Orbiting UV observatory utilizing a commercial spacecraft

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ABSTRACT

We report on a design for a geosynchronous UV observatory optimized for imaging and spectrography of planets and comets. This Solar System Telescope (SST), based on a commercially developed spacecraft, was proposed to NASA as a Discovery Mission. It can also serve as a low-cost orbiting observatory for other disciplines in space astronomy. The SST consists of a 140-cm-aperture telescope with an instrumentation section comprising four spectrographs and a wide-field UV imager. We use silicon carbide mirrors and a telescope structure provided by the Vavilov State Optical Institute in St. Petersburg, Russia. The spacecraft is derived from Lockheed Martin's Commercial Remote Sensing Satellite (CRSS), which provides attitude control, power, communications, and command and data handling, with minimal modifications. Using this approach, we were able to design an observatory with capabilities comparable to the Hubble Space Telescope at approximately 1/20th the cost.

Keywords: telescope, observatory, spacecraft, silicon carbide, ultraviolet

INTRODUCTION

The Solar System Telescope (SST) is a low-cost orbiting observatory optimized for imaging and spectroscopy of planets and comets in the ultraviolet (UV). It is designed for spectrographic observations of solar system bodies at wavelengths between 55 and 320 nm, with $\lambda/\Delta\lambda$ between 100 and 10000 and a spatial resolution of 0.18 arcsec over a 200-arcsec slit. The telescope has an aperture diameter of 140 cm and spatial resolution with a broadband UV imager of 0.05 arcsec. The scientific payload comprises four imaging UV spectrographs, a UV camera, and a solar EUV monitor. The SST provides off-axis light rejection up to 3,500:1 better than the Hubble Space Telescope (HST) and can make observations as close to 7 deg to the Sun.

An inertial angle sensor (IAS) provides an optical reference that is stable in inertial space. This permits the SST to control the line of sight through articulating the secondary mirror in tip-tilt, stabilizing the image to 0.01 arcsec, without imposing costly requirements on the attitude control system.

The 590-kg observatory would be launched on a Delta II 7925 into a 5-deg geosynchronous orbit over the Pacific, with a weight margin of 194 kg. This orbit provides 24-hour observing and minimal interference from terrestrial emissions and simplifies mission operation. It also totally avoids the South Atlantic radiation anomaly that has plagued the International Ultraviolet Explorer (IUE) and HST. Mission lifetime is at least 5 years.

The spacecraft would be derived from Lockheed Martin's Commercial Remote Sensing Satellite (CRSS), providing attitude control, power, communications, and command and data handling with minimal modifications. Using this approach, we were able to design an observatory with capabilities comparable to the HST at approximately 1/20th the cost.

The telescope, instrument, and spacecraft are shown in exploded view in Figure 1.

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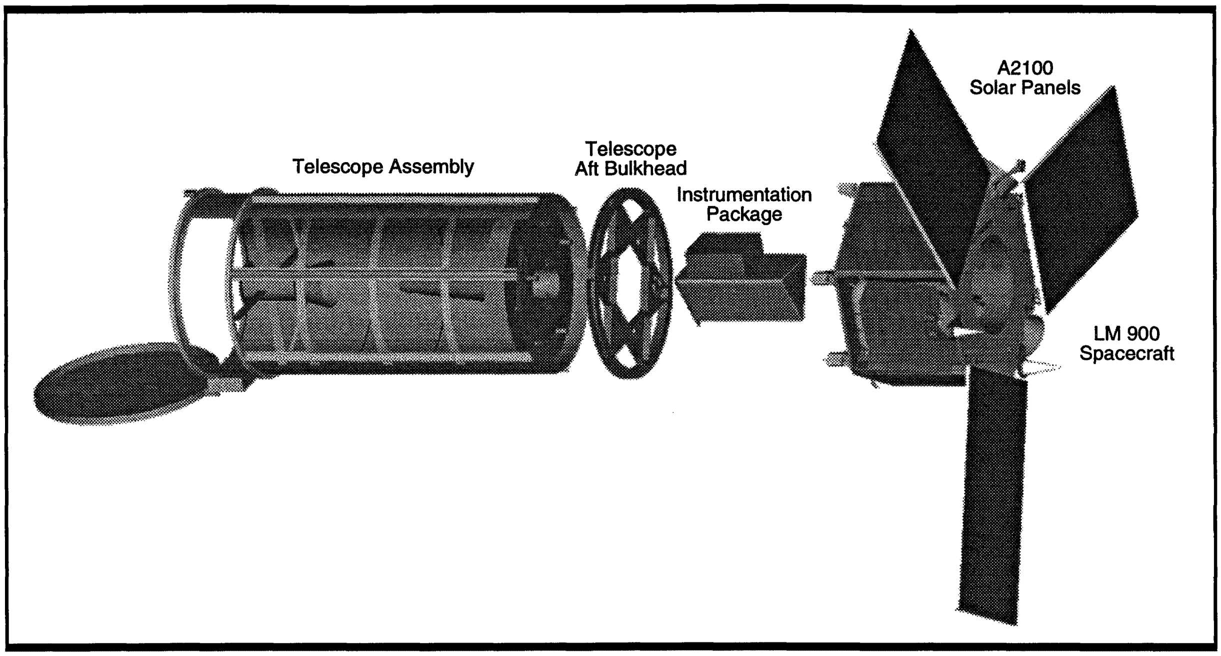


Figure 1. Exploded view of the SST.

SCIENCE OBJECTIVES

The SST is designed to measure UV emission and absorption features of comets, planets, and other solar system bodies. It will provide fundamental scientific results in many key areas of solar system research, such as (1) measurements of noble gases in comets and in the atmospheres of Mercury and Titan, (2) studies of the coupling between solar system bodies and their magnetospheres, e.g., the energy budget of the Io torus, (3) investigations of high-temperature outer-planet thermospheres and hot-atom coronae around the terrestrial planets, (4) atmospheric chemistry studies, through observations of signature absorptions of reflected sunlight from Venus, Mars, and the giant planets, (5) studies of the chemistry of comets and upper atmospheres using signature atomic and molecular emission features, and (6) synoptic observations of solar system bodies to determine weather and climate in response to external and internal forcings.

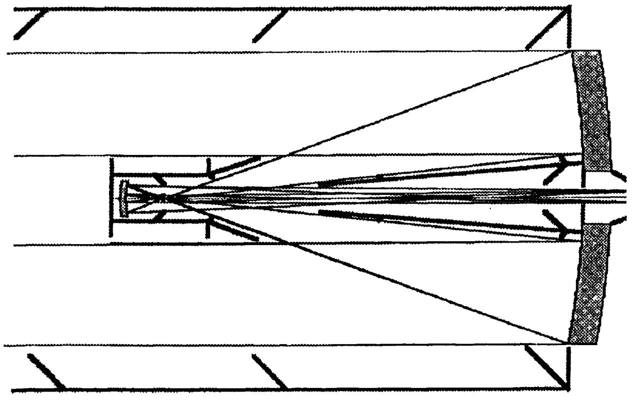
OPTICAL DESIGN

The best two-mirror centered telescope design for suppressing stray light is the Gregorian. The SST has concave primary and secondary mirrors, an aperture diameter of 1.4 m, a focal length of 28 m, and an f/number of 20. Field and Lyot stops, placed at the internal focus and exit pupil respectively, suppress secondary scatter. A Gregorian telescope is slightly longer than a Cassegrain, but its stray light rejection is 10–100:1 better for the same mirror roughnesses, and the additional length of 37 cm does not pose a problem. The Gregorian focal surface is more steeply curved; however, this is acceptable over the fields used by the SST instruments. The design is shown in Figure 2; the prescription is included at the end of this paper.

The near-UV imager, operating over the 250–450-nm spectral band, is adapted from the Cassini imager and is used with minimum modifications. The spectrographs consist of a slit at the Gregorian focus followed by a grating formed on a concave toroid.

Silicon carbide is used for the mirrors, graphite-aluminum (Gr-Al) metal matrix composite for the mirror mounts, and Invar for the metering structure and inserts. The CTE of the Gr-Al and Invar has been adjusted to match that of silicon carbide at room temperature ± 30°C.

The focal plane layout is shown on Figure 3. The center of the field, measuring 0.13 deg square (~ 64 mm) is used by the near-UV imager. Slits for the spectrographs are placed at four locations around the edge of the visible imager, 0.10 deg from the optical axis.



Optical Prescription

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LENS
LI,SST Gregorian 1.4 meter f/20
WV .35 .3 .4 .25 .45
SAY 700
SCY FANG .163
C, SURFACE NO. 0
TH 1.E+20
AIR
C, SURFACE NO. 1
TH 2700
AIR
C, SURFACE NO. 2
CC -.99902174
REFS
CV -2.3809524E-4
COBS 78
CLAP 700
TH -2300
REFL 0 100
C, SURFACE NO. 3
CC -.74866837
PIKUP TH -1 -1 0 0 1
CV .0026875002
CLAP 73.3
REFL 0 -25
C, SURFACE NO. 4
PY
AIR
C, SURFACE NO. 5
CV .004389
EOS
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Figure 2. SST Gregorian telescope.

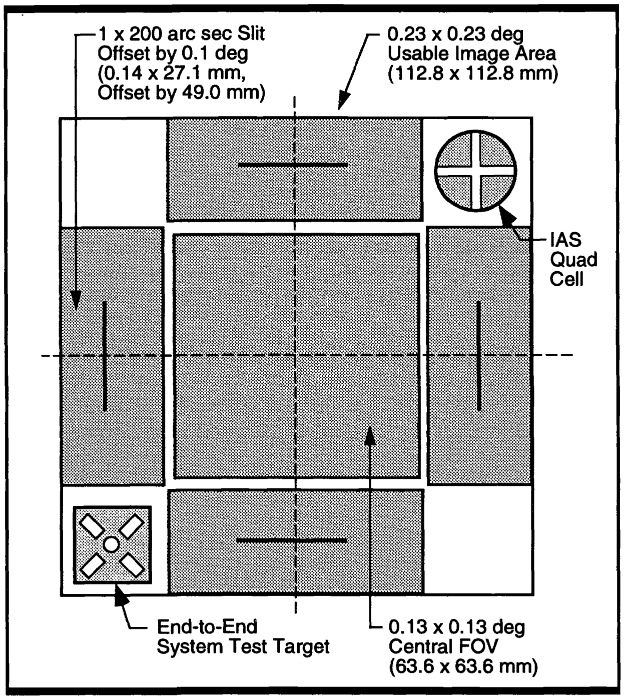

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Figure 3. SST focal plane layout.

The polychromatic diffraction point-spread function (PSF) for the telescope was calculated for the 250–450-nm spectral region. The PSFs on axis and at the edge of the UV imager field of view, at best focus, are shown in Figure 4.

SILICON CARBIDE MIRRORS

The silicon carbide ceramic used for the mirrors is Sicar, which was developed by scientists at the Vavilov State Optical Institute in St. Petersburg, Russia. Sicar is a two-phase material, 83% silicon carbide with a silicon fill. Sicar has isotropic thermal and mechanical properties, specific rigidity nearly equal to beryllium, and thermal stability in the presence of gradients nearly twice as good as Ultra Low Expansion Fused Silica (ULE). Its CTE is moderate, about the same as Invar 39, but its thermal conductivity is 150 times greater than ULE, resulting in a thermal stability superior to that of all of the other materials. Mirrors made of Sicar have shown neither distortion nor hysteresis when cycled between room temperature and 10 K. Sicar can be directly polished to a surface roughness of 10–15 Å. To achieve 3–5 Å, polishing must be done on a silicon overcoat.

The primary mirror is plano-concave with lightweighting cavities and a closed back to minimize gravity deflection. The design of the mirror and mount is shown in Figure 5. The mount is a two-level six-point

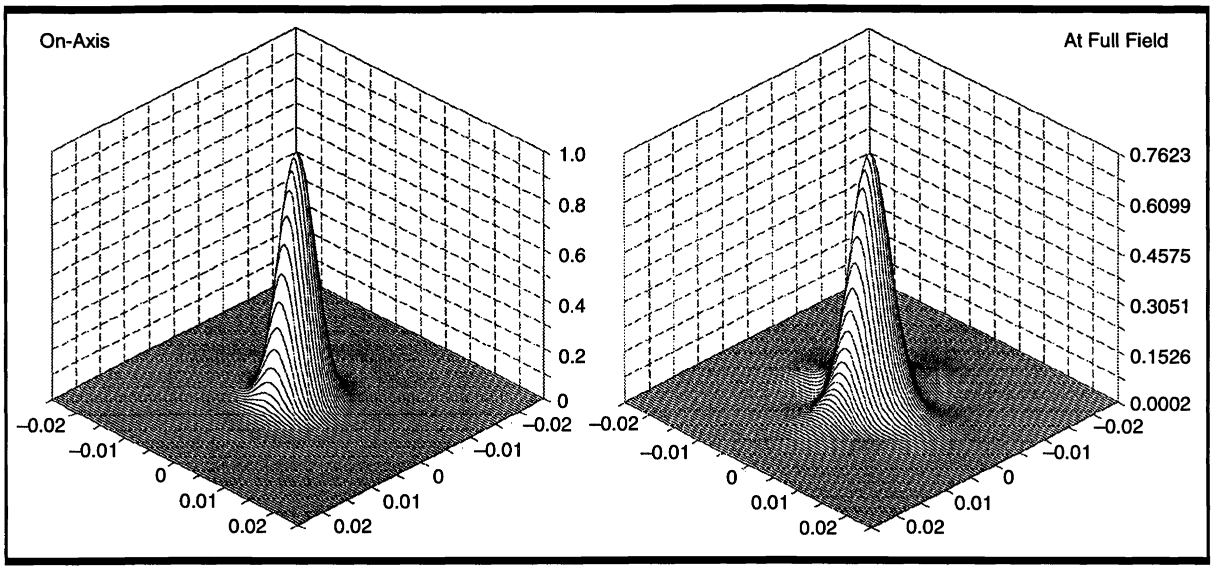

Figure 4. Polychromatic diffraction point spread functions at best focus.

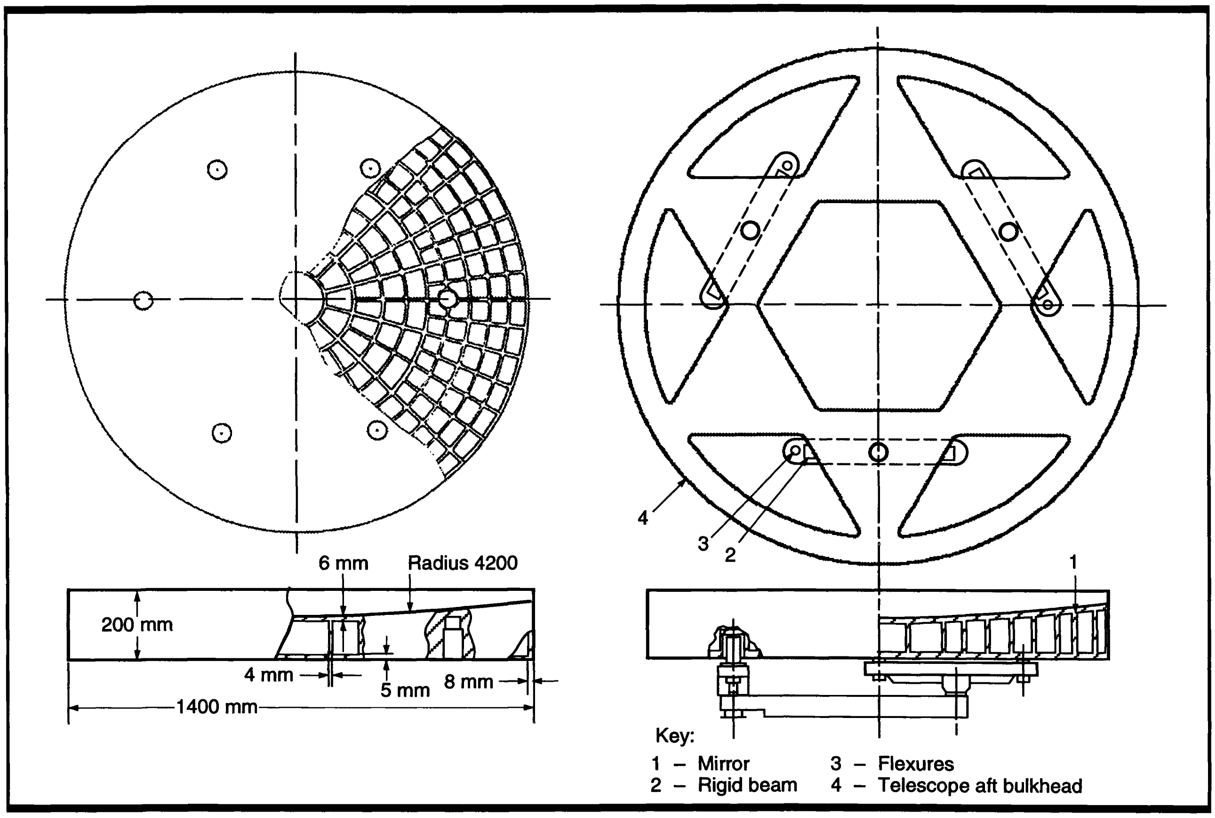

Figure 5. Design of mirror and mirror mount.

design, with Invar kinematic inserts bonded in cavities in the mirror core structure. It is made of Gr-Al metal matrix composite with its CTE matched to that of the SiC and Invar. The gravitational sag of this mirror held in its mount is 0.03 waves at 632.8 nm with a vertical optical axis and 0.014 waves with a horizontal optical axis. This permits us to test the telescope on its side, a major simplification for end-to-end testing of the SST. The small gravity deflections are one of the major advantages of using SiC for mirror material. The results of finite element analysis of the mirror's gravity sag are shown in Figure 6.

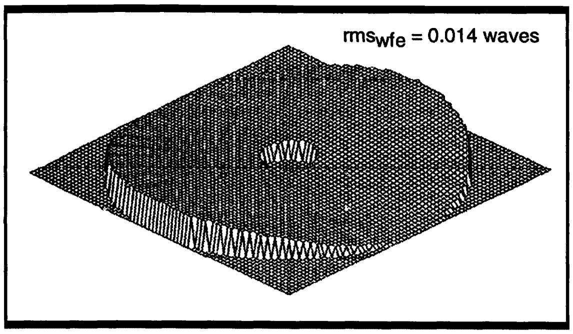

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Figure 6. Gravity sag of SST primary mirror, horizontal optical axis.

COATINGS

Boron carbide has the best reflectivity of any known material in the 58–150-nm spectral region. An aluminum undercoating will allow the telescope to operate satisfactorily in the 250–450-nm spectral region. Reflectivity is so low that the telescope is not suitable for observations in the visible. The reflectivity of boron carbide on aluminum, measured at Goddard Space Flight Center, is shown in Figure 7.

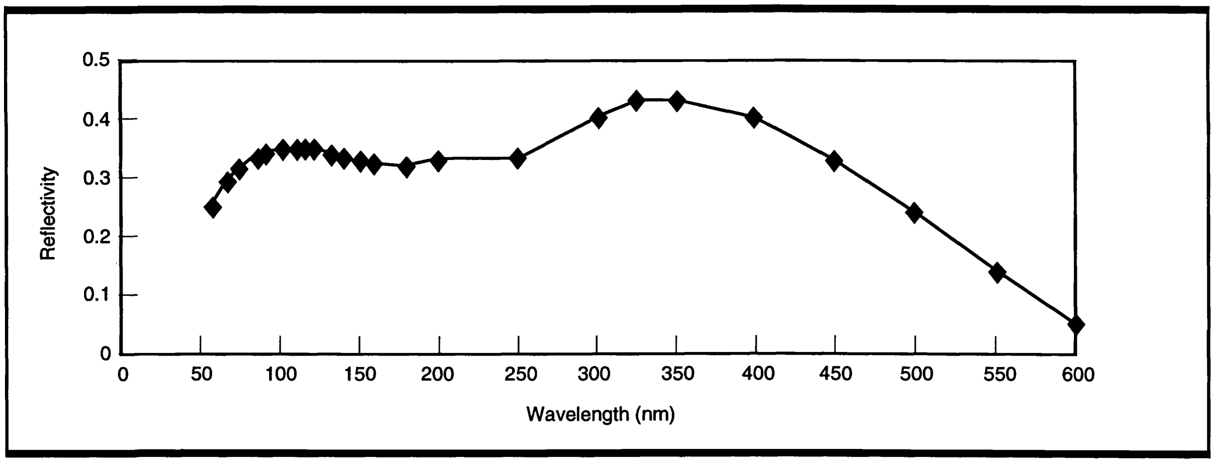
TELESCOPE METERING STRUCTURE

The primary mirror mount is attached to the telescope structure through the GrAl triangular bulkhead shown on Figure 1. The metering tube, an aluminum monocoque structure with stiffening rings and Invar metering rods held in six channels spaced equally around the perimeter, is joined to the bulkhead. The secondary mirror assembly is attached to the metering tube through flexures, which provide the required lateral stability while allowing the aluminum tube to expand and contract as the temperature changes. The Invar rods maintain the separation between the mirrors. This design has been used on a number of existing programs.

STRAY LIGHT CONTROL

Stray light in the SST arises from two sources: (1) primary scatter from the primary and secondary mirrors, due to residual roughness and, possibly, contamination, and (2) secondary scatter, out-of-field light reaching the focal plane due to scatter from inside the telescope. Both sources have to be controlled.

Bare Sicar can be polished to a roughness of 10–15 Å, which is nearly adequate for this program. However, much of the SST's work will involve observations of faint sources in the presence of a bright object (for example, the Saturn



7153/fig 07

Figure 7. Measured reflectivity of boron carbide versus wavelength.

magnetosphere with the bright planet only 40 arcsec away), so we have established a goal of 3–5 Å roughness. This cannot be achieved by polishing on bare Sicar; therefore, the mirror will be coated with a layer of silicon, which will be polished and will serve as the mirror surface.

Baffles, field stops, and a Lyot stop for suppression of out-of-field stray light from primary and secondary scatter are shown in Figure 8. A field stop is placed at the focus of the primary mirror, and a second stop is placed in the hole in the center of the primary mirror. The Lyot stop is placed at the exit pupil for further suppression of stray light. Field and Lyot stops are part of the same structure. The field stop is a perforated four-sided pyramid having specular outside surfaces. It is supported on a four-legged spider assembly of polished aluminum. Each leg has a triangular cross section with the sharp edge pointing towards the primary mirror. There are no direct illumination paths to the focal plane, and both primary and secondary scatter were taken into account in designing the baffles.

The baffle surfaces and the field and Lyot stops are made of bead-blasted aluminum for optimum efficiency in the UV. Most of the surfaces are diffuse, although some (such as the outside of the field stop assembly) are specular to prevent secondary scatter from reaching the focal surface.

We used APART/PADE to calculate radiation scattered from the tube, mirrors, baffles, and struts to a spectrograph slit. The wavelength used was 308 nm, and a 10-cm autocorrelation length was assumed. We calculated the power deposited on a spectrograph slit having a dimension of 1 by 200 arcsec for various point source angles measured with respect to the center of the slit. The calculations were made for a range of surface roughnesses, from 36 Å (the measured value for the HST primary mirror) to 1 Å.

At small point-source angles, scattering from the primary mirror is the dominant factor. Figure 9 shows the point source power at the spectrograph slit as a function of off-axis angle for surface roughnesses between 1 and 36 Å. The two top curves are for the HST and the SST, both with measured 36 Å surfaces. The SST's Gregorian design reduces stray light intensity by about 25:1 compared to the HST, for the same mirror roughness, at off-axis angles up to about 1 arcmin. Reducing the SST's surface roughness to 10 Å will reduce scattered power by about 350:1. If the mirror surfaces can be polished to 5 Å, scattered power will be reduced by about 1400:1, compared to the HST.

With a 10-Å surface, the scattered light from Saturn would be undetectable while imaging the magnetosphere, a marked improvement over the HST, where scattered light has the same intensity as the magnetosphere itself.

We also calculated the scattered light count rate with the Sun 7 deg from the optical axis. The count rate is only 2 counts per second, far below the count rate of a comet near perihelion.

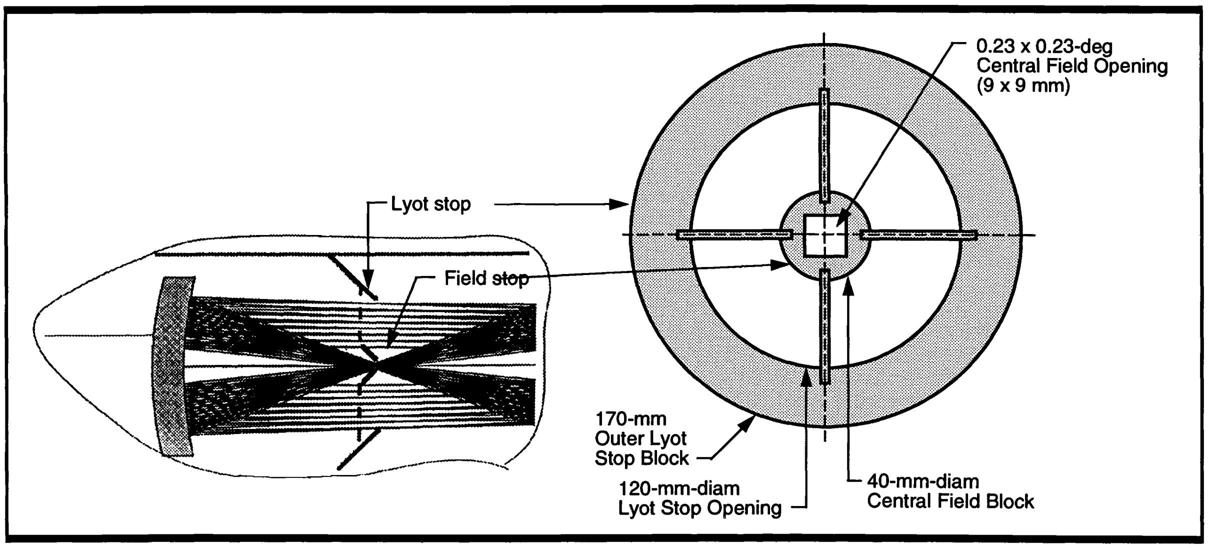


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Figure 8. SST field and Lyot stops.

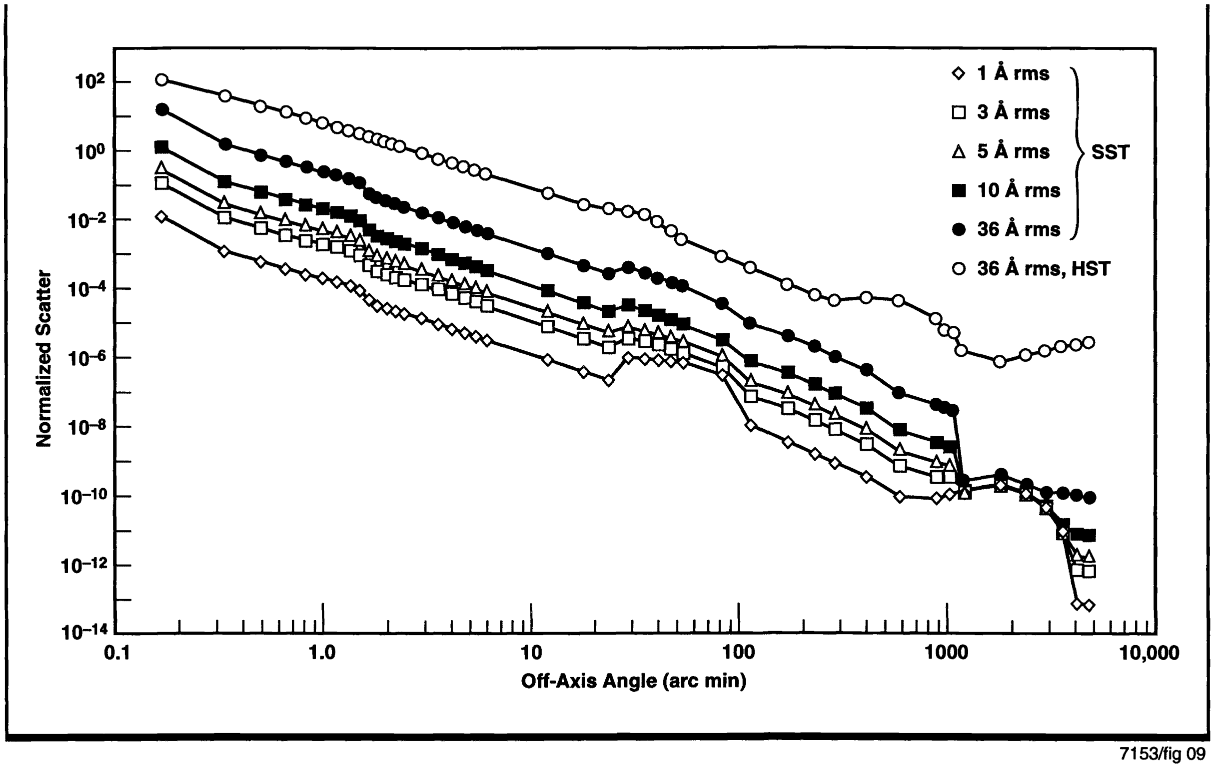

Figure 9. Stray-light intensity versus off-axis angle and rms surface roughness.

THERMAL CONTROL

The SST mirror coatings were designed for optimum reflectivity in the UV, but reflectivity in the visible and near infrared is very low, see Figure 5. This means that the mirror will have high emissivity and will radiate an estimated 300 W during observations against a deep space background. The mirror will also absorb significant amounts of heat during operation in the vicinity of the Sun.

The telescope is designed to remain in focus over very wide temperature ranges, ± 30°C; however, a cold primary mirror will introduce unacceptable thermal gradients in the instrumentation section and, conversely, when observing near the Sun, will cause the instruments to heat up.

Our solution to these conditions is twofold: (1) incorporate active thermal control to hold the mirror at or near nominal temperature while observing against space and (2) control the exposure time when observing near the Sun. We believe that the limit on solar exposure will be driven by the temperature of the instruments, not the telescope.

LINE-OF-SIGHT STABILIZATION

The CRSS spacecraft will provide open-loop pointing to 10 arcsec and a line-of-sight (LOS) stability of 0.2 arcsec, one sigma. However, the SST will produce a polychromatic image approximately 0.05 arcsec in diameter; images will have to be held to that accuracy on the spectrograph focal planes for optimum spatial and spectral resolution. Therefore, additional control of the LOS will be required, ideally to reduce the error residual to about one-fifth of this value, or 0.01 arcsec. This will be accomplished through the use of an inertial angle sensor (IAS), shown schematically in Figure 10.

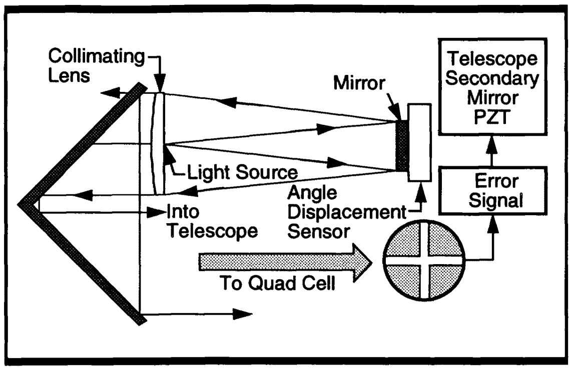

Figure 10. Schematic of inertial angle sensor.

A light source, typically a fiber fed by an LED, is placed at the second principal point of a lens having a diameter of 50 mm. Emitted light is reflected from a mirror placed one-half the focal length away. The mirror is articulated in tip-tilt via signals from an orthogonal pair of Systron & Donner 8301 angle displacement sensors (ADSs), which are commercially available and space qualified; they are used on both HST and GOES.

Light emerging parallel from the IAS remains steady in inertial space and is injected into the telescope to provide a reference. The axis of the IAS beam is pointed so that it makes its way to a quad cell installed in one corner of the focal plane. Any drift from the center of the quad cell will be due to spacecraft drift or other factors. An error signal will be developed and used to move the secondary mirror in tip-tilt, stabilizing the image. Designs of this type, sometimes called inertial pseudo star reference units (IPSRU), have demonstrated LOS stability in inertial space to a few nanoradians for angular deviations of up to about 10 arcsec.

This LOS stabilization method was developed for use on the Space Defense Initiative (SDI), and several versions have been built and tested. The sensor whose performance is illustrated in Figure 11 was able to stabilize the line of sight in this laboratory demo to a maximum error of 34 nrads. This is approximately twice the SST requirement.

OPTICAL TESTING

The telescope will be tested interferometrically using a full-aperture plano mirror, as shown on Figure 12.

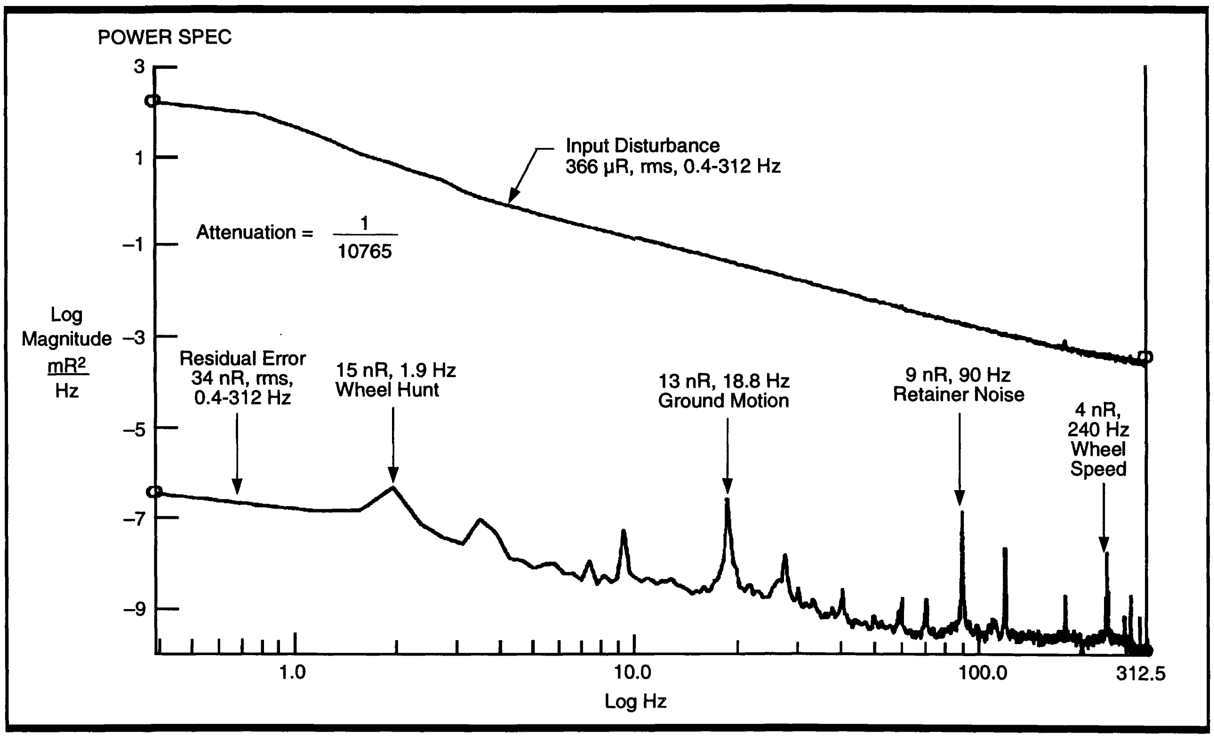

Figure 11. Measured performance of an inertial angle sensor.

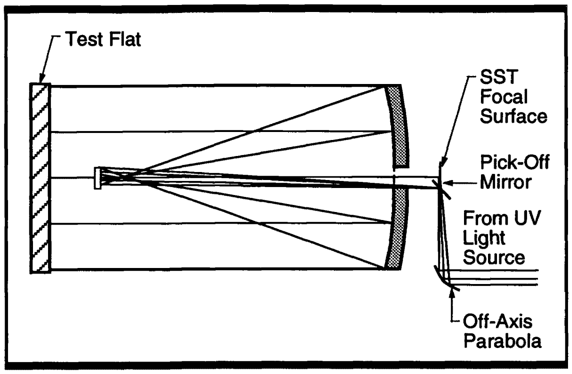

Figure 12. SST end-to-end test setup.

The mirror will be pointable in azimuth and elevation. A pick-off mirror and mask, subtending an angle of approximately 1 arcmin, will be permanently installed in one corner of the flight focal plane. A collimated beam of UV light, from a microwave hydrogen discharge source covering the wavelength range from 58 to 450 nm, will be focused using an off-axis parabola and will illuminate the mask. This illuminated target will be collimated by the telescope and reflect from the plano mirror, then back into the telescope.

The plano mirror will be aimed in azimuth and elevation to cause the return beam to illuminate each of the spectrographs and imagers, one at a time. It will be pointable open loop to approximately 30 arcsec, about half the 1-arcmin mask field; vernier pointing will be done using joy stick control to center the target on each focal plane.

To verify optical performance, we will use phase diversity to recover the wavefront (the second focus position will be obtained by moving the secondary mirror), verifying that the system is within specification. The spectrographs, having much lower resolution than the imager, will be calibrated by measuring throughput, comparing predicted signal levels with those actually observed.

SPACECRAFT

The SST bus is a modified CRSS spacecraft weighing 430 kg. Attitude is controlled by momentum exchange, with four wheels providing stability of 0.2 arcsec one sigma. Inertial reference is from two star sensors, with open-loop pointing to 10 arcsec. Power is provided by a 50-A-h battery and three solar arrays. Command and data handling is from a rad-hardened MIPS R3000 CPU with up to 80 Gbits memory, of which the SST will install 4 to 8 Gbits. Communication is provided by a two-axis gimballed antenna. Active thermal control is provided by strip and zone heaters, and propulsion for wheel desaturation and orbit maintenance is by hydrazine thrusters. The first CRSS flight unit has been assembled and tested, and the second is in final assembly. Thus, we are able to utilize existing Lockheed Martin (LM) production and test facilities to provide a spacecraft bus at minimum cost and with very low risk.

Additional LOS stability beyond LM900's 0.2 arcsec will be provided by actuation of the telescope secondary mirror, using error signals derived from the IAS. LM has experience with articulated secondary mirrors for image stabilization, having employed the technique successfully on a number of programs, including SOHO and SPACELAB II. Its use eliminates the need for an expensive attitude control system.

The CRSS solar arrays do not provide adequate power for SST and will have to be replaced. We will utilize GEO-qualified gallium arsenide solar cells from the LM A2100™ spacecraft, with single-axis gimbal taken from LM's Iridium™ program to orient the arrays toward the Sun during long observations. The gimbal will be locked during data collection to avoid disturbances.

The weight and power estimates for the observatory are given in Table 1.

GROUND STATION

The SST ground station will be a turnkey installation provided by Scientific Atlanta (SA). SA is under contract to provide the ground stations for both the Iridium™ and CRSS programs. The ground station includes a 5-m dish to be used for both transmit and receive operations, a 200-W S-band transmitter, an S-band receiver/demodulator, data recorders, a data server, and joystick control of telescope pointing. The system can operate in either normal or safe mode. In safe mode, automatically activated commands will close the telescope door.

Table 1: Weight and power summary

Item	Weight (kg)	Power (W)
Spacecraft Bus	430	417
Telescope	220	150
Instruments	65	300
Total	715	
Delta II 7923 Capacity	909	
Weight Contingency	194	

During normal operation, commands will be uplinked to the spacecraft in the 2025–2110-MHz band at 10 kbps, and telemetry will be downlinked from the satellite in the 2200–2300-MHz band at 1 Mbps.

OPERATIONAL CONTROL

The telescope will be pointed by commands that place the target in the center of the telescope's field of view. Fine guidance will be provided by a joystick for the operator to position the target in real time. Output from the slit-jaw imagers (for joy stick pointing and correlation tracking), spectrographs, and broadband imager will be routed to the existing data processing subsystem, a MIPS R-3000 rad-hardened CPU addressing on-board high-speed storage unit (HSSU). The HSSU has a design storage capacity up to 80 Gbits, of which we will install 4–8 Gbits, depending on weight, power, and cost. Data are sent to the signal-conditioning electronics, then to the high-gain communication system.

Short-term ground data storage will be provided by a local data server which can be accessed through the Internet. Long-term data storage will be provided through either tape backup or CD-ROM.

LAUNCH VEHICLE

A McDonnell Douglas Delta II 7925 launch vehicle with a 2.9-m fairing is used to launch the SST into a 35,786-km circular orbit at 5-deg inclination. This allows a 200-kg weight margin.

CONCLUSIONS

The original goal of this work was to determine whether combining Russian silicon carbide mirror and telescope technology with a modified commercial spacecraft would enable the replacement of the International ultraviolet Explorer (IUE) satellite at minimum cost. The IUE operated from 1978 to 1996 as a joint NASA-ESA facility for UV space astronomy. For two decades it served as the observatory that did the necessary day-to-day data gathering vital to both paving the way and following up on the discoveries of very large ground-based observatories, such as the Keck and the Palomar.

In September 1996, the Discovery Mission Announcement of Opportunity was released, leading us to perform a detailed cost and technical study to assess the scientific utility of the concept and arrive at a realistic price. We also discovered that the basic design could be adapted, with very minor modifications, for both the planetary mission described in this paper and for the IUE mission mentioned above. Further, we found that the SST design provided significant improvements in capability over the HST. For example, our 1.4-m observatory could outperform the HST in scattered-light rejection by more than 1000:1 for important planetary applications. The use of a geosynchronous orbit also adds major advantages over the HST for uninterrupted observations and long-term monitoring.

A ground-station and analysis facility on a university campus also proved to be feasible, offering both student involvement and real-time feedback and control over the observing process by the scientist.

We suggest that two to four SST-like observatories, each tailored to specific objectives, such as solar-system observations, stellar observations, imaging and spectroscopy of extended cosmic sources, etc., would open major opportunities for space astronomy research and create high leveraging for the results from the HST, Keck, and other premier facilities.

Our Discovery Mission cost estimate of $89M demonstrates that this is a realistic option for NASA and the research community to follow. The 10:1 oversubscription for HST time by the astronomical community clearly shows the need for facilities of this caliber.