a question of the allocation of limited resources to optimize the overall scientific return and balance of NASA's program.

In general, we feel that astronomers' needs can be met by large, general purpose supercomputing facilities and visualization facilities as currently contained in the national supercomputer centers. NASA should support its community's use of these facilities. (Special purpose supercomputing and algorithm development is discussed separately.)

3. DATA STORAGE

Secondary storage devices are needed for large volumes of data. Optical memories (disks and holograms) are being developed as an alternative to magnetic devices. Multi-terabit storage capacity is desirable for the next decade with a few nanosecond access time. Industry is forecasting an increase in helical scan cartridge technology form 5 GB to 67 GB in a few years. It is safe to predict an increase in capacity of 3 orders of magnitude by the end of the decade. NASA needs to be cognizant of and ready to adapt commercial sector developments in storage media, to assure itself of adequate capacity, size, and durability. Mass data storage will also require intelligent data management (see item D.7).

4. DATA DISTRIBUTION

Commercial technology already exists for 20-40 terabyte tape media for distribution. Since long term durability is not required for distribution, it is expected that media capacity will continue to grow exponentially, like data storage media. NASA should stay abreast of developments, but not necessarily develop its own technology in this area.

High speed fiber optic networks with data rates of 2.4 gigabytes/sec would be desirable throughout the NASA community by 1995, increasing to ~10 gigabits/sec by 2000. In the further future (~2010-20), terabit/s networking would be necessary for supporting direct user readout and access to petabyte data bases. Missions data rates are the key technology drivers. We expect flight to ground communication bandwidth requirements of 1 gigabit/sec and beyond in the next 10-15 years.

D. RECOMMENDATIONS

This Panel has come up with two sets of recommendations as enumerated below. The first set, numbered 1 to 5 here, refers to specific technology projects. The second set, numbered 6 to 11, relates to the overall astrophysics data system architecture. We recognize that some of the recommendations may overlap those made by other panels. For example, recommendations 10 and 11 are also considered by Panel 1.

TECHNOLOGY

1. DATA COMPRESSION FOR GROUND SYSTEMS

As data rates of future astrophysics missions become prohibitively large (on the order of hundreds of megabits per second or higher), data compression technology will definitely be required to reduce both transmission bandwidth and storage volume. To satisfy the diversified science requirements, both lossless and lossy compression techniques should be investigated. Lossless compression typically yields savings of at most factors of a few, but where the data volume is very large, the savings for even modest compression are significant. It is important, however, that development and implementation of improved compression methods be accompanied by parallel improvements in error detection and correction, as in their absence the effect of errors on compressed data is usually catastrophic. Non-reversible, lossy compression offers potentially much larger savings, but at the risk of loss of scientific information, since by definition scientists usually cannot predict all important features of the data in advance. Nevertheless, such techniques may be quite justifiable and necessary when the alternative is not to do an experiment. Thus research on lossy compression methods and on methods of minimizing their inherent scientific risk appears warranted. The direction of research should also be geared towards the use of state-of-the-art parallel processing techniques and neural network algorithms. We recommend a workshop be organized to

get data compression researchers and astrophysicists together to promote wider understanding of scientific needs and technological trends, and to propose specific technological developments.

2. APPLICATION SPECIFIC PROCESSORS

The quantity and rate of capture of astrophysics observations in the twenty-first century will require new and application-specific information processing tools. Technologies which are emerging or are available to support these requirements should be supported in Code R's program. Examples of such technologies are:

(a) Smart Memory Technology

The successful development of large volume data storage systems will depend not only on the ability to store data, but also on the ability to manage such data once they are in the system. Mass storage data management needs highly intelligent data management services which would allow the manipulation, updating and accessing of data in a logical manner and which are powerful enough to support the performance needs of a large mass storage system. This includes information processing approaches which, in the process of archiving data for later use, store the data items which have physical relationships with each other so that these relationships are maintained and are available for later use in data retrieval. Two examples of such systems are the Sparse Distributed Memory of Kanerva and the CMAC of Albus.

(b) Special Purpose Processors

Some information processing functions necessary for future astrophysics missions and information systems will execute much too slowly on conventional general purpose processors. Two specific examples are correlators (for interferometry missions, assuming the signals are being sent to ground systems) and data base query processors (for large archival research systems). It will be necessary to develop special purpose processors to do such functions.

(c) Artificial Neural Networking

This area of technology shows great promise for accelerating pattern matching applications, scheduling, etc. The appropriateness of new hardware architectures for neural networks should also be investigated.

3.   ASTRONOMY ALGORITHMIC RESEARCH USING FUTURE ARCHITECTURES

Massively parallel architectures, scaling to teraflop speeds, are necessary for development of astrophysics-specific algorithms including: galaxy formation, evolution and clustering; star formation, structure, and evolution; and the formation and behavior of astrophysical jets.

In today's conventional supercomputers, stellar dynamics solutions are limited to simulations involving tens of thousands of stars. More realistic simulations would utilize millions or billions of stars, and require massively parallel systems. Fluid dynamic calculations using finite difference schemes are currently limited to coarse grids and short integration intervals. Massively parallel architectures, scalable to teraflop speeds, are required for 3-D simulations with fine grids. Terabyte memories are needed to support those simulations.

4.   SOFTWARE EXCHANGE, MANAGEMENT, AND DISTRIBUTION

In general, the cost of developing new software must be balanced against the cost of locating, understanding, and evaluating previously existing software, and against some estimate of the probability of successfully finding a suitable program for any given need. Evidently this makes the ease of locating, accessing, and evaluating candidate software critical, as the size of the pool of available software grows. In view of the large costs of software development, it is important to give adequate support to improvements in indexing and information retrieval in this area. The problem is intrinsically difficult because real software is so complex.

Technology is needed to provide to the astrophysics community the full range of developed and documented software for astrophysical applications. Users on the National Research and Education Network (NREN) should be able to transparently locate, retrieve and\or store software that has been developed nationally. Levels of validation should be applied to provide potential users with a confidence factor in the available software. Software should either be electronically transferred or accessed directly for execution from a remote mode on NREN.

5.   PROTOCOLS FOR ADVANCED DISTRIBUTED SYSTEMS

Increasing use of high speed networks, workstations, and new distributed system services requires the development of new protocols and interfaces, to accommodate remote access to data bases, data archives, and supercomputing or other special processors. The high level requirement is to permit access to these services from a distributed set of users, operating on a heterogeneous mix of systems. These interfaces should permit local autonomy to be honored while providing a common access mechanism for remote users.

NASA should promote or sponsor the development of concepts, designs, and prototypes of the science user interfaces that will efficiently support both the scientists' interactions with data archives and their computing and analysis capabilities. The efforts should address the synthesis of a variety of advanced technology areas such as expert systems, advanced query processing, object oriented information management and data visualization. The objective of such efforts is to achieve an efficient and easy user interface. One approach may be to simulate dialogs in the users' context, thereby insulating them from systems characteristics.

ARCHITECTURAL

6.   FUTURE ARCHITECTURE OF ADS

The Astrophysics Data System (ADS) or future versions of this system, must be capable of evolving to new services, facilities, and uses. This evolution will inevitably encompass changes in h/w platforms, network protocols, data storage and archive systems, processing speeds, and user interfaces. The fundamental paradigm of a user at a workstation interacting with a set of distributed services is not expected to change over this time frame, but the appearance of the system, the locale of the services, and the modes of interactions most certainly will evolve over time.

7.   MANAGEMENT TOOLS FOR ADS

The ADS system should be augmented with new mechanisms to provide for automated monitoring and analysis of the operation of the system itself. This should include tools to gather statistics, to analyze system use and performance, and to examine system loading. These tools should permit the system to be tuned as a result of these analyses to better meet usage patterns. These tools should be integrated into an expert system which can allow the system to dynamically tune itself.

8.   INTELLIGENT DATA MANAGEMENT

Technology is needed to manage and maintain the volumes of expected data through the use of "intelligent" data management systems. These systems would characterize data sets based on the content of the data rather than on the traditional discrete identifiers (time of observation, RA, DEC, etc.). Intelligent systems build a knowledge database through a "learning" process as the physical scientist interacts with spatial data, etc. Traditional approaches require substantial overhead in searching and typically would not allow the scientist to pose questions based on content features. The large volumes of data which will be archived from astrophysics missions will require intelligent data management.

9. DISTRIBUTED PROCESSING

This technology should accompany the evolving distributed astrophysics computing environment to make better and perhaps unique use of the computing resources ranging from workstations to supercomputers. There are two related classes of distributed processing.

First, the geographical dispersion of data sets relevant to a given research problem may make it efficient to distribute the computer processing workloads to the sites where the data sets reside, thereby avoiding massive data movement. The intermediate results from local processing would be transferred and/or integrated, but the data itself would not have to be moved.

Second, techniques should be developed to allow the use of "excess" cycles on remote machines. This is particularly relevant as more and more astronomers obtain workstations which may be idle for periods of time. A scientist could be allocated available computer cycles on a remote machine, in order to perform a specific calculation that is beyond the ability of a single system to provide in a reasonable time. This could lead to the clustering of supercomputers and specialized processors as well as workstations.

10. DIRECT READOUT FROM SENSORS TO USERS

We would like to consider an architecture in which users could directly receive data from an instrument, bypassing the standard processing and archiving. The intent here is not control but data receipt by an individual researcher at his or her home institution, in real or near-real time, regardless of where the data are eventually processed and archived.

11. REMOTE CONTROL OF SENSORS

Users have scientific requirements to directly control the sensor in terms of pointing and exposing for the purpose of acquiring data and carrying out their observations in unique and flexible ways. The model is much like that of IUE, where continuous contact makes direct user involvement possible. The intent is to avoid a centralized infrastructure, and to allow distributed observing.

PANEL 5

DATA ANALYSIS, INTEGRATION, AND VISUALIZATION

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PANEL 5: DATA ANALYSIS, INTEGRATION, AND VISUALIZATION

A.   INTRODUCTION

An information system consists of 4 types of building blocks or components: hardware, software, "data-ware," and "human-ware." By human-ware we mean the human operators and processors of the subsystems, as well as the procedures, tools, displays, and documentation needed to assist the human users. Panel 5 was charged with studying the future technology needed to enhance the productivity of scientific users. Thus the Panel is concerned with such topics as analysis techniques and tools, data visualization technology, fusion of data from multiple sources or multiple wavelengths ("panchromatic astrophysics"), and the automation of some research assistance functions. The emphasis of the Panel is on enhancing the "desktop power" of scientists.

The Panel identified two major problems, and a set of smaller problems that will confront the scientist of the early 21st Century. The first and foremost problem is labeled as "drinking from the firehose (of data)". That is, the quantity of science data in many fields already exceeds human processing and comprehension capabilities, and the problem will rapidly become worse as modern space experiments produce truly enormous data sets. The second major problem is the extreme difficulty of real-time collaboration between scientists located at different sites. The Panel came up with a number of recommendations to NASA in response to these and other challenges.

B.   REQUIREMENTS AND TECHNOLOGY ASSESSMENT

1.   IMPROVED TECHNIQUES FOR COMPREHENSION AND VISUALIZATION OF VERY LARGE DATA VOLUMES

Faced with the prospect of "drinking from the firehose" of the enormous data sets of the future, the astrophysicist needs powerful tools for visualization, animation, and "sonification" of large data sets. While many of these tools already exist, they require customization for astrophysics and migration to nonproprietary hardware/software environments. Furthermore, complexity, diversity and the distributed nature of data and tools require too much non-science time from a scientist, which enhances significantly the turnaround time from the acquisition of raw instrument data to the publication of results. Since there will not be enough people to make use of the large quantity of science data effectively without intelligent assistance, there is a need for a sophisticated software package incorporating artificial intelligence capabilities -- in effect, an automated research assistant. The most beneficial aspects of an automated research assistant are the immediacy of results from analysis and the feasibility of undertaking more sophisticated, in-depth analysis. An automated research assistant can be a cooperative partner in problem solving and an autonomous assistant for certain analytical tasks.

2.   IMPROVED CONNECTIVITY AND ACCESS TO COMPUTING RESOURCES

A second major problem is the difficulty of real-time collaborations among geographically dispersed scientists. Real-time collaboration requires the visualization of

large data sets or the results of large numerical computations with the cabability for scientists at several sites to manipulate the data such that scientists at other sites can see what is happening and interact.

Addressing the need for improved computing and networking capabilities is essential for meeting this challenge. For example, the computer industry is developing parallel processors, but astrophysicists are not yet using this new technology effectively. Also, software used for pipeline data processing for astronomical missions is not generally available to users. Some users have clever ideas for the custom reprocessing of large data sets to solve specific science questions that were not anticipated when the standard pipeline processing requirements were written. These users should be able to acquire the pipeline processing software and to customize it at their home institutions. On the networking front, gigabit bandwidth is now being developed, but I/O technology does not seem to be available to take advantage of these new networks when they become available.

3.   IMPROVED ACCESS AND INTERFACE STANDARDS

The Panel identified 5 areas requiring improved access and interface standards.

(a)   On-Line Access to Software Tools

There is a clear need for on-line information and access to trustworthy astrophysics software tools and support for the development and maintenance of these tools. On-line information on the availability and quality assurance of software tools needed by the astrophysicist is frequently not available. Usually the degree of testing and reliability of these software tools is not known or determined by the original users. Also, constructing interfaces between heterogeneous software tools can occupy an enormous amount of the astronomer's research time.

In the astrophysics community the major user interfaces are based upon terminal access and/or proprietary systems such as SUNview. The dumb terminal is rapidly becoming the "Model-A" of CPU access devices; industry efforts now concentrate on workstations for which prices now approach those of PCs and terminals. The best guess is that X11 and Motif will become the general standard for workstation user interface development. Users need assurance, however, that whatever windowing/network interface becomes the standard, it must operate in a heterogeneous computer environment and support transparent remote procedure calls and distributed file services.

(b)   Access to Ground-Based Data and Data from Foreign Spacecraft

Ground-based data and data from sounding rockets, aircraft, and foreign spacecraft are often required for the analysis of space-based data but are not generally available in archives. Object or science-oriented astrophysics generally requires data from many portions of the electromagnetic spectrum. Thus the development of astrophysics requires that major ground-based data sets be archived in a usable way and that they be accessible through the ADS.

(c)   Standard Formats for Data Storage

The absence of standard formats for data storage frustrates the swapping of data between the different environments that astronomers commonly employ. For many applications the astronomer would like to analyze multiple but heterogeneous data sets with the same software package, or swap data between different software environments (e.g. IRAF, AIPS, IDL) efficiently so that heterogeneous software can interoperate on the same data. The absence of standard formats for data storage now frustrates the scientist's desire to map science questions onto complex data bases. Format standards are needed for both on-line and stored data to complement the present International Astronomical Union (IAU) approved FITS standards for data transfer. Also, the access language to a variety of data bases should be made more user friendly.

(d)   Transfer Standards for Application Software

Applications software is typically developed within one environment, but should be easily transported to other environments. Modularity would help in stringing together heterogeneous software tools. The development of applications software should be done using an approved standard language such as ANSI-approved FORTRAN or C.

(e)   On-line Documentation for Astrophysics Datasets

The documentation of most data sets, journal articles, and graphics is not presently available in on-line databases. The National Extragalactic Data Base and the ADS are the first systematic attempts to accomplish a portion of this task, but most of the documentation, even for space-based data sets, is not available on-line.

4.   IMPROVEMENT IN TRAINING

The next generation of astronomers is not receiving adequate training in the development of software tools for the reduction and analysis of space data. Astronomers need to be trained to understand and effectively use the rapidly developing software tools and computing environments. We need to educate and re-educate computer literate astrophysicists who will operate comfortably in the new environment. Since most of the training of the next generation of astrophysicists and the research effort in the discipline occurs at universities, most of the funding for the development of research aids should be allocated by the NRA process rather than by assigning tasks to large Centers.

Despite the good intentions and efforts of NASA, there continues to be inadequate funding for graduate students, postdocs, young researchers, and computer resource people. This is an ongoing problem. Insufficient support forces astronomers to devote an increasing fraction of their research time to the writing and reviewing of proposals.

C. RECOMMENDATIONS

KNOWLEDGE-BASED TECHNIQUES

To deal with the problem characterized above as "drinking from the fire hose", NASA should support a coherent program for the development of techniques for the comprehension and visualization of large amounts of N-dimensional data, and these techniques should be made available to users. The program should consist of the following steps:

1. KNOWLEDGE-BASED ASSISTANCE IN ACCESSING DATA AND TOOLS

NASA should support the development of knowledge-based techniques for acquiring, accessing and utilizing pertinent data and tools.

This is the first level of help that takes care of configuration requirements necessary to perform the task of acquiring raw data and processing them into some format necessary for data analysis and visualization. Presently, a scientist must spend considerable time finding out where and how to access the data and required tools. A knowledge-based system that uses this information to retrieve requested data autonomously and to suggest proper analysis tools, methods and formats would greatly reduce the non-science time currently required for a scientific endeavor.

2. KNOWLEDGE-BASED ASSISTANCE IN DATA ANALYSIS

NASA should support development of Knowledge-based techniques in data analysis and interpretation as the next level of automation.

These tools should include pattern recognition algorithms for detection of features in images, spectra and temporal phenomena, and higher-level strategies for performing preliminary analysis. For example, automatic classification of data or formation of new classes where none were previously specified should be one type of data analysis capability of an automated research assistant.

3. AUTOMATED ASSISTANT WITH LEARNING CAPABILITY

NASA should support development of an "Automated Research Assistant" (some panel members have suggested the term "Sorcerer's Apprentice"), which should incorporate embedded learning systems.

Learning capabilities should include automated knowledge acquisition and evolution of knowledge bases as new knowledge is discovered. These capabilities allow an automated research assistant to function in a more automated mode. This system would perform extended analyses with minimal human intervention. The examples which serve as input to the learning system are provided by the scientist users. Such extended analyses might be specified by a scientist, or result from decisions made by the automated research assistant itself. As an automated assistant learns, this learning should

reflect in automated changes to the system's knowledge representation model and subsequent decisions derived from this model.

4. VISUALIZATION AND COMPREHENSION OF MULTI-DIMENSIONAL DATA SETS

NASA should support either the development or adaptation of generic tools to enable scientists' visualization and interpretation of multi-dimensional data sets.

The visualization and comprehension of multi-dimensional astrophysical data sets will require the customization of generic code which may already be available. It is important that this code evolve to nonproprietary hardware/operating systems. Specific needs include the development of pattern recognition tools and animation techniques.

To support the development of visualization tools, NASA should establish an office similar to the existing FITS Office. This Visualization Tools Office should create standards across NASA missions and include not just astronomers and other scientific users, but also invite participation by elements of the commercial sector. For example, companies such as STARDENT (one of their products is Application Visualization System (AVS)) have already created significant scientific visualization tools for medical, meteorological, and molecular sciences with no input from NASA and thus have not incorporated some of our high data-volume needs into their products. (With appropriate modifications and enhancements a system such as AVS, for example, could be extremely useful for EOS data analysis.)

High speed access to network-based data archives is essential to the long term development of USEFUL visualization tools, since tools that are starved for information to manipulate are useless.

CONNECTIVITY AND ACCESS TO COMPUTER RESOURCES

5. VIDEOCONFERENCING AND TECHNOLOGY

NASA should support the collaboration of scientists with computer experts to develop video teleconferencing and other methods of teleanalysis.

6. I/O TECHNOLOGY FOR GIGABIT NETWORKS

NASA should look into the problem of I/O technology for networks use, and determine which technology developments to support.

7. ALGORITHMS FOR PARALLEL PROCESSING

NASA should support the development of algorithms and new paradigms to effectively utilize the new parallel processing technology.

8. PORTABLE PIPELINE PROCESSING SOFTWARE

The Project Data Management Plan for each mission should include the task of making pipeline processing software portable and available to users.

ACCESS AND INTERFACE STANDARDS

9. MANAGEMENT SYSTEM FOR SOFTWARE TOOLS

NASA should support the development of a management system for software tools used in astrophysics applications. The management system should concentrate its attention on software rather than hardware, because hardware changes on a time scale of months whereas software requires a greater investment in time and dollars. It is often useful to separate strictly computational requirements (such as supercomputer hydro-code modelling) from analysis/display/visualization requirements.

NASA's 1989 NRA for Astrophysical Software Aids was a good start in this direction, but the program must be continued and expanded to meet the needs of the community, and there should be an on-line mechanism for providing information on the existence and range of applicability of these software and analysis tools. In effect, we need the astronomical equivalent of "Numerical Recipes". The user interface to this information should be as syntax-free as feasible.

A specific task is the development of a directory of astronomical software including a library of capabilities. This directory should have browsing capability and automatic links in hypertext.

10. ARCHIVING OF GROUND-BASED AND FOREIGN SPACE MISSION DATA

NASA should work with the NSF in encouraging the archiving of ground-based data sets and their access through the ADS. NASA should also encourage foreign space agencies to make their data available on-line, and it should consider which sounding rocket and airplane data sets are most needed for on-line access.

11. INTERFACE STANDARDS FOR DATA STORAGE

NASA should encourage the definition of I/O interface standards for both on-line and stored data to complement the present FITS (Flexible Image Transport System) standards for data transfer.

12. DATA TRANSFER STANDARDS

The FITS data transfer standards were adopted by the IAU to facilitate the easy transfer of data between diverse users. This concept is being eroded by the proliferation of de facto transfer standards inconsistent with FITS. NASA, through its FITS Office at GSFC, should require new projects to obtain IAU FITS Committee approval for requested modifications or variances in FITS.

13. STANDARDS FOR APPLICATIONS AND ANALYSIS SOFTWARE

NASA should encourage the development of such appropriate standards, perhaps starting with a workshop to which applications software experts and sophisticated astronomical users would be invited. It is desirable that applications and analysis software be written in a modular way to facilitate the stringing together of programs.

Data analysis systems of the future should be flexible and provide very simple methodologies for including user-supplied applications software. The IRAF package, in particular, does not readily permit users to add their own software.

Astronomers often need to intercompare heterogeneous data sets that now are best analyzed by different software packages -- i.e., VLA radio maps processed with AIPS and CCD images processed with IRAF. However, IRAF and AIPS are fairly mutually exclusive, except for the commonality of FITS.

14. ON-LINE DOCUMENTATION OF DATA SETS AND JOURNAL ARTICLES

NASA should support investigations concerning the most efficient methods for providing documentation of data sets, journal articles, and graphics into on-line data bases.

TRAINING

15. TECHNIQUE AND TOOL DEVELOPMENT AT UNIVERSITIES

NASA should continue to encourage the development of algorithms, data analysis tools, and panchromatic data analysis by individuals and small groups at universities. In particular, NASA should avoid the specialization and customization of research capabilities that disenfranchise people outside of the large Centers.

16. ENCOURAGING COLLABORATION BETWEEN COMPUTER SCIENTISTS AND ASTRONOMERS

While the ability to access, manipulate, and analyze astronomical data is increasingly dependent upon the technology of computer science, effective collaborations between astronomers and computer scientists are rare. We call attention to the clear need for the creation of interdisciplinary research opportunities to integrate the work of computer scientists with that of research astronomers. We therefore recommend that NASA create specific NRAs to support research efforts that combine the latest computer science developments (visualization, user interfaces, data storage) with the data analysis requirements of the astronomy community. University environments are the most fertile arenas for collaboration of computer scientists with astronomers.

17. DATA ANALYSIS, THEORY, AND RESEARCH WORK AT UNIVERSITIES

NASA should increase its support for data analysis, theory, and instrument development at universities.

SUMMARIES

DISCUSSIONS FROM FINAL PLENARY SESSION

Edward W. Ng
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On the last day of the workshop, a final plenary session was held to encourage discussions on cross-cutting or overarching topics not easily fit into the 5 Panel themes. Seven managers in NASA were asked to form an ad hoc panel to catalyze discussions. They are:

G. Riegler	Chief of Science Operations Branch, Astrophysics Division, NASA Office of Space Science & Applications
W. Hudson	Assistant Director for Spacecraft Systems, Space Directorate, NASA Office of Aeronautics, Exploration, & Technology (OAET)
P. Hunter	Manager for the High Performance Computing Initiative, OAET
G. Giffin	Manager for the Civil Systems Technology Initiative Program, OAET
M. Halem	Chief of Space Data and Computing Division, Goddard Space Flight Center (GSFC)
J. Dalton	Chief of Data Systems Technology Division, GSFC
J. Fanselow	Manager of Advanced Computer Systems and Technology Section, Jet Propulsion Laboratory

The panelists began with summary perspectives on the workshop. All expressed positive feedback about the workshop, mostly in the vein that this was a very healthy start to collectively involve scientists, technologists and NASA managers to define technology needs and to seek consensus towards a robust technology program for future missions. Throughout the workshop, the theme of user involvement received much coverage, with the emphasis that users should be involved in all aspects of information systems planning, development and operations. They were also pleased to see that the five panels attempted to explicitly define technology needs that are astrophysics-unique vis-à-vis those that are relevant to many space science disciplines. In the following we summarize other major issues raised and discussed in this final plenary session.

A.   MODELS OF INNOVATION

The paper by Denning contrasting linear or ladder models of innovation with cyclic models was frequently referred back to in several contexts. The linear model, which makes a linear path from requirements to technology without any iteration or feedback was asserted by several participants in the workshop to be the way that NASA runs its missions. It was generally agreed that Astrotech 21 should be planned and ultimately implemented following a cyclic model but in which the science objective is still

the ultimate motivation and guidepost for the design of the mission and the setting of goals for technology development.

Doty discussed another model, the technology opportunity model, which has motivated the HETE mission. Here science rationale is not the primary motivation and impetus for introducing technology. Rather a new technology becomes available. Its applicability to astrophysics can only be conjectured but it is nevertheless applied to observations. Many of the discoveries in high energy astrophysics and radioscience in the last half century represent the successful application of the technology opportunity model.

It seems to us to make more sense to allow for more than one paradigm. The way we had structured the workshop was specifically inviting people to educate us on the technology opportunities as well as on the scientific opportunities. The fact that it is scientific criteria that dominate in mission and instrument selection means that the mission has to turn into a science driven mission before it has a chance of getting selected.

B.   SYSTEMS ENGINEERING

The need for systems engineering was a recurrent theme throughout the workshop. Criticisms of the present situation ranged from the failure in use of system engineering tools, the lack of good system engineering specialists available to NASA and even the obsolescence of the systems technology discipline itself. It was claimed that no new methodologies had been introduced in the last 20 years. A splinter group for systems engineering was considered but did not actually form.

Sophisticated systems engineering capabilities are needed for implementing a cyclic style of innovation. If the behavior of the system cannot be characterized and the effects of alternative implementations easily evaluated, then there is no information on which to refine requirements, to explore new design approaches or to evaluate the impact of new technology.

C.   RAPID PROTOTYPING

The need for rapid prototyping is emerging strongly in the context of future mission needs. This is one aspect of implementing a cyclic approach to development where the second or third cycle would take place at the systems level. Rapid prototyping is needed to validate and thereby build confidence in the systems tools. It is also needed to reveal effects that are not modeled and establish the confidence for proceeding to the next stages of development.

D.   TESTBEDS

Testbeds are another aspect of carrying the demonstration and evaluation of a new technology to hardware. Testbeds provide a more comprehensive assessment of a technology than rapid prototyping. There was no specific discussion of the role of ground-based testbeds versus a space testbed or space demonstration.

E.   SUPERCOMPUTING

This is a topic discussed in several Panels. While a number of issues were identified, no consensus was arrived at the workshop. In general, the scientists feel that their present supercomputing needs are met by the NSF-sponsored supercomputing facilities. At the same time, the rapid advances in the capacity of mini-supercomputers with concurrent decline in costs give the scientists hope that future research groups will all have supercomputing capability dedicated to their special needs. However, some technologists cautioned that there would always be special needs pushing the limit of computing power, and that NASA should always plan for some institutional capability. They add further that NSF supercomputing will soon evolve to an operational phase when users may have to pay a substantial share of the costs. Halem announced the recent change of name and nature of the supercomputing center at Goddard Space Flight Center to Computational Sciences Center in order to better serve the science users in NASA. At the same time, JPL is also developing a supercomputing capability to serve the scientists within JPL as well as outside scientists associated with JPL's space missions.

F.   RISK AVOIDANCE

In view of the tremendous investment in space missions it is only appropriate that risk avoidance be given high priority. Unfortunately for a variety of reasons, risk avoidance has tended to encourage reliance on older technologies. Why is this and is there any way of introducing new technologies which offer tangible performance advantages without increasing risks?

Clearly, new technologies can introduce an increased element of risk to a project: greater uncertainties in development costs, in performance and in the potential for unanticipated failure modes. Where the performance gains are large enough, the new technology may be adopted despite these uncertainties as was the case with the charge coupled device (CCD) sensors introduced in the Hubble Space Telescope (HST). In most cases, it seems that the trade goes the other way and NASA's once deserved reputation for spearheading the introduction of new technology suffers.

In many cases these decisions represent rational decisions. If the objective of the mission were to introduce a new technology into space then the outcome may have been different of course. However, there are cases where the introduction of new technology is inhibited by NASA's policies and systems of incentives. Changes in these might be considered in order to foster a more aggressive introduction of new technology in space.

NASA's policies towards the funding of technology may be inhibiting the introduction of new technology into space. Technologies must be "mission enabling" to receive highest priority for funding by Code R. However, the user, typically a project manager, may consider that if the mission is entirely dependent on the technology then it is too risky. Restructuring of the mission so that a failure in the technology can be tolerated may undermine the case for funding. The skillful technology manager can sometimes navigate around this Catch 22 situation. However, adopting a criterion for funding a technology which is seldom of practical value is hardly good technology management.

New technologies which consist of systems of many individual components are particularly promising for reducing risk. The most obvious examples are in

computational systems but phased array communications antennas and interferometer arrays comprised of many telescopes and detectors also illustrate this approach.

G.   COST IMPACT

The impact of new technology on reducing the costs of implementing missions does not get as accurate a depiction as it should in assessing the impact of technology. Mission operations costs is one area of impact.

Reducing cost is not viewed as glamorous an enterprise as inventing a new capability. Furthermore, cost is seldom even viewed as a legitimate engineering parameter in advanced planning activities. It is introduced as an afterthought computed with experience based models which provide little guidance on how cost might be saved while still preserving capability.

H.   FITTING THE FUNDING NICHE

One revelation at the meeting (see Holcomb's chart) was the one-to-one mapping between Astrotech 21 and the ground computing and space processing elements of HPCI. GSFC is heading up the ground computing segment and JPL the space segment. There appears to be great potential for building a case for astrophysics support on this base.

Many technologies for astrophysical information systems may appear too specific for support under a general technology development program but too high risk for supporting under the agency's Science Operations program. Joint programs seem to be the best hope in these cases or alternatively an effort to distill the generic value from the program and through careful selection and planning to maximize the chances of success.

I.   CODES O AND R

Both Dalton of GSFC and Fanselow of JPL commented on the substantial overlap of the programs with work funded by Code O. This overlap should be viewed as an opportunity for synergistic developments with Code O funding activities that are potentially nearer at hand including rapid prototyping and Code R funding more basic research.

TECHNOLOGY NEEDS AND OPPORTUNITIES: SUMMARY

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INTRODUCTION

The goal of the workshop on Astrophysical Information Systems for the Twenty-First Century was to assist NASA in the development of a technology program for the astrophysics missions of the two-decade period from 1995 to 2015. NASA's specific objectives for the workshop were to develop an understanding of future astrophysical information systems requirements, the potential role of technology in meeting these requirements and areas where NASA technology investment might have impact. By establishing a comprehensive understanding of the relationships between mission requirements and technology, NASA is better able to set and update priorities for technology development.

In this summary, we review the astrophysical mission drivers for technology development, the existing NASA/OSSA science operations infrastructure and the existing and planned OAET technology programs. We then summarize the conclusions of the five technical panels and the ad hoc NASA management panel and present a synthesis of their conclusions.

NASA ASTROPHYSICS MISSIONS OF THE TWENTY-FIRST CENTURY

NASA's program of missions for the period 1995-2015 includes "panchromatic" observations throughout the electromagnetic spectrum from gamma rays to microwaves. Large throughput telescopes and interferometers will acquire simultaneously high spatial and spectral resolution data on celestial objects. These data will be pre-processed on board the spacecraft and then communicated to earth for further analysis. The reduction of vibrations with Control-Structures Interaction technology, and the active figure maintenance of optical surfaces will also require high performance space processors. Increases of many orders of magnitude in both the amounts of data processed in space and handled on the ground are expected, relative to the four Great Observatories planned for launch during the 1990s. Scheduling, acquisition, processing and utilization of these data will place unprecedented demands on the space and ground infrastructure. Further details on the missions of the New Century Program are given in the paper by Cutts and Newton.

SCIENCE OPERATIONS INFRASTRUCTURE

To support these needs, NASA will need to build on its current science operations infrastructure managed by the Astrophysics Division in OSSA. The current infrastructure consists of four components: (a) the Astrophysics Data System (ADS), which provides for the remote access and retrieval of data, and for the subsequent data analysis; (b) the science operations research program, consisting of guest observations and archival research by members of the Astrophysics community; (c) the science support services, which include multimission archive centers and science databases; and (d) the management function of mission operations and data analysis carried out at the center in

charge of the particular mission in question. Further details on the Science Operations infrastructure are given in the paper by Riegler.

NASA'S INFORMATION SYSTEMS TECHNOLOGY PROGRAMS

The Information Sciences and Human Factors Branch of OAET conducts a broadly-based technology program. The current program allocates substantial funding to Space Science including technologies for Earth Science, Astrophysics, Space Physics and Planetary Science. Resources for these program elements are associated with four technology thrusts: the Base Research & Technology program, the Civil Space Technology Initiative, the Exploration Technology Program and the High Performance Computing Initiative. Further details on program content are given in the paper by Holcomb and Erickson.

PANEL RECOMMENDATIONS

Recommendations on technology needs for Astrophysical Information Systems were addressed at the workshop by five panels: Mission Planning and Operations; Space-Borne Data Processing; Space to Earth Communications; Science Data Systems; and Data Analysis Integration and Visualization. Many panels embraced the concept of meeting the needs of a growing astrophysical program with evolutionary approaches for the medium term, looking to advanced technology to handle the challenges of the next century. Here we summarize the recommendations of the panels and explore common themes and interrelationships between the panel reports. The reader is referred to the individual reports for additional details.

The **Mission Planning and Operations Panel** identified some near-term technical improvements that have been under study for some time and provided a long range focus on developing a capability for telescience.

> Near-Term Technical Improvements. Specific suggestions were the development of distributable planning tools, distributed operations and data dissemination, improved link bandwidth and instrument access and direct communications to small experiments. The panel recommended obtaining access to several planning tools which are currently being developed by NASA for non-Astrophysics applications but which are potentially useful for Astrophysics applications.

> Long-Range Focus. The term "telescience" captures the essence of many of the capabilities sought in the longer term: real-time access to data from space-based observatories, real-time control of observations, coordinated panchromatic observations of objects, and ultimately an interrupt-driven capability for observing targets of opportunity. Automated protable multi-site scheduling systems, instrument modelling and health evaluation techniques are key elements in the evolution of a telescience capability.

The **Space-Borne Data Processing Panel** considered approaches for dealing with the data explosion in space, at the source, and identified space hardware and systems technologies that could contribute.

Space Hardware. Analog and digital processing of the output of heterodyne spectrometers and interferometers is a unique area of interest to astrophysics. High speed spaceborne general purpose processors and spacecraft data storage systems are comparable in importance but appear to be common needs with other areas of space science. Space-borne data processing hardware seems to have been lagging a decade or more behind ground technologies. Because of the power and mass limitations in space, there is a compelling need to reduce this time lag and develop more power efficient technologies to meet these needs.

Systems and Software. To ready these hardware technologies for early application in space, new tools will be needed for the early characterization of end-to-end systems. Complex multi-processor, fault tolerant systems will demand new approaches, including tools for concurrent hardware and software development. Systems for permitting multilevels of reliability in large complex systems are required if costs are to be contained.

Development Methodology. New approaches to developing space hardware, including wider use of simulation and rapid prototyping, are recommended in order to accelerate the pace of introduction of new technologies into space.

The **Space-to-Earth Communications Panel** considered the issue of handling data in increasing volumes and also delivering the data in the most efficient fashion to the ultimate user. The current and projected space network is not being scoped to accommodate these needs and would have even greater difficulty coping with coordinated panchromatic observational programs and coordinated observations of targets of opportunity. Various approaches to meeting these needs are advocated.

Evolutionary Approaches To Be Explored. These include new forms of communications networks based on the ATDRSS and ACTS architectures and advanced data compressor and modulator/demodulator technologies. Space-borne optical communications technology is needed for the high bandwidths needed by some of the missions considered. The continued development of Ka Band agile multi-access communications systems will play an important complementary role in allowing our space-based networks to more closely resemble the switching capabilities of the advanced ground-based networks. New technologies such as high temperature superconductivity may have an important impact on these future systems.

The **Science Data Systems Panel** explored three issues: participation in national technology development programs; development of astrophysics-specific technologies; and evolution of the Astrophysical Data System.

Participation in National Technology Development Progams. In four areas, networking; supercomputing; data storage; and data distribution media, NASA is either a user or participant in larger national efforts involving other government agencies and industry. NASA should take the posture of a smart user or a proactive advocate and participant in technology development such as the High Performance Computing Initiative. NASA should develop the proper infrastructure for cost effective multidiscipline applications of these technologies.

Astrophysics-Specific Technologies. Certain technologies such as data compression, algorithms for modelling stellar dynamics and software management are specific to astrophysics and NASA will need to take the initiative in solving these problems.

Astrophysics Data System Evolution. The fundamental paradigm of the ADS with a user at a workstation interacting with a set of distributed services will not change in any way that is forseeable. However, continuing evolution is expected in the hardware platforms, network protocals, data storage/archive systems and user interfaces. The more revolutionary changes sought here are direct readout from sensors to users, bypassing the standard processing and archiving; the implementation of knowledge-based technologies for assimilating data; and new technologies for remote communications between scientists. This implies new capabilities in both Space-to-Earth Communications and Mission Planning and Operations.

The **Data Analysis, Integration and Visualization Panel** probed the issues of collecting, sorting, assimilating and interpreting the large amounts of data expected from future missions. Four areas in particular were highlighted:

Knowledge-Based Techniques. If the efforts to provide the technologies and infrastructure to acquire, transmit and store science data are successful then the user will be presented with an unprecedented challenge to effectively utilize the data. New techniques are required. NASA should invest in the development of knowledge-based techniques for data access, data analysis and interpretation, and ultimately for learning. New visualization and comprehension techniques for N-dimensional data sets are needed.

Networking and Access to Computer Resources. The panel corroborated the conclusions of panel 4 that both access to

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supercomputer and networking resources is needed, and reinforced the needs for Astrophysics specific tools to provide that access.

Access and Interface Standards. The panel also stressed the need for interface standards and software portability. This will enhance the range of data and tools available in the evolving Astrophysics Data System.

Training. The role of vigorous university-based programs in developing data analysis tools was emphasized.

SYNTHESIS

A three part vision of the future emerged during the workshop and was elaborated upon by the five panels:

Open Communications. Near-continuous high-speed two-way communications would allow new observations to be scheduled easily without having to undo all previously scheduled discrete events, and to allow data to be distributed to multiple users directly via data distribution satellites.

Transparent Instrument and Observatory Observations. Each observatory or instrument is treated as a node on a large NASA-wide network. This will allow a common approach to ground-space communications, and permits the possibility of instruments broadcasting news of interesting events (targets of opportunity) which could then be picked up, and possibly acted upon, by other instruments.

Sorceror's Apprentice. New information processing methods including knowledge-based technologies would be brought to bear to select, analyze and ultimately "learn" from the vast volumes of data returned from the missions and thereby enhance the ability and effectiveness of the researcher in exploiting the advances in information acquisition technology.

The approach to realizing this vision has several aspects, outlined below:

Near-term vs. Long-term Development. Needs and opportunities were identified for both near-term evolutionary developments and also for long-range developments involving more ambitious and higher risk technologies. The Astrophysics Data System is likely to be the focal point for near term developments with upgrades to the existing communications infrastructure and the introduction of distributed processing.

Astrophysics Specific vs. Space Science in General. Space astrophysics shares some needs for technology with space science in general and with the broader commercial market in information technology. However, some needs are astrophysics

specific. NASA will need to assure access of its astrophysics users to commerically-developed technologies, participate in national programs to develop supercomputer networks and new information system technologies, and will need to specify the development of those key technologies that are not receiving support from other sources.

<u>Space Based vs. Ground Based</u>. Astrophysics has needs for processing technologies for the space-based segment including high speed space processors and storage, correlators, acousto-optical filters and systems software development aids. Specialized development is also needed for the ground-based segment.

<u>Space-to-Earth Communications</u>. Orders of magnitude improvement in capability are needed and are possible in the longer term through the introduction of both optical communication and "agile-pointing" Ka band phased array hardware.

<u>Development Methodology</u>. Traditional development methods will not be able to keep pace with future needs, hindering the rapid introduction of new technologies into ground and space systems. Needed innovations include simulation techniques for anticipating the performance characteristics of new hardware before building it, and rapid prototyping for building it, and rapid prototyping for delineating and corroborating requirements. Thus, the traditional linear or ladder model of development must be replaced by a "cyclic" or "spiral" model which permits iterative development on a much shorter time scale than recent practice with space hardware.

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15. Supplementary Notes

16. Abstract In 1989, the Astrophysics Division of the Office of Space Science and Applications initiated the planning of a technology development program, Astrotech 21, to develop the technological base for the Astrophysics mission developed in the period 1995 to 2015. An infusion of new technology is considered vital for achieving the advances in observational technique needed for sustained scientific progress. Astrotech 21 was developed in cooperation with the Space Directorate of the Office of Aeronautics and Space Technology, which will play a major role in its implementation. The Jet Propulsion Laboratory has led the planning of Astrotech 21 for the agency.

The Astrotech 21 plan was developed by means of three series of workshops dealing respectively with: Science Objectives and Observational Techniques; Mission Concepts and Technology Requirements; and Integrated Technology Planning. Traceability of technology plans and recommendations to mission requirements and impacts was emphasized. However, "breakthrough technologies," whose ultimate applications cannot be anticipated, were also considered. Proceedings documents are published for each workshop. A summary report has also been prepared which synthesizes the results of the planning effort.

The Astrophysical Information Systems Workshop was one of the three Integrated Technology Planning workshops. Its objectives were to develop an understanding of future mission requirements for information systems, the potential role of technology in meeting these requirements, and the areas in which NASA investment might have greatest impact. Workshop participants were briefed on the astrophysical mission set with an emphasis on those missions that drive information systems technology, the existing NASA space-science operations infrastructure, and the ongoing and planned NASA information systems technology programs.

Program plans and recommendations were prepared in five technical areas: Mission Planning and Operations; Space-Borne Data Processing; Space-to-Earth Communications; Science Data Systems; and Data Analysis, Integration and Visualization. The workshop also recommended that NASA introduce new approaches to the implementation of its future astrophysics program. These included radically improved communications and scheduling; transparent instrument and observatory operations; and a cyclical research and development methodology.

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