N93-27043

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.

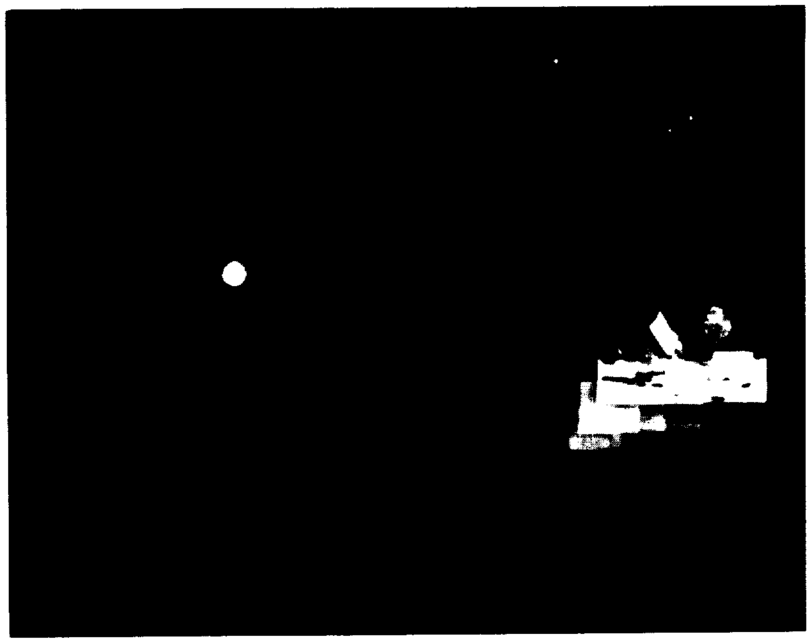


Figure 1. Imaging interferometers can provide a higher angular resolution capability than conventional imagers. One objective of an optical interferometer is to resolve planets around nearby stars.

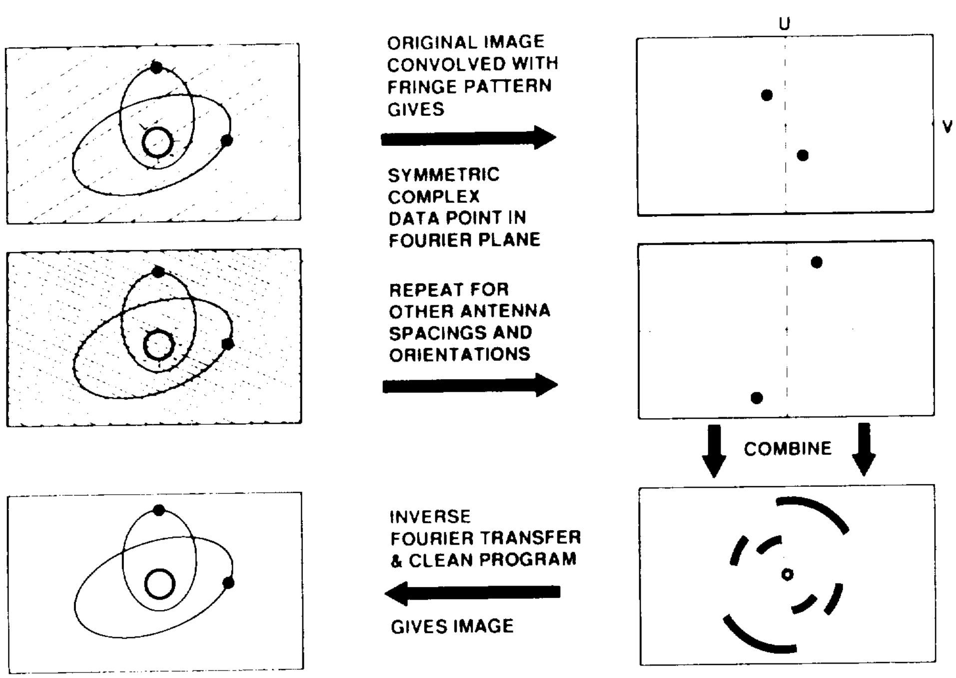
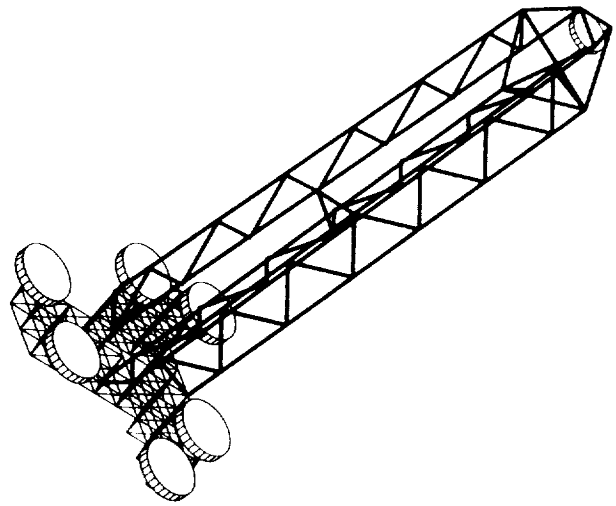


Figure 2. A high resolution image from an optical interferometer is reconstructed from a number of interferograms obtained with different telescope array orientations and spacings.

a)



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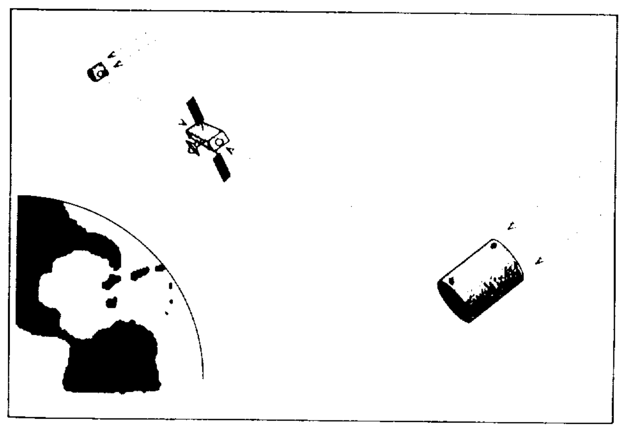


c)

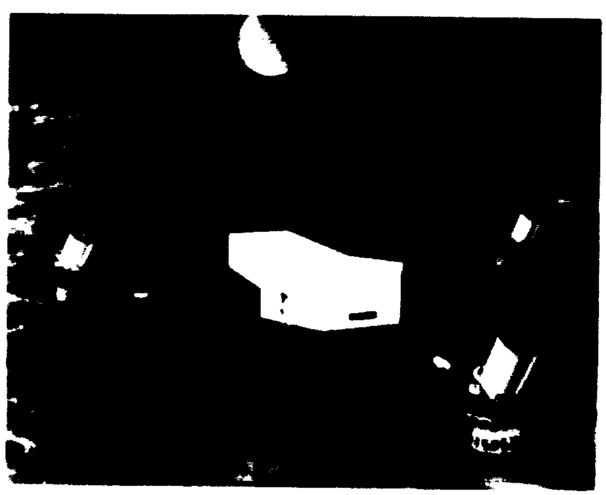


Figure 3. Alternative implementations of a space optical interferometer a) on a large space structure; b) on multiple spacecraft; and c) on the lunar surface.

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.

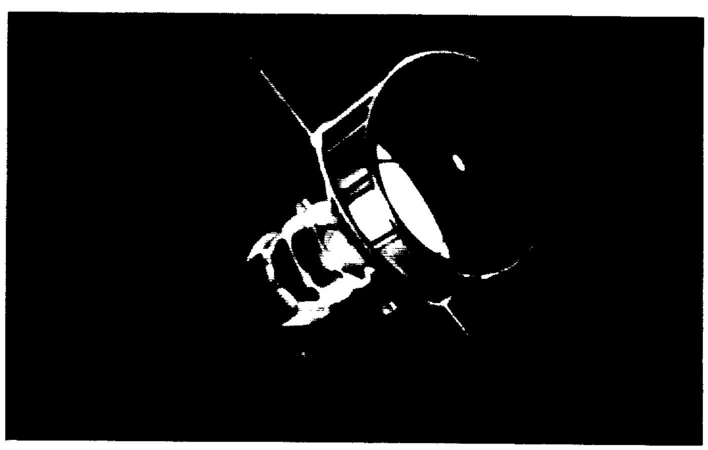
a) Submillimeter Missions

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.

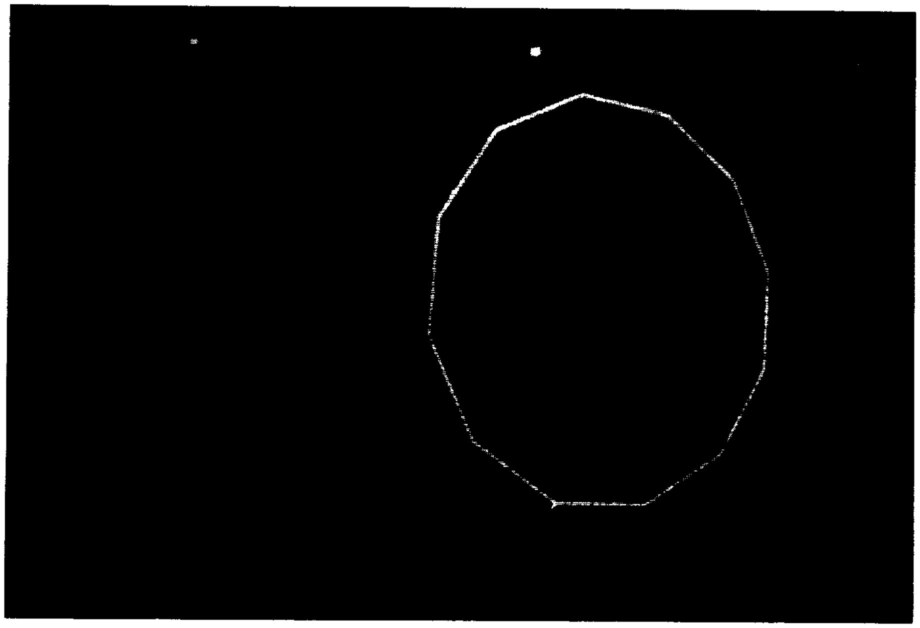
c) High Throughput-High Energy Missions

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.

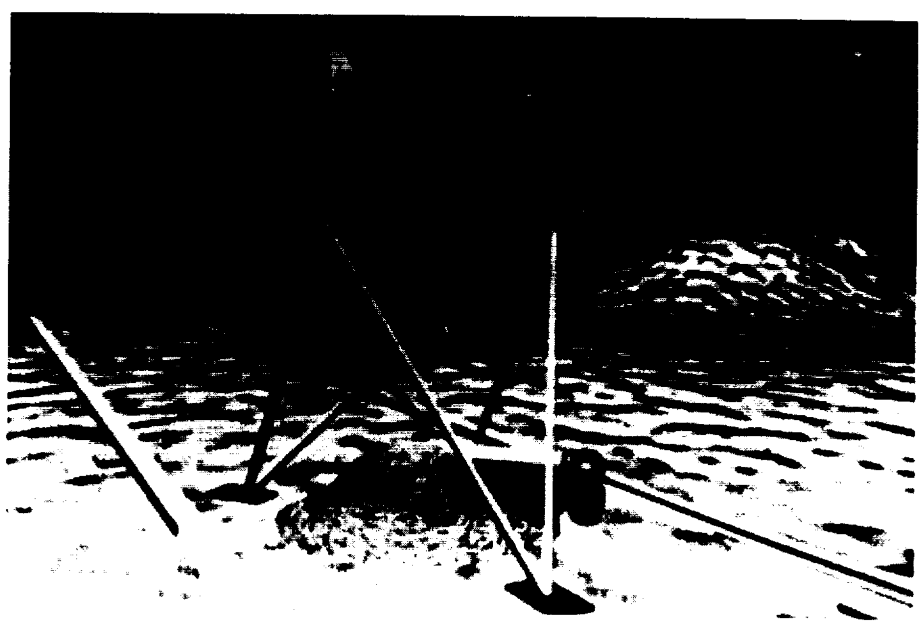
Under the oversight of the High Energy Astrophysics Management Operations Working Group (HEAMOWG), the Marshall Space Flight Center will be carrying out pre-phase A studies of these X-ray mission concepts. The importance of these studies to technology definition can be appreciated in the context of the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

The contributions of a number of individuals to the Astrotech 21 planning process are acknowledged. They include but are not limited to A. Bunner, L. Caroff, J. Fordyce, R. Gershman, G. Giffin, W. Hudson, P. Joss, R. Key, D. Lawson, E. Ng, A. Pappano, C. Pellerin, G. Riegler, R. Stachnik, P. Swanson and J. Weiss.

The work described in the paper was conducted at the Jet Propulsion Laboratory/California Institute of Technology under a contract with the National Aeronautics and Space Administration.

References

1. Space Science in the Twenty-First Century: Imperatives for the Decades 1995 to 2015, Report of the Study Steering Group, Space Science Board, Washington, D.C., National Academy Press, 1988.

2. Astrotech 21 Space Infrastructure Handbook, Jess Fordyce Editor, Jet Propulsion Laboratory, Internal Document JPL D-7430, June 1990.

3. Astrotech 21: Terahertz Technology for Space Astronomy in the 21st Century, Proceedings of the First International Symposium on Space Terahertz Technology March 5-6, 1990, pages 69-73, University of Michigan, 1989.

4. The Next Generation Space Telescope, Proceedings of a Workshop held at the Space Telescope Science Institute, Baltimore, Maryland, 13-15 September, 1989, published and distributed by the Space Telescope Science Institute, 1989.