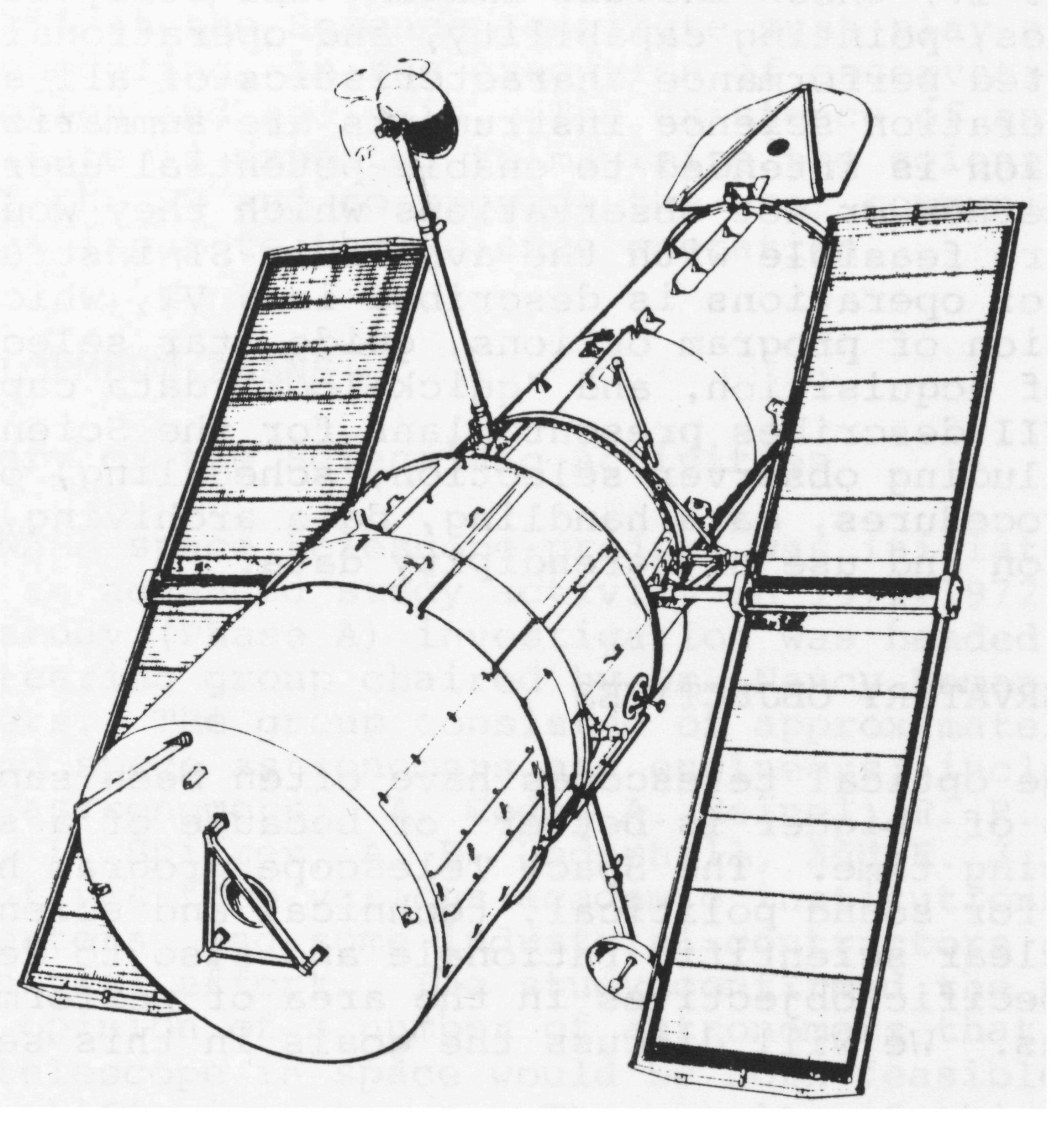
THE SPACE TELESCOPE OBSERVATORY

by

John N. Bahcall
Institute for Advanced Study, Princeton, N.J. 08540

and

C. R. O'Dell
Marshall Space Flight Center, Huntsville, Ala. 35812



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I. INTRODUCTION

The purpose of this review is to provide a convenient guide to the expected characteristics of the Space Telescope Observatory for astronomers and physicists. We have tried to provide enough detail so that a professional scientist, observer or theorist, can plan how the observatory may be used to further his observing program or to test theoretical models. Further detail is available in NASA documents that are referenced throughout this report.

The plan of this review is given below. The general objectives of the ST observatory are summarized in § II. The plans for the development of the observatory are described in § III; this section includes a brief history of the scientific activities; an account of the scope of the present program; a summary of the major responsibilities of the contractors; and a list of the project milestones. The overall performance characteristics of the observatory are given in § IV; these include imaging and stray light characteristics, pointing capability, and operational access. The expected performance characteristics of all six of the first-generation science instruments are summarized in § V. This section is intended to enable potential users of ST to decide whether or not observations which they would like to perform are feasible with the available ST instruments. The mode of operations is described in § VI, which includes a discussion of program options, guide star selection, methods of acquisition, and "quick-look" data capabilites. Section VII describes present plans for the Science Institute, including observer selection, scheduling, observational procedures, data handling, data archiving, and the acquisition and use of serendipity data.

II. OBSERVATORY OBJECTIVES

Large optical telescopes have often been supported on the basis of "bigger is better" or because of a scarcity of observing time. The Space Telescope program has had to provide (for sound political, technical and scientific reasons) a clear scientific rationale and also to develop a set of specific objectives in the area of performance and operations. We will discuss the goals in this section.

The performance goals can be stated as follows: Development of a telescope of at least 0.1 arcseconds resolution, capable of integrating images for 10 hours of observation, reaching a stellar magnitude of 27 m_V at a

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signal-to-noise ratio of 10 in 4 hours, able to perform surface brightness photometry and to operate over the entire range of wavelengths from about 1150 Å to 1 mm. The expected operating lifetime of the ST Observatory is at least fifteen years.

The operations goals are less quantitative. Obviously, we must be able to control and receive data from the observatory. We must be able to point to any region of the sky and place the correct astronomical objects in the field of view of a scientific instrument, even if the entrance aperture is the same size as a stellar image. We must control the amount of light which enters the Space Telescope from the Sun, Earth, and Moon so that stray light does not become brighter than $23^m/\square''$ (visual), thus permitting the Space Telescope to be used for measurement of faint sources throughout much of each orbit.

An independent Space Telescope Science Institute will be responsible for the scientific aspects of operations. This means that the Science Institute must play an integral role in scheduling, in the execution of observations and in data reduction and analysis. The existence of an independent institute is expected to maximize the scientific usefulness of the ST and to provide the user community with fundamental input to the science operation.

III. DEVELOPMENT PLANS

A. History of the Scientific Activities

The NASA space telescope project was initiated officially by an advanced study activity in 1971-1972. This advanced study (Phase A) investigation was headed by a science steering group chaired by Dr. Nancy Roman of NASA Headquarters. The group consisted of approximately ten optical and space astronomers and engineers, including the following astronomers: A. Code, A. Meinel, C. R. O'Dell, J. B. Oke, L. Spitzer, A. B. Underhill, and E. J. Wampler. Representatives from various academic institutions, several NASA centers, and some industrial contractors assisted in this initial effort. The study confirmed the previously-expressed opinion of a number of astronomers that a large orbiting telescope in space would be both feasible and of great scientific importance. The results of this study are summarized in an interesting form (for the ST aficionado) in NASA Technical Memorandum TMX-64726, the *Large Space Telescope Phase A Final Report, Vol. I* (1972); this document contains the justification for many of the decisions that have shaped the ST program.

The scientific definition (Phase B) study was led by Dr. C. R. O'Dell of Marshall Space Flight Center (and the University of Chicago). The study was conducted during the years 1973-1976. The scientific goals, mode of operation, and preferred instruments were defined during this Phase B activity by a panel of fourteen competitively chosen scientists who served on a space telescope working group. The scientific members of this working group included: J. N. Bahcall, R. Bless, A. Boggess, E. M. Burbidge, A. Code, R. Danielson, G. Field, L. Fredrick, G. Neugebauer, R. Noyes, C. R. O'Dell, N. Roman, L. Spitzer, Jr., and R. West. A readable summary of some of the early Phase B scientific and technical considerations are contained in the document Large Space Telescope - A New Tool For Science (1974).

The final Design and Development activities (Phase C and D) began officially in 1977. These activities will continue until the launch of the ST. The identification of the scientific requirements for the ST observatory is the responsibility of a Science Working Group (SWG), which is again headed by C. R. O'Dell. There are eighteen members of the SWG including principal investigators of the instrument development teams, the data and operations team leader, telescope scientists, and interdisciplinary scientists. The individual members of the SWG are listed in Appendix A. The SWG is assisted by individual instrument teams consisting of some 52 scientists and engineers under contract to NASA, which represent 26 separate academic or research institutions. The ST Project Manager has established several other working groups that assist in the design and development of the ST Program. The working groups which are of particular relevance to science operations include the Data and Operations Team, the Software Working Group, and the Missions Operations Working Group. In addition, the European Space Agency (ESA) has approximately 12 scientists and engineers working on their science instrument (the faint object camera).

B. Scope of the Present Program

The basic program policy is defined by NASA Headquarters, which also allocates the resources that can be used for developing ST. Several people at NASA Headquarters have a continuing, frequent responsibility for helping to develop ST policy. These include the Associate Director for Space Science (Dr. N. Hinners until April 1979), as well as W. Keller, B. Norris, and N. Roman.

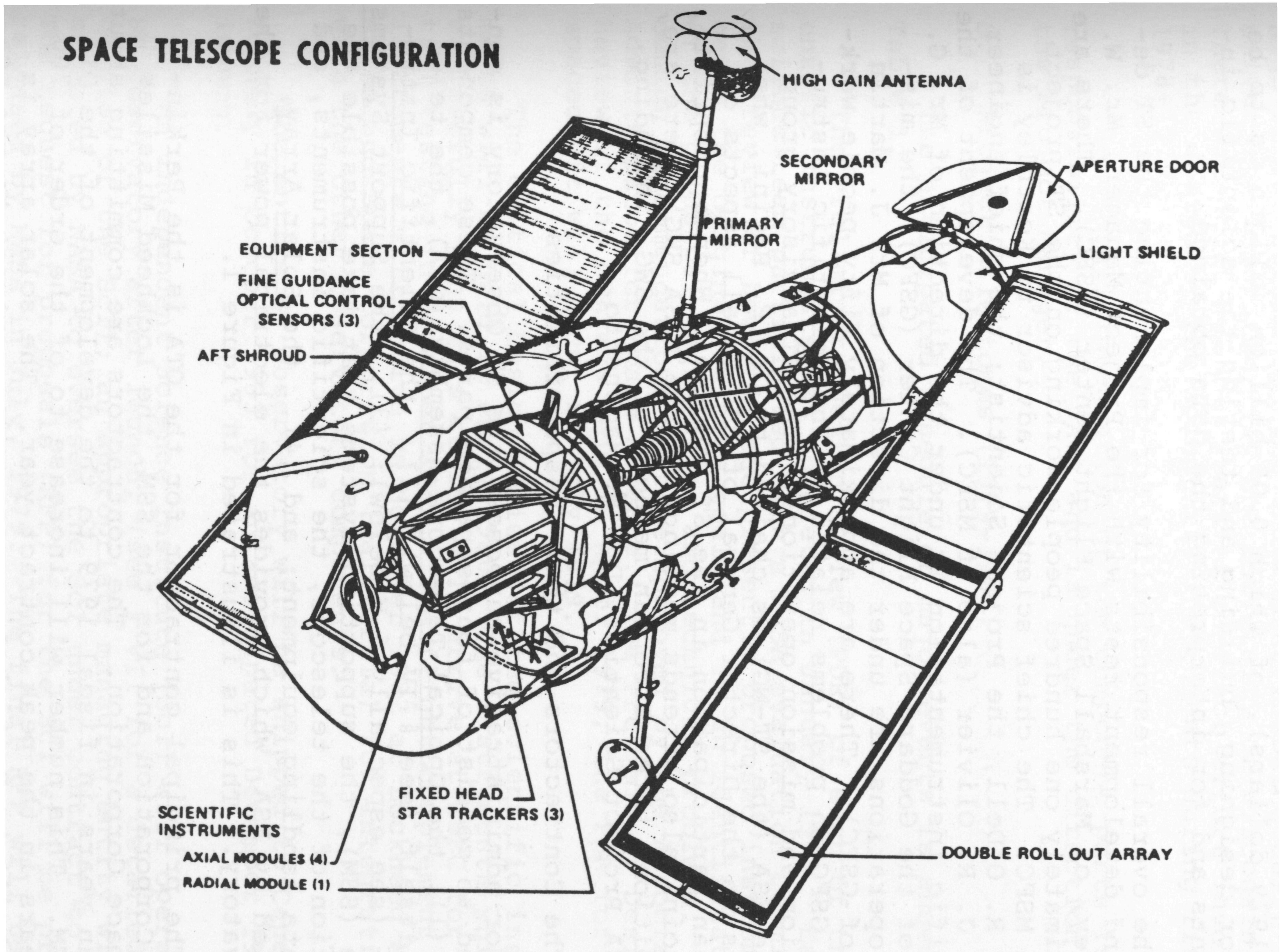

Figure 1. Space Telescope Configuration

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The total program is expected to cost 0.44 billion dollars (1979 dollars), of which 0.09 billion dollars is to be used for designing, building and testing the scientific instruments and for interpreting the data obtained.

The overall responsibility for implementing the ST design and development rests with the Project Manager, Mr. W. Keathley, of Marshall Space Flight Center (MSFC). There are approximately one hundred people working on the ST project at the MSFC. The chief scientific advisor to Keathley is Dr. C. R. O'Dell, the Project Scientist; the chief engineer is Mr. J. R. Olivier (also of MSFC). The development of the scientific instrumentation is under the direction of Mr. G. Levin of the Goddard Space Flight Center (GSFC); the missions operations are under the direction of Mr. J. Martin (also of GSFC). There are approximately fifty people working at GSFC on problems related to the scientific instrumentation and mission operations. The ST advisory group for the ESA (the ST-WG) is chaired by Dr. F. Pacini, who reports to the Director General of ESA on all aspects of European participation in the ST program. When appropriate, Dr. Pacini also attends meetings of the NASA SWG; there are, in addition, three European members of the SWG, including the ESA Project Scientist, Dr. F. Macchetto.

C. The Contractors and their Responsibilities

For administrative purposes, the ST Observatory is considered to consist of four separate parts. These components are: (1). the Optical Telescope Assembly (OTA), the telescope itself (see § IV below); (2). the Scientific Instruments, (see especially § V below); (3). the Support Systems Module (SSM), the supporting systems that make possible the operation of the telescope, the scientific instruments, and the data handling equipment; and (4). the Solar Array, supplied by ESA, which provides the electrical power for the observatory. This is illustrated in Figure 1.

The principal contractor for the OTA is the Perkin-Elmer Corporation and for the SSM, the Lockheed Missiles and Space Corporation. The contractors are committing about 420 man years in fiscal 1979 to the development of the OTA and SSM. This number will increase to of the order of 700 man years in the peak contract year. The solar array is being built by British Aerospace under contract to the ESA. The scientific instruments were selected in 1977 by NASA after an extensive competition and peer review, which also made use of the Phase B recommendations. Contracts with various suppliers have been negotiated by NASA and the Principal Investigators of the instruments. In one case, the High Speed Photometer, the instrument is being built in a university laboratory (at the University of Wisconsin). There are about 300 man years of contract effort involved in the design of the scientific instruments during fiscal 1978-1979.

The overall integration of the component parts is the responsibility of the NASA and is under the direction of the Project Manager.

D. Project Milestones (1979-1984)

The anticipated schedule of major events is shown in Table 1.

The Preliminary Design Review (PDR) of each of the scientific instruments was completed in January 1979. Each science team participated with a NASA evaluation committee in a review of how well the presently proposed instrument meets the original science goals and in an identification of the principal engineering and technical problems. The design recommendations must be approved by the Associate Administrator for Space Science. The Preliminary Design Review of the OTA was held in April 1979; the PDR for the spacecraft will occur in July 1979.

The Critical Design Reviews of the scientific instruments will be held in early 1980. The instruments which successfully pass this review will arrive at GSFC for initial testing in December 1981. The flight complement of instruments will arrive in November 1982 at Lockheed Missiles and Space Corporation (California) for integration with the other observatory components.

The entire ST observatory will be shipped to Cape Kennedy in October 1983 for an anticipated December 1983 launch.

An independent Science Institute (ScI) will operate the ST Observatory after launch, (see § VII for a detailed discussion of the ScI); an appropriate managing entity will be selected by NASA to oversee the ScI under contract to NASA. The request for proposals (RFP) for the ScI will be prereleased by NASA in July, 1979. The final RFP will be released by NASA in November 1979 (or somewhat later). Requests for clarifications and suggestions related to the

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Table 1. Major Milestones (Tentative): 1979-1894

Year	Month	Event
1979	January	Preliminary Design Review (PDR's) of Science Instruments
	April	PDR of the Optical Telescope Assembly (OTA)
	July	PDR of the spacecraft Pre-release of the Request for Proposal (RFP) of the ScI
	November	RFP for the ScI
	February	ScI proposals submitted
1980	January-April	Thermal Studies of the Instruments
	March	Critical Design Review
	May	RFP for the Combined Overall Ground System (COGS)
	November	ScI contract award
1981	March	COGS contract award
	December	Instruments arrive Goddard Space Flight Center (GSFC); begin testing.
1982	June	COGS hardware available for installation in ScI
	November	Science Instruments arrive Lockheed (California); mated to OTA
1983	September	Entire COGS available
	October	ST Observatory shipped to Cape Kennedy

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RFP may be submitted to NASA prior to the final release date. The proposals to manage the ScI at a designated site will be submitted to NASA in February 1979. It is expected that the ScI contract award will be made in November 1980.

The Combined Overall Ground System (COGS) will be supplied by a contractor to be selected by NASA by about March 1981. The COGS contractor will develop, for both the ScI and the Science Support Center (SSC) at GSFC, the following subsystems: major hardware (including automatic data processing equipment and operational consoles); software systems (except that developed by the PI's or ScI); and system engineering and integration. The COGS hardware for the ScI will be ready for installation in the Institute by June 1982. The entire COGS will be completed by September 1983.

E. Postlaunch Activity

After launch, the ST science program will be conducted by the Science Institute, which will operate (see § VII) in much the same way as do other national observatories and laboratories in the United States.

The ST may be visited from time to time, for maintenance and refurbishment, by Space Shuttle personnel. It is estimated that every two or three years, at least, repairs and maintenance will be carried out by a space-suited astronaut. Existing instruments may be replaced by new instruments. In addition, many support subsystems are replaceable in orbit. The ScI, with appropriate NASA headquarters support, will take the lead in encouraging the development by the outside scientific community of new instrumentation for the ST. Approximately every five years, the ST Observatory may be returned to the ground with the aid of the Space Shuttle for major refurbishment.

IV. PERFORMANCE OF THE OBSERVATORY

A. Imaging Performance

The true diffraction-limited telescope exists only in theory; any real telescope has some imperfections. In the Space Telescope program, the performance goals were brought as close as practical to the theoretical limit; any further increase in performance would cause the cost to rise rapidly. It is expected that the Ritchey-Chrétien optical system will produce on-axis images with the point spread func-

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tion shown in Figure 2. Images of this quality will be guaranteed throughout ten hours of exposure, which will be about 24 hours of clock time.

The Ritchey-Chrétien optical system produces excellent quality images over a large field of view. At large distances from the optical axis astigmatism begins to become important, although the images are very narrow in the sagittal or tangential surfaces. Figure 3 shows the change of the image radius (the radius containing 70% of the energy) across the field of view. The focal surface has been divided so that the central region feeds the radial scientific instrument bay, while the remainder of the inner region is shared by the four axial scientific instruments. The outer astigmatic region is used by the Fine Guidance Sensors for providing guiding signals from field stars and for performing astrometric measurements. The reimaging optics of off-axis instruments are capable of forming stigmatic stellar images.

Space Telescope optical performance has been specified at the same wavelength as it will be tested, λ6328 Å. The performance at longer wavelengths should monotonically and quickly approach the diffraction limit; at shorter wavelengths, the improvement in image quality that is expected eventually becomes offset by the fact that the imperfections in the mirrors become larger fractions of these smaller wavelengths. Exactly where this transition from improvement to degradation occurs will not be certain until we know the final characteristics of the finished mirrors. We expect that below the transition wavelength the images will be approximately constant in size down to about 1200 Å.

B. Stray Light

In its low earth orbit (from 500 to 600 km above the earth's surface), the Space Telescope will be moving rapidly between conditions of direct sunlight and earthlight into night operation. In order to make maximum use of each orbit, Space Telescope will employ an internal light baffle system that will diminish the stray-light effects to acceptable levels. The specification calls for stray light to be no brighter than $23^m/\square''$ (Visual) whenever the distance from the sun is $\geq 50^\circ$, or $\geq 70^\circ$ from the bright limb of the earth or $\geq 15^\circ$ from the full moon. This level was set recognizing that the zodiacal light will be the primary source of background radiation and that it diminishes to a surface brightness of $23^m/\square''$ (Visual) for two small regions in the antisolar hemisphere.

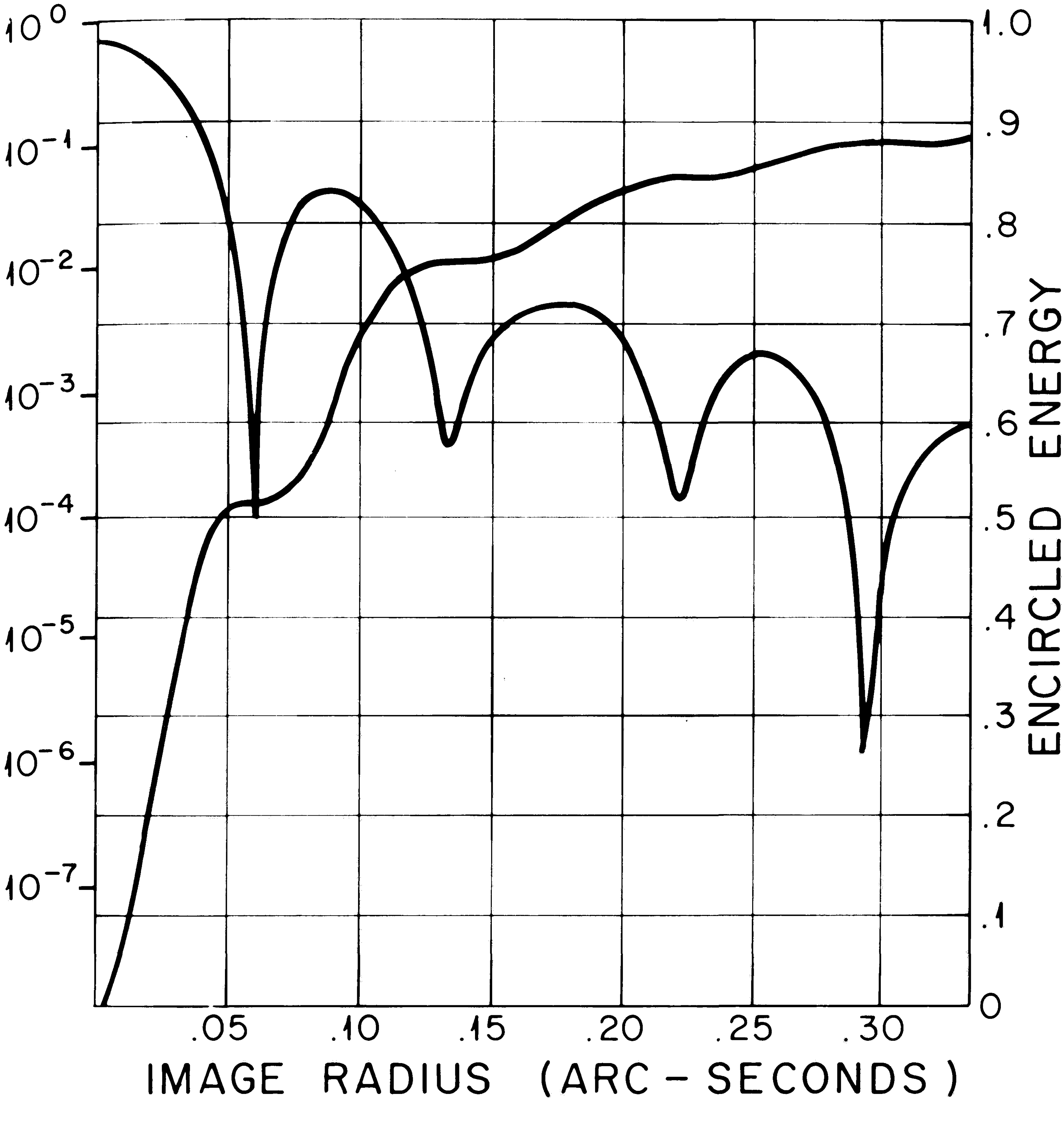

Figure 2: The expected optical performance (λ6328Å) is illustrated in terms of the image surface brightness distribution and the encircled energy. The central obscuration and deviations from perfect mirror figure and alignment have been incorporated in these predictions.

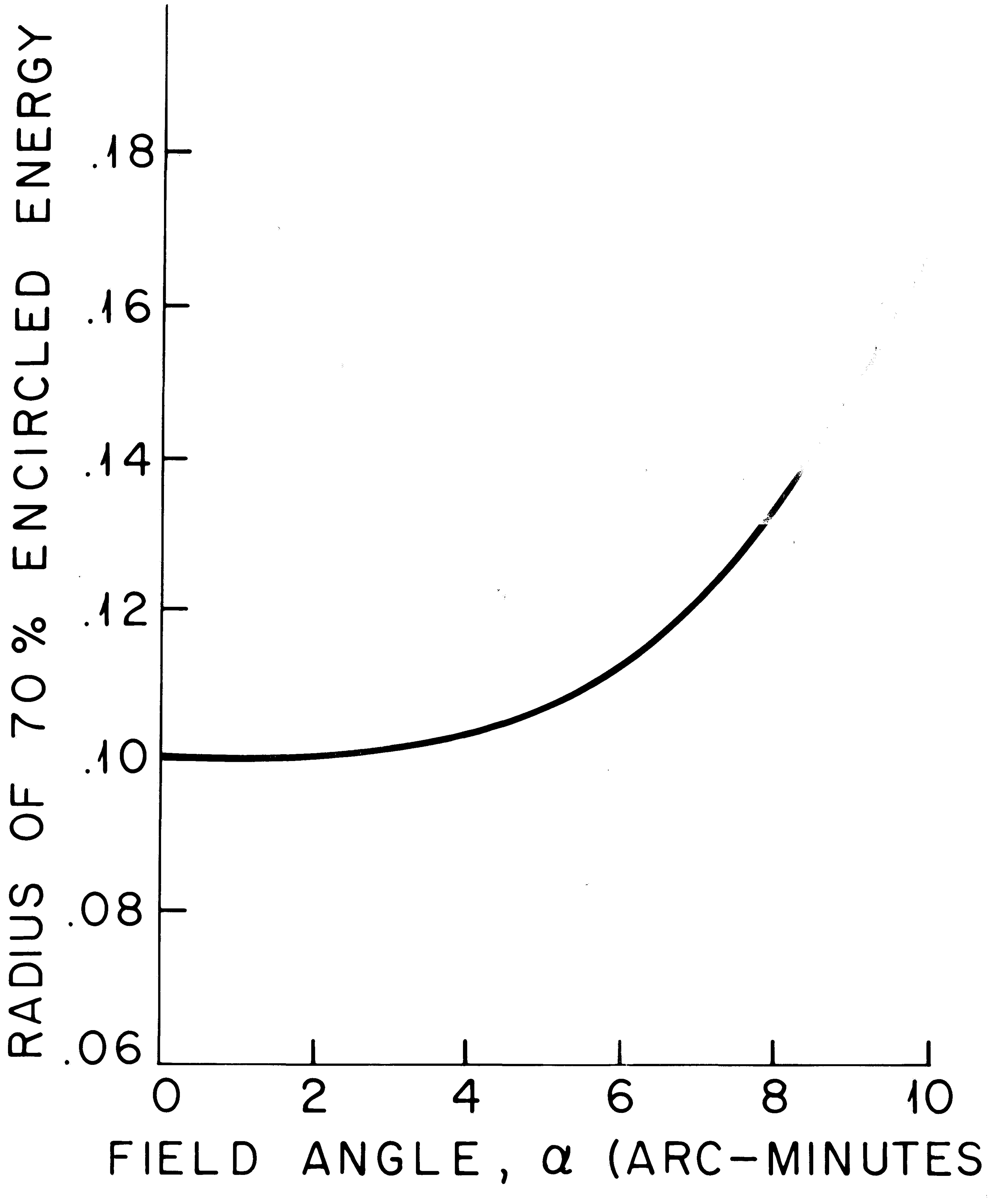

Figure 3: The variations of the image quality as a function of off-axis distance are shown for the expected flight conditions.

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This day/night pattern, combined with blocking of parts of the sky by the Earth, gives a definite seasonal pattern to the periods when the faintest objects can be observed.

C. Pointing Capability

Space Telescope has three sources of information on its orientation: the Rate Gyroscopes, the Star Trackers and the Fine Guidance Sensors. Since the primary goal is the prompt and accurate acquisition of preselected guide stars, all three sources of information are used when Space Telescope is pointed to a new object. The slewing rate is determined by the reaction wheels that are used and is specified to allow movement to an object 90° away in no more than 20 minutes, including angular acceleration and deceleration, with the reference frame provided by the Rate Gyroscopes. The Star Trackers then use bright stars to determine the pointing to a few arcminutes, which is sufficient to place the guide stars in the field of view of the Fine Guidance System. Following a scan to select the correct guide star, the guide-star images are put through a 1" aperture and fed to an interferometric device which gives the fine error signal that results in the overall guiding stability of 0.007" rms. The positioning of the Fine Guidance Sensors can be set to an accuracy of 0.01".

D. Operational Access

Operational control of Space Telescope will come from the ground and the scientific information from the observatory will be sent to the ground; a two way communication link must be established. This will be done using antennae on both the ground and the spacecraft; a pair of geosynchronous relay satellites, the Tracking and Data Relay Satellite System (TDRSS), will allow radio-wavelength "viewing" of the Space Telescope for about 85% of each orbit. The capabilities of this system are finite and there are many potential users. It is expected that commands can be sent to Space Telescope about 20% of the time. Data will be stored on-board the Space Telescope on tape recorders or sent directly to the ground. In any event, it is expected that a transmission rate of one megabit/second will be available about 20% of the time and four kilobits/second for about 70% of the time. These constraints impose important but not severe restrictions on the process of scheduling observations. Real-time control of the Telescope will not be possible except for small corrections in positioning, although pre-programmed options can be included if required for special observations.

V. THE SCIENCE INSTRUMENTS

There are six first-generation science instruments that are scheduled to be included in the ST Observatory from the time of its launch through the first few years of ST operation in orbit. The Wide Field/Planetary Camera is the radial bay instrument to which the central 3 arc-min of the f/24 focal surface is relayed by a pick-off mirror. There are four axial bay instruments: the faint object camera, the faint object spectrograph, the high resolution spectrograph, and the high speed photometer. The four axial bays view the unvignetted field at distances of 3 arc-min or greater off-axis. Compensation for astigmatism and field curvature of the Optical Telescope Assembly is achieved within the scientific instruments. Also, the Fine Guidance System can be used for astrometric observations, an effective sixth instrument. The ST project has made certain that all aspects of the Observatory are consistent with the possible future inclusion of an infrared instrument operating anywhere in the range from 1 μ to 1 mm. The entrance apertures of all of the instruments are effectively located in the focal plane of the telescope, which has a scale of 3.58 arcseconds per millimeter. The four axial bay configurations are modular and can be exchanged one for the other. The typical weight of an axial bay instrument is about 700 pounds with dimensions of 0.9 by 0.9 by 2.2 meters; the Wide Field/ Planetary Camera is somewhat smaller and lighter. All instru ments will draw of the order of 110 to 150 watts during observations. They are designed so that removal, or installation, of a new instrument can be achieved in-orbit by a suited astronaut operating from the Space Shuttle.

We describe below the expected basic performance characteristics of all six of the first-generation science instruments. The cited characteristics are, in most cases (see references to Tables 2-7), minimum performance characteristics specified in the current contracts for the hardware of the science instruments. The final ground-based tests of the instruments will not be carried out at GSFC until early 1982. There may also be some adjustments in details of the designs before this date (e.g., in the choice of filters or gratings). The performance characteristics in orbit will not be known for certain until the instruments are tested under orbital conditions in 1984.

The four axial bay instruments are designed to count individual photons. Thus the limiting magnitudes and signal-to-noise ratios given below and in the tables of performance characteristics can be scaled using the "most-optimistic" formulae: $m \propto 2.5 \log(\mathrm{time})$ and $S/N \propto (\mathrm{time})^{1/2}$. These relations are based only on Poisson statistics and they neglect, among other things, background noise from the detector, sky background, and radiation effects (see sections on the individual instruments for estimates of these quantities), but are probably adequate for rough estimates of what may be feasible (and may be almost as accurate as the available data on the performance characteristics of the instruments warrant). The above scaling relations can be used for crude estimates of the sensitivity as a function of time of the Wide Field/Planetary Camera although readout noise and radiation effects will limit the usefulness of combining exposures for this instrument (the detailed data in §V A below on read out noise, sky background, and dark count for the Wide Field/Planetary Camera can be used to compute more accurately the performance characteristics of this detector).

With the above cautionary remarks, the characteristics given here should be sufficient for advanced planning of ST observations.

Some science programs that have been identified by the instrument development teams are described briefly. These programs are listed for illustrative purposes only. General observers can, and in most cases will, carry out significant parts of these programs.

A. Wide Field/Planetary Camera (WF/PC)

The Wide Field/Planetary Camera can be operated in two modes that are characterized loosely by the two names: Wide Field Camera (WFC) and Planetary Camera (PC). The WFC mode will be used primarily for deep sky surveys (field: 2.7×2.7 $(\mathrm{arcmin})^2$). The PC mode will provide high-resolution imaging over a moderate field of view for faint sources or objects requiring a wide dynamic range (field: 1.2×1.2 $(\mathrm{arcmin})^2$) and/or wavelengths beyond 6000 Å. The basic performance characteristics in both these modes are given in Table 2.

The WF/PC is unique among the ST science instruments in several ways. It is located in a radial (not an axial) bay; light is transferred into the instrument by means of a pick-off mirror centered on the optical axis of the optical telescope assembly. An external thermal radiator, which will be a part of the exterior surface of the ST, will be used for cooling. The wavelength range is larger than for any of the other instruments; the red response is particularly crucial for many scientific problems. The quantity of data (bits per year) generated by the WF/PC in the pri-

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Table 2. Wide Field/Planetary Camera*

This instrument can operate at two different focal ratios: f/12.88 or f/30. In the first mode, the instrument is referred to as the Wide Field Camera (WFC) and, in the second mode, as the Planetary Camera (PC). Pictures can be taken, in either mode, with any one of a wide variety of spectral filters or transmission gratings.

Characteristics	WFC	PC
Field of View	$2.67\times2.67(\text{arcmin})^2$	$1.15\times1.15(\text{arcmin})^2$
Angular Resolution (1 pixel)	$0.1\times0.1(\text{arcsec})^2$	$0.043\times0.043(\text{arcsec})^2$
Bandwidth (quantum efficiency$\geq$1%)	1.15×10^3 Å to 1.1 μ	1.1×10^3 Å to 1.1 μ
Photometric Accuracy	~ 1%	~ 1%
Dynamic range ($S/N\geq3$)	$9.5 \leq m_V \leq 28.0$	$8.5 \leq m_V \leq 28$

*References: (1). J. A. Westphal, et al. (1977), Technical Proposal - Instrument Definition Team, WF/PC for ST, submitted by the California Institute of Technology to NASA; (2). J. A. Westphal et al. (1979), WF/PC GSFC Preliminary Design Review Package (CM-04).

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mary and serendipity modes is expected to exceed that of the other instruments.

In both the WFC and PC modes, the detectors are four (800×800) charge-coupled devices (CCDs). The incoming light can be directed onto either the four WFC CCDs or the four PC CCDs by means of a pyramid mirror that can be rotated about its apex. The WF/PC contains two complete optical relay and detector systems, each capable of producing a four-part image mosaic. The CCDs are being developed by Texas Instruments for both the Galileo and the ST Projects. The center-to-center pixel separation is 15μ. The CCDs will be cooled to -95° ±0.5° C in order to reach a small, known dark current. The wide wavelength coverage is possible because the CCDs are coated with an organic phosphor, coronene, which converts ultraviolet photons into visible photons; the intrinsic long wavelength response of the CCDs is very good (see below). The optical performance in the visible band of the WF/PC will be approximately equivalent to that of an optical system with a total wavefront error of λ/10. Because of a slight overlap between the edges of the different 800×800 arrays, it will be possible accurately to register and reassemble the four pictures to form one large picture without any significant loss of data.

The WF/PC will provide a sensitive and highly linear detector over a broad wavelength region (1,150 Å to 1.1μ) and a wide dynamic range (8^m to 28^m in the visual band). The minimum exposure time is 0.1 sec (determined by the speed with which the shutter can be opened and closed). The typical long exposure will be of order 3,000 seconds (corresponding to one-half an orbital period). A read-out noise of about 15 electrons per pixel, and radiation effects, limit the advantage of stacking different exposures (the OTA plus WF/PC optical throughput is ~ 0.33 and the CCD quantum efficiency ~ 0.55 at 5500 Å). The following typical results can be obtained for observations of single stars through a V filter (assumed to be an 890 Å bandpass centered at 5500 Å) all with a signal to noise ratio greater than or equal to three (sky = 23 $m_V/(\mathrm{arcsec})^2$, dark count = 0.01 electrons per pixel per second, image = 5 pixel patch at f/12.9):

<u>0.1 second exposure</u>	- WFC	$9^m.5$ to 17^m
	- PC	$8^m.5$ to 16^m
<u>3,000 second exposure</u>	- WFC	21^m to 28^m
	- PC	20^m to $27^m.5$

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Note that planets, because they are not point sources, will be observable with short observing times in the planetary mode even though their integrated brightnesses exceed the 7.5 magnitude limit. The full throughput quantum efficiency of the flight WF/PC is expected to exceed the following requirements: 3% from 1200 Å to 3,000 Å; a peak value in excess of 40% in the region 3,000 Å to 7,000 Å; and 8% from 7,000 Å to 1 μ. The above data allow the computation of rough performance characteristics for intermediate exposure times and for a variety of wavelengths. Absolute photometric calibration will be achieved primarily by observation of standard stars; flat-field calibrations will be made using the limb of the illuminated earth.

A large number of filters, transmission gratings, and polarizers will be available for special purpose observations. Filters having a bandwidth $\Delta\lambda/\lambda = 0.2$ will be provided throughout the range 1200 Å to 1.1 μ, including U, B, V, R, and I filters; also filters with $\Delta\lambda/\lambda = 0.1$ will be available from 3400 Å to 1,050 Å. A number of special line filters (typical widths 20 Å to 60 Å) may be available including: Ly-α, C IV λ 1550, [O III] λ 3727, [Ne III] λ 3870, [O III] λ 4363, H-β, [O III] λ 5007, [O I] 6300 Å, H-α, and He I λ 10830. There will be 0° and 60° polarizers in U and R, a uv/visible IR transmission prism (~ 1200 Å to 1.1 μ) and a visible/IR transmission grating. The prism and grating can be used to produce low dispersion spectra of the objects in the field.

The instrument development team listed a number of important scientific applications of the WF/PC in their original technical proposal to NASA and in the preliminary design review. These objectives include: determination of H_O; tests of cosmological models; comparative studies of distant and faint galaxies; stellar population studies to faint magnitudes; high resolution luminosity profiles of galactic nuclei; energy distributions of stars and compact galactic and extragalactic objects; dynamic motions in supernovae remnants and proto-stars; search for extra-solar planets; synoptic studies of planetary atmospheres; and high resolution and UV studies of comets.

B. The Faint Object Camera (FOC)

The primary purpose of the FOC is to utilize the full optical performance of the ST, reaching the faintest limiting magnitudes and highest angular resolution possible. The basic performance characteristics of the FOC are summarized in Table 3. The FOC is being developed (and will be furnished) by the European Space Agency to the NASA ST program.

Table 3. The Faint Object Camera (FOC)*

The faint object camera consists of two independent camera systems that operate, respectively, at f/96 and f/48. The f/96 system contains a coronagraphic facility that can be used to mask the light from bright objects. The f/48 system also provides for long-slit (10 × 0.1 $(arcsec)^2$) spectroscopy with a fixed grating.

Characteristic	f/96	f/48
Field of view (see text)	11 × 11$(arcsec)^2$	22 × 22$(arcsec)^2$ 44 × 44$(arcsec)^2$ at slightly degraded resolution
Pixel Size	0.022 × 0.022$(arcsec)^2$	0.045 × 0.045$(arcsec)^2$
Wavelength Range (quantum efficiency ≥ 1%)	1,200 Å - 6,000 Å	1,200 Å - 6,000 Å
Dynamic range (cumulative 10 hour observations without attenuating filters or combining pixels; S/N=4)	point sources: 21 m_V to 28 m_V extended sources: 15 $m_V/(arcsec)^2$ to 22 $m_V/(arcsec)^2$	point sources: 21 m_V to 28 m_V extended sources: 15 $m_V/(arcsec)^2$ to 22 $m_V/(arcsec)^2$
Photometric Accuracy (When not photo-noise limited)	at least 2%	at least 2%

*References: (1). F. Macchetto and R. J. Laurance, (1977), The Faint Object Camera, ESA SN-126; (2). J. J. Brahm, FOC Scientific and Technical Status Report, ST Science and Operations Project, internal GSFC report - February 12, 1979; (3). F. Macchetto, (1979), "Status of the ST Project in Europe," in ESA/ESO Workshop on the Space Telescope, ed. F. Macchetto, F. Pacini, and M. Tarenghi.

The FOC is complementary to the WF/PC. The FOC provides a higher spatial resolution and the WF/PC a larger field of view. The FOC will be faster than the WF/PC (by a factor of between 10 and 50) in the wavelength range between 1200 Å to 4000 Å if the actual noise levels for both cameras are consistent with current expectations. The two systems will be about equal in speed at 5,000 Å. As one goes further into the red, the WF/PC is increasingly more advantageous, being faster than the FOC by a factor $\gtrsim 10$ for $\lambda > 6000$ Å.

The FOC contains two independent camera systems, one operating at f/96 and one at f/48. The f/96 relay slightly oversamples the expected point spread function of the OTA at 6328 Å; the focal plane image is magnified by a factor of four in order to minimize the resolution loss resulting from detector spatial sampling. The pixel size is 25 μ which corresponds to 0.022 arcsecs at f/96. The f/48 system magnifies by a factor of two in order to include a wider field with only moderate resolution loss due to detector sampling.

The f/96 mode contains a coronagraphic facility which allows the camera to suppress light from bright objects while observing faint sources in the nearby field. When centered on a stellar image, the occulting disc (0.6 arcsec diameter on the sky) reduces the total measured flux from the image by a factor of 20. It is estimated that imaging of a faint object near (1 arcsec) a bright object will be possible for a difference in magnitudes as large as $\Delta m_V \simeq 7$ to 10 (depending on how long one is willing to observe).

The f/48 system provides a long-slit [10 × 0.1 (arcsec)^2 spectrographic capability for observing extended objects. A fixed grating can be used to disperse the light and provide first, second, and third order images covering the wavelength ranges 3600-5400 Å, 1800-2700 Å, and 1200-1800 Å. This spectrographic mode complements the two U.S. spectrographs described below (V C and V D). The spectral resolution is 2×10^3 (a factor of ten less than for the HRS) and the limiting magnitude on point sources is 3.4 magnitudes brighter than that of the FOS. However, the FOC spectrographic mode is unique in that it makes possible spectroscopic profiles of extended objects with an angular resolution of order 0.1 arc second. This option will be useful in, for example, measuring velocity dispersions as well as temperature, density, and composition distributions in galaxies, comets and nebulae.

Independent sets of special purpose filters will be provided for the f/96 and f/48 modes. The f/96 mode will have four filter wheels, each containing 12 positions, that can be inserted in the optical path. The filter wheels will contain a variety of filters, including five neutral density filters (Δm = 1, 2, 4, 6, 8), two objective prisms ($\lambda/\Delta\lambda$=50 at 1500 Å and $\lambda/\Delta\lambda$=100 at 2500 Å), three polarizers for measuring linear polarization (0°, 60°, 120°), and a number of special purpose filters. By suitably combining the neutral density filters a maximum attenuation of Δm = 12 can be achieved thus allowing the overall dynamic range of the FOC to extend from m_V = 5 to m_V = 29. The f/48 mode will have fourteen insertable elements including the two objective prisms described above, five order-sorting filters, six broad-band filters, and a Lyman-alpha blocking disc.

The identical detectors for the two f-ratios count individual photons; the conceptual design is similar to the imaging photon detectors developed by A. Boksenberg. The first stage of each detector is an EMI-developed three stage, magnetically-focused, image intensifier tube having a gain of approximately 10^5. The first-stage photocathodes are "hot bialkalis" on $Mg\ F_2$, which have useful sensitivity over the wavelength range 1,150 Å to 7,000 Å. The thermionic dark currents of the photocathodes are expected to be very low at ambient temperatures, of order 10^{-4} counts/pixel/sec. The camera tube that scans the output of the intensifier is a high-gain Westinghouse (WX 32 719) TV tube, which is a high sensitivity, high resolution, electrostatically-focused-image-section EBS/SIT tube.

The basic limitation on the field size at highest resolution is determined by the amount of data that can be stored with a limited but dedicated memory. The memory limitation corresponds, with 16 bit words, to a total number of pixels that can be scanned of 512 × 512 or equivalent combinations. Each detector consists of 1024 × 1024 pixels. A variety of imaging formats will be available (currently): 1024 × 512 (with an 8 bit address), 1024 × 256, 512 × 512, 256 × 256, 128 × 128, 64 × 64. At f/96, the 512 × 512 format corresponds to 11.3 × 11.3 $(arcsec)^2$; a larger field, 22.5 × 11.3 $(arcsec)^2$ can be obtained also at f/96. The largest field that will be available for the f/48 mode is 22 × 22 $(arcsec)^2$, obtained by scanning data read from 2-by-2 pixel areas. It is possible that a time-resolved imaging mode will be available for small fields with a time-resolution of order one second (for use in searching, e.g., for optical counterparts of radio pulsars or variable X-ray sources).

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The limiting magnitudes given in Table 3 for the brightest objects that can be observed are determined also by the TV scan rate. If the count rate becomes too high, the detector response is significantly non-linear. Much brighter objects than those listed in Table 3 can be observed with the aid of attenuating filters or by using small-scan formats. The faint limiting magnitudes in the ultraviolet may be one or two magnitudes fainter than the faint visual-magnitude limits shown in Table 3. A cumulative exposure of 10 hours should lead to a signal to noise ratio of at least four for stellar objects as faint as $m_V = 28^m$.

The possible applications of the FOC are very numerous. Some of the studies that have been stressed by the ESA Project Scientist and the Instrument Science Team include observations of RR Lyrae stars, Cepheids, bright supergiants, globular clusters and giant H II regions as distance indicators out to expansion velocities $\gtrsim 10^4$ km s^{-1}; investigation of time-dependent features on planetary surfaces; the resolution of spectroscopic and astrometric binaries to establish stellar masses; detailed studies of shock fronts, condensing gas clouds and the relationship of young stars to the gas around them in regions of star formation, optical identification of faint radio and X-ray sources; and the search for direct evidence that quasars and BL Lac objects are the brightest nuclei of faint galaxies.

C. Faint Object Spectrograph (FOS)

The Faint Object Spectrograph is a versatile instrument that can perform moderate and low resolution spectroscopy on faint (and bright) objects in the ultraviolet and visible, as well as spectropolarimetry and time-resolved spectroscopy. The basic performance characteristics are listed in Table 4.

The FOS provides three modes of varying spectral resolution. The moderate resolution mode has $R \equiv \lambda/\Delta\lambda \sim 10^3$ and provides coverage from 1,150 Å to 9,000 Å in six bandpasses, utilizing concave gratings to obtain a resolution of $\lesssim 1200$ when convolved with the 0.25 arcsecond entrance aperture. A low resolution mode, $R \sim 10^2$, consists of three spectral bandpasses - two low dispersion gratings which provide $R = 10^2$ for 1100 Å $< \lambda <$ 2200 Å and 4000 Å $< \lambda <$ 8000 Å and a prism spanning the range 2700 Å at $R = 3 \times 10^2$ to 8,000 Å at $R = 20$. There is also a nondispersed image that will be used for target acquisition.

The spectrograph contains two identical optical paths

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Table 4. Faint Object Spectrograph (FOS)*

The Faint Object Spectrograph can perform moderate ($R=\lambda/\Delta\lambda \sim 10^3$) or low ($R=10^2$) resolution spectroscopy over a wide wavelength range as well as spectropolarimetry and time-resolved spectroscopy. Two photon-counting Digicon sensors (512 diodes each) are provided that differ only in their (red-biased or blue-biased) photoemissive cathodes.

Characteristics	Expected Performance
Spectral Resolution	$R = \lambda/\Delta\lambda \sim 10^3, 10^2$
Entrance Apertures	0.1 to 4.3 arcsec
Wavelength Range (FOS system efficiency $\geq$ 1%)	1,150 Å to 7,000 Å
Limiting Magnitudes (no sky contamination; 10^4 sec exposure; S/N(detector) = 5)	1.2×10^3 Å to 7×10^3 Å
$R=10^3$ (flat spectrum)	$19^m \leq m_V$(faintest) $\lesssim 22^m$
$R \sim 10^2$ (flat spectrum)	$22^m \leq m_V$(faintest) $\lesssim 26^m$
Dynamic Range	5×10^7
Photometric Accuracy	at least 1%
Time Resolution	
minimum exposure	50 μ seconds
continuous exposures	100 exposures (10ms) per second
Linear Polarization Measurements (10^4 second exposure)	1.2×10^3 Å to 3×10^3 Å
$R=10^3$ (flat spectrum)	$11^m \lesssim m_V$(faintest) $\lesssim 15^m$
$R=10^2$ (flat spectrum)	$13^m \lesssim m_V$(faintest) $\lesssim 17^m$

*References: (1). R. Harms, (1979), Scientific Investigation Studies Report for the FOS, UCSD Report: FOS-UCSD-SC-01 (February 1979). (2). R. Harms, et al. (1977), UC/MMC Faint Object Spectrograph for the Space Telescope, Technical Volume-Instrument Definition Team, submitted by the University of California to NASA (July 1977).

which form a spectral image on a red-biased and a blue-biased detector. Each beam is reflected from a grazing incidence mirror through an order-blocking filter and then onto one of the grating elements selected from a ten-position carousel. The selected grating disperses the light in first order onto the faceplate of the Digicon. The carousel can supply to the Digicon certain filter/grating combinations or a non-dispersed image. The polarizing assembly can be inserted ahead of the grazing mirror assembly.

The FOS uses two magnetically focused, photon-counting Digicon sensor systems that differ only in their photoemissive cathodes and window materials. Digicon detectors are single-stage, photon-counting devices that operate by re-imaging photoelectrons onto a monolithic silicon diode array of 512 diodes. In order to cover the broad wavelength range of the FOS, two independently-operable Digicons are used. The ultraviolet/visual sensor has a magnesium fluoride faceplate and a bialkali photocathode. The visible/near-IR sensor has a silicon oxide faceplate and trialkali photocathode. Each diode has a width of 40 μ and a height of 200 μ; the image scale at either Digicon will be 140 μ per arc second, corresponding to a magnification of 0.5 of the OTA focal plane.

The FOS will be an accurate and sensitive spectrograph over a wide wavelength range. For both the moderate and low resolution modes, the FOS efficiency is expected to exceed one percent over the entire range from 1200 Å to H-α, two percent from 1200 Å to 2000 Å, seven percent from 2000 Å to 4000 Å, and will have a peak efficiency exceeding ten percent. The FOS background noise during inflight conditions is expected to be low: less than 2×10^{-3} counts/sec/diode. The counting rate from a constant source should be constant to a one percent accuracy for 99 percent of the diodes over periods up to four hours for all spectral regions in each mode (holding the spectral region and observing mode fixed over the observing period).

The limiting magnitude that is achievable depends on the resolution mode ($R = 10^3$ or 10^2) and the spectral region. The peak sensitvity occurs in the range 4000 Å to 5000 Å. The faintest attainable magnitudes are approximately the same (plus or minus of the order of one magnitude) in the entire range from 2000 Å to 7000 Å. The sensitivity falls off rapidly below 2000 Å or above 7000 Å; at 8000 Å the typical faintest attainable magnitudes are 6 magnitudes brighter than at 4500 Å. Some range of faintest limiting magnitudes attainable in 10^4 second exposures are given in Table 4.

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The indicated limiting magnitudes were computed using the advertised ST performance, the 0.25 arcsec FOS entrance aperture, the FOS efficiencies described above, internal background of 0.002 counts/sec/diode, and a pessimistic sky background. The limiting magnitude is defined to be that which results in 0.01 counts/sec/diode from a stellar target. As another example, note that the FOS will achieve a signal to noise ratio of seven per diode at 4000 Å in the $R = 10^3$ mode for a three-hour integration on an unreddened A0V star of magnitude V = 23. Stars as bright as $m_V = 6$ can be observed in the $R = 10^3$ mode.

For spectropolarimetry, the relevant measure is the limiting magnitude for which both of the Stokes parameters describing the state of linear polarization can be obtained with, for example, one-percent accuracy. In a 10^4 second observation, the faintest magnitude for which this accuracy can be achieved in the $R = 10^3$ mode rises monotonically from $m_V = 10.8^m$ at 1200 Å to $m_V = 15^m$ at 3000 Å for a source with a flat spectrum (F_V = constant). For the $R = 10^2$ mode, the faintest magnitudes attainable vary from $m_V = 13^m$ to 17^m over the same spectral range under the conditions specified above.

The FOS can provide exposure times as short as 50 μ seconds duration. A continuous set of exposures, each of duration 50 μ sec to 10 msec, can be made at a rate up to approximately 100 512-channel exposures per second.

The FOS design also incorporates special entrance apertures matched to the ST optics to maximize the signal from a nebulosity surround a stellar source (for example, a quasar that occurs in a galaxy).

The scientific applications of the FOS are numerous and varied in character. The instrument development team and the principal investigator have discussed a number of possible investigations (see references to Table 4). These include: high spatial resolution spectra of quasars, Seyfert and other active galactic nuclei in order to determine physical conditions; observations of H II regions and planetary nebulae in the Local Group Galaxies to measure population abundances; the study of globular clusters in the Virgo Cluster to determine stellar populations and to measure radial velocities; the measurement of the ultraviolet spectra of the central stars of planetary nebulae; time-resolved spectrophotometry of X-ray sources; ultraviolet spectrometry of comets to measure various spectral features and some radial velocity measurements of wave structure in cometary tails; and ultraviolet spectropolarimetry of stars and reflection nebulae to help determine the origin of instellar polarization, as well as spectropolarimetry of white dwarfs, quasars, and Seyferts to help delineate the physical processes occurring in these objects.

D. High Resolution Spectrograph (HRS)

The High Resolution Spectrograph is a photon-counting, ultraviolet instrument that will provide a resolving power equal to that of the largest ground-based Coudé spectrographs It can perform moderate and high resolution spectroscopy in the region between 1100 Å and 3200 Å. The basic characteristics of the HRS are shown in Table 5.

The HRS (like the FOS) provides three modes of varying spectral resolution. The primary HRS observing modes are with a resolving power $R = \lambda/\Delta\lambda = 1 \times 10^5$ (by far the highest on ST) and with $R = 2 \times 10^4$, both covering the wavelength 1.1×10^3 Å to 3200 Å. Most of the numerous scientific programs that have been suggested so far (see below) for the HRS refer to these two primary modes. The moderate resolution mode has $R = 2 \times 10^3$, similar to the FOS. However, this HRS moderate resolution mode is limited to the region 1050 Å to 1700 Å. The moderate resolution of the HRS will be used for efficient target acquisition, for estimating exposure times at higher resolution, and to provide valuable sensitivity in the short wavelength region where the OTA efficiency is low and higher resolution spectroscopy is not feasible. The partial redundancy with the FOS is intentional

The HRS will contain two square entrance apertures of 0.25 and 2.0 arcseconds, designed to accommodate the astigmatic defocussing of the OTA beam. (The HRS will not resolve spatial information within the 0.25 arcsecond slit.) Slit selection is accomplished by orienting the telescope so as to place the image of the target in the slit. Within the spectrograph, the light is reflected by a collimator to one of six plane gratings in a rotatable carousel.

The HRS (like the FOS) contains two independent Digicon detectors, each with 512 diodes. For one of the HRS Digicons, the photocathode/window combination is Cs Te/Mg F_2, while for the other it is Cs I/Li F(peak efficiency at ~ 1250 Å). Three of the gratings (blazed at 1600 Å, 2000 Å, and 2700 Å) diffract the light towards a camera mirror which focuses a first-order, high resolution ($R = 2 \times 10^4$) spectrum on the Digicon having a Cs Te/Mg F_2 combination. A fourth grating (blazed at 1400 Å) produces a similar spectrum on

Table 5. The High Resolution Spectrograph (HRS)*

The HIgh Resolution Spectrograph can perform high ($R=10^5$ and $R=2\times10^4$) and moderate ($R=2\times10^3$) resolution spectroscopy in the ultraviolet, as well as time-resolved spectroscopy. Two photon-counting Digicon detectors are provided, one with a Cs Te/Mg F_2 photocathode/window combination and the other with Cs I/Li F.

Characteristics	Expected Performance
Spectral Resolution	$R = 1 \times 10^5$, 2×10^4, 2×10^3
Entrance Apertures	0.25×0.25 (arcsecond)^2 2.0×2.0 (arcsecond)^2
Wavelength Range (HRS Efficiency: 0.4% to 4.0%; preliminary estimate)	$(1.1$ to $3.2) \times 10^3$ Å $(R=10^5)$ $(1.1$ to $3.2) \times 10^3$ Å $(R=2 \times 10^4)$ $(1.1$ to $1.7) \times 10^3$ Å $(R=2 \times 10^3)$
Limiting Magnitude (2×10^3 sec; AOV star near peak HRS efficiency; $S/N \geq 10$)	$m_V = \begin{cases} 11 & (R=10^5) \\ 14 & (R=2\times10^4) \\ 17 & (R=1\times10^3) \end{cases}$
Photometric Accuracy (count rate $\leq 10^4$/sec/pixel)	~ 1%
Minimum Exposure Time (reset time $\leq$ 0.002 sec)	0.025 sec

*References: (1). J. C. Brandt et al. (1977), A High Resolution Spectrograph for the Space Telescope, Technical Proposal-Instrument Definition Team, submitted by GSFC to NASA Headquarters, HRS-680-77-01; (2). J. C. Brandt, et al. (1979), Proceedings, Society of Photo-Optical Instrumentation Engineers, Vol. 172, in the press.

the Digicon with the Cs I/Li F combination, using a second camera mirror. The moderate-resolution ($R = 2 \times 10^3$) mode is also recorded in first order by this Digicon. The highest resolution observations ($R \gtrsim 10^5$) will be achieved with the aid of a sixth, echelle grating that can be used with either Digicon. A limited range of the spectrum is recorded by the array at one time. In the $R = 2 \times 10^4$ mode, the length of the spectrum on the detector varies from about 30 Å at 1100 Å to about 45 Å at 3200 Å. The spectrum length for the $R = 2 \times 10^3$ mode is about 290 Å. In the echelle, high-resolution mode ($R = 10^5$), the spectrum length varies from 4.5 Å at $\lambda = 1100$ Å to 16 Å at $\lambda = 3200$ Å.

The sensitivity of the HRS in various wavelength ranges depends on the efficiencies of the gratings and Digicons as finally manufactured by the HRS vendors. The sensitivity goals are: for the $R = 2 \times 10^4$ mode, a quantum efficiency in excess of 1% over the interval from 1200 Å to 2800 Å and a maximum of at least 3% within this spectral range; for the $R = 10^5$ mode, a spectrograph efficiency in excess of 0.4% at the blaze wavelengths over the entire interval from 1200 Å to 2800 Å, and a maximum efficiency no less than 1.2% within the 1800 Å to 2800 Å range.

The brightness ratio of signals ($\geq 10^5$ total counts) from any two channels within the image format and within the Digicon dynamic range will remain constant to within 1% (1σ) of the mean ratio value over periods up to 30 days. For count rates randomly distributed in time up to 10^5 counts/sec/channel, the measured rate will be correctable to the true rate to an accuracy better than 4%. For count rates between 1 and 10^4 counts/sec/pixel, the measured rate will be correctable to the true rate to an accuracy of better than 1%.

The HRS will achieve a signal-to-noise ratio of at least 10 in each channel at a flux maximum near the wavelength of maximum HRS efficiency in a 2×10^3 second integration period on an unreddened A0V stellar flux distribution corresponding to approximately $V = 14^m$ at $R = 2 \times 10^4$ and to approximately 11^m at $R = 1 \times 10^5$. (This assumes an OTA throughput of 0.6, a radiation background of 0.001 counts/channels/sec, and a sky background of 10^{-3} photons cm^{-2}sec^{-1} Å^{-1} arcmin^{-2}. At ambient temperature, the photocathode dark current will be less than 0.01 counts/diode/sec.)

The minimum integration period for a single frame of data will be 25 milliseconds when data are transmitted directly and 50 milliseconds when data are stored on-board.

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The reset time, that is the time between successive integrations, will be less than 2 milliseconds.

Accurate calibration of wavelengths and system response will be achieved by the use of three types of internal light sources: a Pt-Ne lamp for calibrating the wavelength scale, (accurate to 0.40 pixels, 1-σ), lamps that provide an ultraviolet continuum, and "flat-field" illumination of the Digicons.

The principal investigator and the instrument development team have discussed (see references to Table 5) a number of important observations that are to be made with the HRS. These include: studies of the very local gas, of dense clouds, and of previously undetected molecules all in the interstellar medium; studies of mass loss, mass transfer, and coronal winds in stars using OB supergiants in the Magellanic Clouds, red giants in the Galaxy, close X-ray binaries, and late-type stars; a spectroscopic investigation of the nuclei of Seyfert galaxies and a detailed study of the uv spectrum of 3C 273; a study of the structure of the atmospheres of the Jovian planets, of auroral activity on other planets and satellites, and a measurement of the D/H ratio in Halley's comet.

E. High Speed Photometer (HSP)

The High Speed Photometer is designed to provide accurate, time-resolved photometric observations over a wide wavelength range, as well as linear polarization measurements in the ultraviolet. The basic performance characteristics are listed in Table 6.

The HSP will be capable of resolving two events separated in time by more than 16 microseconds. Observations of rapidly varying sources over time scales this short are difficult or impossible to obtain from the ground because of atmospheric fluctuations. Events measured with the HSP can be related to ground-based time standards with an accuracy of at least 10 milliseconds.

The HSP is designed to be the simplest instrument in the initial group of scientific instruments. It contains no mechanical parts and relies entirely on the fine-pointing of the spacecraft to place an astronomical target onto one of its approximately 100 filter/aperture combinations.

The HSP consists of four magnetically focused image dissectors (two sensitive in the visual and near UV and two

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Table 6. The High Speed Photometer (HSP)*

The High Speed Photometer can perform accurate high-time-resolved photometric photometry over a wide wavelength range. Four image dissector devices and one photomultiplier tube are used.

Characteristics	Expected Performance
Wavelength Range (HSP efficiency $\geq$ 1%)	1200 Å - 8000 Å
Spectral Resolution	Defined by Wavelength Filters
Entrance Apertures	0.4, 1.0, and 10 arc sec diameters
Linear Polarization	2100 Å - 3800 Å
Time Resolution	16 μ sec
Dynamic Range	10^8
Photometric Accuracy	~ 0.2%
Limiting Magnitude (S/N=10; integration time 2×10^3 sec)	$m_V = 24$

*References: (1). R. C. Bless (1977), A High Speed Photometer/ Polarimeter for the Space Telescope, A Proposal to the NASA by the Space Astronomy Laboratory, University of Wisconsin; (2). R. C. Bless, et al. (1978), High Speed Photometer GSFC Preliminary Design Review Package (CM-04).

sensitive in the UV) and one (red-sensitive) photomultiplier tube. (For simplicity, one can think of an image dissector as a photomultiplier tube with spatial resolution.) Two dissectors will have a nominal S-20 spectral response for operation in the 2000 Å to 6500 Å range. Two other image dissectors will utilize a Cs Te Photocathode with a Mg F_2 window for operation in the range 1150 Å to 3000 Å. One of the S-20 dissectors will be used as a polarimeter in the range 2100 Å to 3300 Å. Each dissector will operate as a simple, high-speed beam photometer or polarimeter. In addition, the photomultiplier tube will utilize a Ga As photocathode for operation in the 6000 Å to 9000 Å range.

The choice of entrance-aperture/filter combination will be determined by ST positioning of the optical image within the HSP. This procedure simplifies the instrument design and eliminates the moving parts that occur in a more conventional photometer. Every dissector will be preceded by a focal-plane filter/entrance aperture assembly that will contain about 12 wavelength filters, each with a pair of associated 0.4 arc sec diameter and 1.0 arc sec diameter aperture stops. There will also be, for area photometry without a filter and for target acquisition, a 10 arc sec diameter aperture on each dissector faceplate. Standard filters from various photometric systems will be included. The filter plate assembly for the polarimeter will contain wavelength filter strips each overcoated with a polarizing film transmitting light plane-polarized in four separate orientations, enabling the linear polarization to be measured.

Three operational modes will be used: star-sky photometry with a single filter/aperture combination, requiring no special ST motion; photometry or polarimetry with several filters viewed sequentially by small ST motions with corresponding dissector beam deflection; and area photometry over a 10 arc sec diameter aperture without a filter, requiring no special ST motion.

The photometric accuracy at all wavelengths should be very high, of order 0.2 percent or 1.3 times the combined photon noise alone, whichever is larger. The maximum signal to noise ratio attainable in a single exposure will be at least 4000; the dynamic range will be at least 10^8 with the photometric accuracy described above for the lowest six decades of the dynamical range. The HSP will have a system efficiency of at least 1% over the entire range from 1200 Å to 8000 Å with a peak efficiency of at least 9% at 4000 Å.

The limiting visual magnitude will be at least 24 with

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a signal to noise ratio of at least 10 after a 2000 second integration on the source.

The HSP makes possible a number of important scientific programs. The principal investigator and the instrument development team have discussed some typical interesting observations. These include: determination of the properties of components of binary star systems; searches for optical counterparts to radio pulsars; measurement of the shortest time-scales for variability of compact extragalactic sources; accurate brightness measurements of the zodiacal light and diffuse galactic light; determination of the wavelength and time dependence of polarization in a variety of galactic and extra-galactic sources; and measurements of the diameters of stars and solar system objects, as well as determinations of the profiles of the physical parameters of planetary atmospheres. One class of "service" observation will be of special importance to the general astronomical community, i.e., the establishment of faint stellar calibration standards, magnitude system transformations, and transfers between previously established photometric sequences and ST targets.

F. Astrometry with the Fine Guidance System (FGS)

The Fine Guidance System (FGS) consists of three identical sensors distributed in an annulus centered upon the optical axis of the ST. Each sensor has its own accessible area [69 $(\mathrm{arcmin})^2$]. In normal operations, two of the sensors will be used for fine pointing with the aid of prespecified guide stars. The sensor that is not used for telescope pointing, which can be any one of the three FGS sensors, will be available for astrometric measurements. The basic characteristics of the FGS as an astrometric instrument are listed in Table 7.

An FGS sensor consists of a set of rotating mirrors such that any star within its field of view can be placed on an image dissector/interferometer combination. The encoder readings of the rotating mirror axes supply the object position in the field of view; the output of each of the pair of interferometers supplies a fine error signal. The system determines accurate relative positions to ±0.002 arcseconds (by repeated short measurements) of all predesignated point sources within the field of view of the FGS astrometric sensor. The spectral range available will be 4670 Å to 7000 Å, with appropriate band filters.

Astrometric measurements will be accurate and short.

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Table 7. Astrometry with the Fine Guidance System (FGS)

The Fine Guidance System contains three sensors, two of which are required for guidance while the third can be used for astrometry. The position and magnitude (within broad magnitude limits) can be measured for any pre-designated star within the area of the FGS sensor that is acting as the astrometric sensor.

Characteristics	Expected Performance
Total Area Accessible to each Sensor	69 (arcmin)^2
Relative Positional Accuracy (of any two objects accessible to a given FGS)	0.002 arc seconds
Magnitude Range of Astrometric Targets (with neutral density filters)	$4^m \lesssim m_V < 20^m$
Spectral Range (with a minimum of three filters)	4670 Å to 7000 Å
Duration of Observation	10 objects in 10 minutes, down to 17^m
Photometric Precision (10 minutes on a $m_V = 17^m$ object)	1%
Pointing Stability of the ST (r.m.s.) (10 hours of observing time)	0.007 arc seconds
Field of View of Each Detector	1 (arcmin)^2
Magnitude Discrimination of FGS	$\pm 0.4^m$

References: (1). W. H. Jefferys et al. (1977), Space Telescope Instrument Definition Team - Astrometry; Technical Proposal submitted by the University of Texas (Austin) to the NASA; (2). W. F. van Altena et al. (1977), Space Telescope Instrument Definition Team - Astrometry; Technical proposal submitted by Yale University Observatory to the NASA; (3). P. J. Shelus and the ST Astrometry Team (1978); Astrometric Observations with the FGS of the ST, technical report, University of Texas (Austin).

With the aid of neutral density filters, stars in the magnitude range of $4^m \lesssim m_V < 20^m$ should be measurable (the faint limit will lie between 17^m and 20^m). It will be possible to determine the positions of 17th magnitude (visual) stars and to measure ten stars in ten minutes within the field of one of the fine-guidance sensors. A photometric precision of one percent will be achievable in ten minutes on a 17th-magnitude (visual) star.

The FGS can be used in three astrometric modes: primary astrometric targets stationary with respect to the field of view; primary target moving with respect to the field of view; and a scan to obtain the transfer function for each object in the field of view.

The principal investigator and the instrument development team have identified a number of important astrometric problems for which the FGS can be used. These include: positional information of the natural satellites of the outer planets; parallax information on nearby stars and possible unseen companions; resolution of important binaries and mass determinations of nearby spectroscopic binaries; establishment of an inertial reference frame relative to quasars and selected radio sources; and relationships among radio, optical, and dynamical fundamental reference systems.

VI. OPERATIONS

A. Program Options

Because of its complexity and remote location, Space Telescope will be operated in a more automatic manner than large ground-based optical telescopes. The relatively frequent access provided by the TDRSS allows many of the elements of observing that are traditional and convenient. However, there will be many more constraints in scheduling than are normally encountered in operating ground based telescopes.

Observations will be preprogrammed. This means that a series of time-sequenced spacecraft commands will be generated to carry out an observation automatically using a succession of planning steps that involve some previous knowledge of the object being viewed, as well as the operational constraints and capabilities of the Space Telescope and its Science Instruments. This method of operation will allow observing programs to be combined into an efficient schedule that produces the maximum amount of science.

Some scheduling flexibility will be required in a

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certain fraction of the observing programs because of the unusual nature of the astronomical source. In such cases, there will be assignments of "block time", analogous to short observing runs on ground-based telescopes. Observers will do detailed preprogramming of their observations, but can include the possibility of selecting between predesignated choices during the block time.

B. Guide Star Selection

In section IV, it was explained that guide stars would be selected from the edge of the field of view to provide the error signal for the most precise level of pointing control. There will be three Fine Guidance Sensors, each with a field of view of about 69 $\square'$. Guide stars as bright as $m_V = 9^m$ are usable and desirable, but are not sufficiently numerous. The system should be sensitive enough to guide on stars down to 14.5^m, a brightness level at which there will be more than enough candidates to satisfy the performance requirements that there be at least an 85% probability of finding two usable guide stars at the Galactic Poles. Close binary stars will not be usable since they would confuse the interferometric pattern of the Fine Guidance Sensor. There will also be contraints imposed by very crowded star fields (confusion in identification), bright background signals (some regions near very high surface brightness nebulae), and azimuthal angle (off-optimum roll of the spacecraft and correspondingly low electrical output of the Solar Array).

The selection of appropriate guide stars will be one of the important problems in the planning of any ST observation. These guide stars will be used by the FGS to acquire and hold a target in an entrance aperture of a science instrument. The choosing of guide stars is a more difficult and crucial task for ST observations than for corresponding ground-based optical observations since the fine guidance sensors are interferometric devices without imaging capabilities (over even a small field). No "picture" is obtained with the FGS. The actual field of view of each detector is only 1 $(\text{arcmin})^2$, which implies that reasonably accurate pre-selected guide star positions must be available for all science targets. Moreover, the fields of views of the science instruments are even smaller, requiring in some cases positions accurate to arcseconds. The magnitude discrimination of each detector is 0.4^m (visual); candidate guide stars should not have companions within 0.5 arcmin that differ in brightness by less than 0.4^m. Star catalogues are not available throughout the sky with the required star density and accuracy. The astrometry instrument definition team, and the ST project in general, are investing a great deal of effort in defining and designing an appropriate guide star selection procedure.

C. Modes of Acquisition

In the Pointing Capability section of part IV, we described the automatic pointing method for Space Telescope, mentioning that guide stars could be acquired with an accuracy of 0.01". Positional information of this accuracy will not be available for most stars and fortunately there will usually not be a requirement for pointing this precisely. Available plate material should give positions accurate to about 0.5", which is adequate for those instruments (Wide Field Camera and Faint Object Camera) with fields of view that are much larger. Small entrance aperture instruments (spectrographs and photometers) will be limited by the lack of astrometric quality data on their objects vis-a-vis the candidate guide stars and possible drifts in position of the entrance slits vis-a-vis the Fine Guidance Sensors.

Two methods of fine acquisition are available for the small-aperture science instruments. The science instrument may provide an internal scan of a small field of view and then send commands to the spacecraft pointing system to center the object. Obviously this method is limited to relatively simple fields. The alternative is for the science instrument to perform some type of image scan and send this information to the ground, where the astronomical observer makes the judgement as to where the Space Telescope should actually be pointed. The latter method demands, if it is to proceed efficiently, a close coupling between ST scheduling and the TDRSS availability.

D. Quick-Look Capabilities

An observer using Space Telescope will want to see his data as soon as possible, not only because of intellectual curiosity, but also to allow consideration of changes in the immediate and near-term observations. Because of the constraints of the ground data handling system, the ideal of "all the data immediately" will not be achieved. However it will be possible to quickly send a slightly noisy version of the data at a rate of at least 56 kilobits per second to the Science Institute via an electronic data link between GSFC and the ScI. This information can be used to assess the observational program being executed and to judge the necessity of changing the observing plan.

VII. THE SCIENCE INSTITUTE

A. Plan for Contracting and Developing

The NASA has developed a plan for science operations that is intended to be as similar as possible to the management of other national laboratories in the United States by other Federal Agencies. The analogy cannot be complete since only the NASA has the technical expertise to develop and maintain the Space Telescope, as well as the control and communications system to generate direct spacecraft commands. The intent of the NASA approach is to place the responsibility for performing science with the ST in the hands of the scientists themselves. A call for proposals to operate a Space Telescope Science Institute (ScI) will be issued in the autumn of 1979 and the successful operating group will be selected in the summer of 1980. This gives the ScI about 3½ years to prepare for launch and operations. During this period, the ScI will establish itself at a permanent location, hire staff (about 70) and scientists (about 30), and develop the hardware and software necessary to carry out the functions that are described below. The intent of NASA is to support the ScI throughout the lifetime of the Space Telescope.

An authoritative account of the detailed plan for the operation of ST and the ScI is contained in the document entitled "Science Operations with the Space Telescope: Current Concepts", January 1979, prepared by the ST Program Office. Copies are available from the ST Project Scientist, C. R. O'Dell.

B. Observer Selection

One of the first and most important functions of the ScI will be the selection of the users of the ST. It is expected that requests will far exceed capability. This means that the wisest possible policy must be followed in the selection, based on both scientific judgement and technical feasibility. Certain conditions must be observed in the selections. The many scientists who are now helping to develop the Space Telescope Observatory and the individual science instruments have been guaranteed by NASA a limited fraction of the observing time. At the end of the initial checkout period, 100% of the observing time will go to these users and their fraction will decrease to zero after 30 months, averaging 30% over this period. The scientists with guaranteed observing time will identify their observing programs prior to the first selection of general

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users; their plans will be considered in the selection of other users. In addition, at least 15% of the observing time will go on the average to scientists from member nations of the European Space Agency in recognition of an approximately proportional financial contribution to the Space Telescope program.

The first call for observing proposals will be issued about one year before the initial launch of ST. These proposals will be examined for technical feasibility by the ScI staff and for scientific quality by an external science peer review group. Then a selection committee, convened by the ScI but largely composed of non-ScI personnel, will make the final recommendations to the ScI director. The participation of United States observers will be funded by the ScI: non-United States users will have to provide their own funding. New proposals will be reviewed periodically throughout the lifetime of the Space Telescope Observatory.

C. Scheduling

The user programs that are selected may employ one or several of the science instruments and may involve a single observation or many. This means that there will be a variety of needs to be integrated together into a coherent observing schedule. Moreover, the newly selected users will not understand fully how the science instruments perform and are operated. The necessary education as to science instrument capability and use will come from ScI reading material and interaction with science instrument representatives. As the observing plans are refined, an iterative scheduling cycle begins. The first steps in the planning will probably occur some six months ahead of the actual observations and give little more than total time requirements. The final step will be a detailed 24-hour observing schedule, which may be prepared a week or two in advance.

D. Observations

Since the Space Telescope Observatory is highly automated and the appropriate operations are performed remotely, on board a spacecraft, one may well ask what will be the role of the scientific user during an observation. Many of the observations can be done independent of the scientific user since the pointing of ST is automatic, the sensitivities of the Science Instruments will be calibrated accurately, and many results do not require immediate evaluation. On the other hand, some special observing programs may require extensive real-time interactions by the user in cases in which the object is difficult to acquire or the inherent variability of the source demands a quick (few seconds to

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minutes) scientific judgement as to how to proceed.

Clearly, the Space Telescope Observatory and the ScI must be able to accommodate both extremes. This capability is planned, although there will be important constraints upon real time interactions due to the limited command access through the Tracking and Data Relay Satellite System. The most commonly used interactive capability will be "quick-look", in which the scientific data will be available at the ScI in a matter of several minutes. This information could then be used to update the next day's observing plan.

E. Data Handling

The scientific data coming from Space Telescope will be characterized by two, usually contradictory, terms: priceless and abundant. This means that the data must be treated with great care and the data handling system must be able to handle enormous quantities of information.

The involvement of an ST observer with data handling begins while his particular observations are still being planned. The observer must understand the various steps involved in observing and data reduction in order to plan appropriate observations.

After the observations are made, the data are sent to the Goddard Space Flight Center (GSFC) where standard processing operations are performed. This step includes rearranging the data and identifying, then correcting, errors that have occurred in the transmission. This accurate and packaged data is then sent to the ScI for the first steps of data reduction. The ScI will perform a set of standard operations on the data from each science instrument. These standard operations will not require scientific judgement, although the work will be supervised by scientists. The observer may use either calibrated or raw data in subsequent analyses. General programs for data analysis will be available for use at the ScI or for copy and use at a home institution. As users develop their own analytical programs, they can be added to the common store of ScI programs.

This method of data handling should be efficient, since repetitive tasks can be done by the (responsible-to-the community) ScI. Users will have a wide variety of analytical tools available to them.

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F. Data Archiving

The NASA policy of open access to its data is compliant with law and must be observed by the ScI. This means that all scientific data must be available to all United States users. The precedent has already been set for establishing proprietary periods in order to allow observers time to have the benefits of "first rights" to the data. This period will be one year for the Space Telescope. For programs in which the intrinsic nature of the subject (e.g., parallaxes and very long period variables) demands a longer proprietary period, special exemptions will be made on a case-by-case basis.

This general policy implies that special attention will be given by the ScI to cataloging and cross referencing the data in the archives, since this increases their value to future users. It is expected that proposals to use archived data will be received and funded.

G. Serendipity Data

Since the wide field of view of the Space Telescope is divided into sectors, more than one science instrument can be operated at a given time. This will be done as often as is desirable scientifically within the constraints imposed by the availability of electrical power and the necessity for thermal dissipation. At the very least, the WF/PC can be operated along with any one of the other four axial instruments. This multiple observing capability makes possible two uses of the Space Telescope Observatory that have not been described thus far.

Shared-time observations will result from observing programs requested by the proposal process and accepted for execution. These programs may be very flexible in terms of when and where observations are made (e.g., photometry of the diffuse radiation arising from Zodiacal, Diffuse Galactic and Intergalactic Light) or they may be tied to other observations (e.g., monitor variable stars whenever another science instrument is looking at the Large Magellanic Cloud). These data will be subject to secondary status in scheduling but will be given to the requester on a proprietary basis.

Serendipity data are those secondary observations made by Space Telescope science instruments on an "as-available" basis under direction of the ScI. ScI personnel will identify scientifically justified opportunities for using a second science instrument to obtain measurements at the same time as a primary observation. Frequently, these will be exposures with the WF/PC. These secondary data will be subjected to the routine processing done on observations prior to being delivered to the observer and will become available immediately to any scientist who proposes using them in an acceptable program. There is enormous scientific potential in the Serendipity data. This will be one of the important areas of activity of the ScI, both in recognizing opportunities and in cataloging the data.

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This report is dedicated to our colleague, R. E. Danielson. He spent much of his time and energy helping to create the Space Telescope, knowing that he would not be able to share in its use. His technical work underlies the design of Space Telescope; his example of dedication and courage serves as a guide to those who knew him.

Appendix A. Space Telescope Science Working Group

J. N. Bahcall	Interdisciplinary Scientist	Inst. for Advanced Study
R. C. Bless	PI - HSP	Univ. of Wisconsin
J. C. Brandt	PI - HRS	GSFC
J. J. Caldwell	Interdisciplinary Scientist	SUNY at Stony Brook
W. G. Fastie	Telescope Scientist	Johns Hopkins Univ.
E. J. Groth	Data & Operations Team Leader	Princeton University
R. J. Harms	PI - FOS	Univ. of Cal., San Diego
R. W. Hobbs	Data & Operations Scientist	GSFC
W. H. Jefferys	Astrometry Team Leader	Univ. of Texas at Austin
D. L. Lambert	Interdisciplinary Scientist	Univ. of Texas at Austin
D. S. Leckrone	Scientific Instruments Scientist	GSFC
M. L. Longair	Interdisciplinary Scientist	Univ. of Cambridge
F. D. Macchetto	FOC Project Scientist	ESA
C. R. O'Dell	Chairman & Project Scientist	MSFC
N. G. Roman	Program Scientist-Ex Officio	NASA Headquarters
D. J. Schroeder	Telescope Scientist	Beloit College
H. C. van de Hulst	FOC Science Team Leader (ESA)	Leiden
J. W. Warner	Assistant Project Scientist	MSFC
J. A. Westphal	PI - WF/PC	Cal. Inst. of Tech.