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THE ULTRAVIOLET IMAGING TELESCOPE: DESIGN AND PERFORMANCE

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ABSTRACT

The Ultraviolet Imaging Telescope (UIT) was flown as part of the *Astro-1* Spacelab mission on the Space Shuttle *Columbia* in 1990 December. The ultraviolet images of a wide variety of astronomical objects were recorded with a 40′ diameter field of view. Images of targets as faint as magnitude 21 (ultraviolet) were secured with a resolution of about 3″. This *Letter* describes the design, flight operations, data reduction, and overall technical performance of the UIT.

Subject headings: artificial satellites, space probes — telescopes

1. INTRODUCTION

The Ultraviolet Imaging Telescope (UIT) consists of a 38 cm Ritchey-Chrétien telescope equipped for ultraviolet filter and grating imagery over a 40′ field of view (FOV). UIT contains two detector systems: a far-UV detector system (B) with a CsI photocathode and a near-UV camera (A) with a CsTe photocathode. As part of the Astro complement of three co-mounted ultraviolet experiments, the UIT is mounted on the Spacelab Instrument Pointing System (IPS) in the Space Shuttle payload bay (Fig. 1, Plate L1). We describe the instrumental configuration, calibration, and operations during the first flight of the UIT on the *Astro-1* mission, 1990 December 2–10. The UIT produced 361 near-UV frames and 460 far-UV frames on 66 astronomical targets, comprising four solar system objects, 29 galactic fields, eight Local Group galaxy fields, 16 other galaxy fields, and nine deep fields, including clusters of galaxies and quasar fields. Most images were made with the broad-band NUV (A1) and FUV (B1) filters; a medium width FUV filter (B5) was also used frequently during orbital day. The optics, light baffling, and image motion compensation system are summarized in § 2; detectors and electronic subsystems are described in § 3; the instrument computer and flight operations are discussed in § 4; instrument calibration is reported in § 5 and data reduction in § 6.

2. OPTICAL DESIGN

The UIT design is illustrated in Figure 2. UIT is a 38 cm Ritchey-Chrétien telescope; the measured optical and mechanical properties are listed in Table 1 and Figure 3. A diffraction analysis demonstrates that a 0.0075 mm diameter (0″.45) circle in the focal plane encloses 80% of the flux in an on-axis image of a point source at wavelength 632.8 nm. A rotating diagonal mirror directs the converging light from the secondary mirror to either of the two detector systems. Additional fixed mirrors fold the light paths to produce a more compact packaging of instrument components. A six-position filter wheel is located about 70 mm in front of each detector to accommodate either metal-dielectric interference filters, crystalline plates, or fused quartz. The most efficient filters are when the crystals or the fused quartz alone defines a transmission band from its short-wavelength limits and the long-wavelength limits are defined by the cathode's photoelectric threshold. The crystals are MgF_2, CaF_2, SrF_2, and crystalline quartz. Parfocalization assures that each complement of filters shares a common focal plane. The plane-parallel transmission filters introduce axial and lateral chromatic aberrations and some spherical aberration in the converging light beams. These aberrations are partially compensated by the use of a plano/convex lens for the image tubes in the designs of the detector system MgF_2 windows. The UIT total response curves measured for each of the filters used in the *Astro-1* mission are shown in Figure 3. An empty filter wheel slot in detector system A (CsTe detector) is used during grating mode observations. When in this mode, a spectral resolution of 19 Å is achieved over the FOV. The spectral resolution is limited by the detector rather than by the

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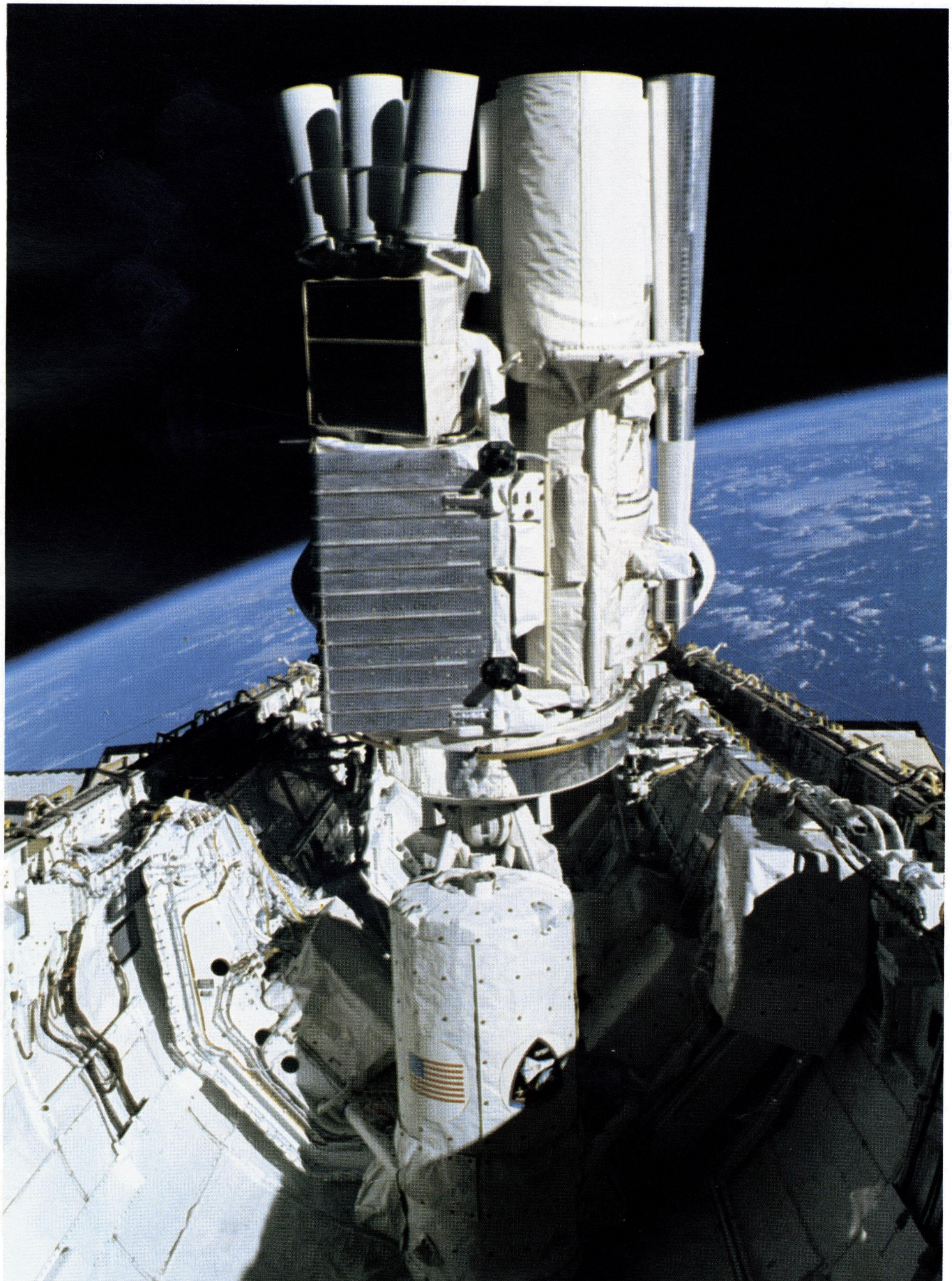

FIG. 1.—*Astro-1* observing from the Space Shuttle *Columbia's* bay showing the Ultraviolet Imaging Telescope and the startracker that is attached to UIT on the right.

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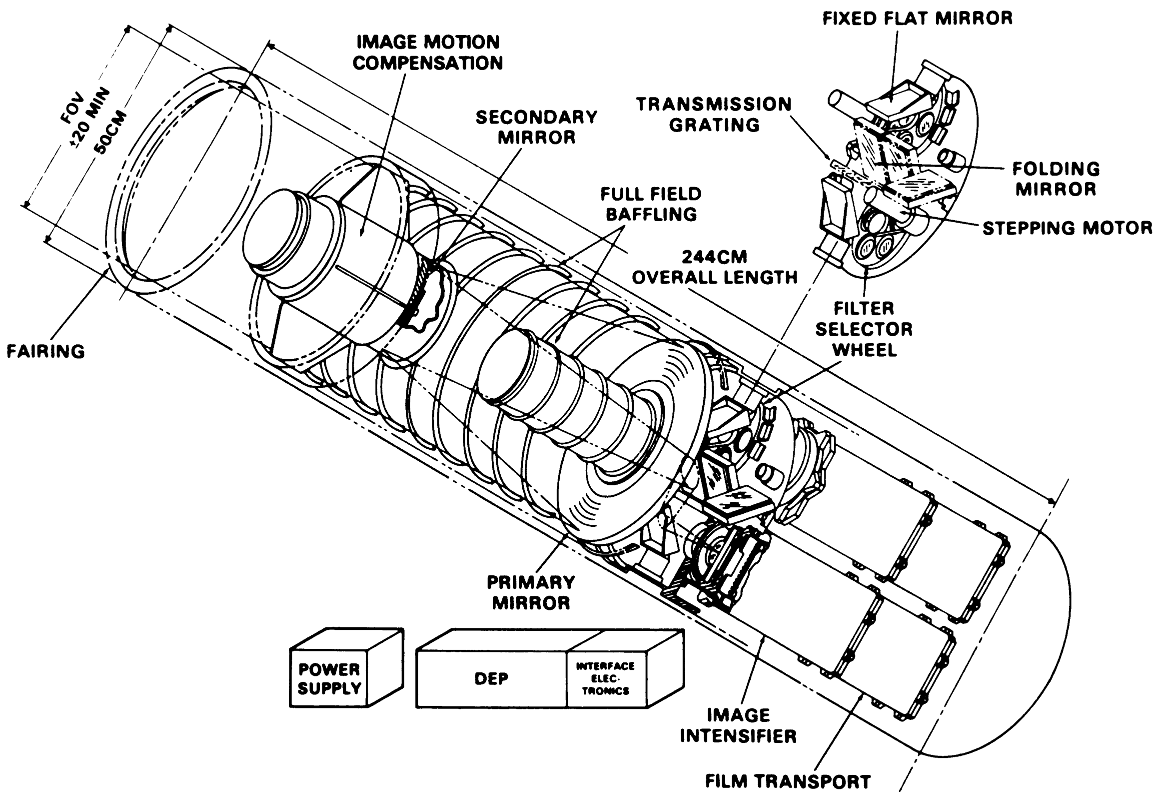

FIG. 2.—Optical diagram of the Ultraviolet Imaging Telescope

optics. The 75 lines mm^{-1} transmission grating is ruled on a CaF_2 substrate with a center thickness of 4.920 mm. The blaze angle is 1°16 and the linear dispersion is 840 Å mm^{-1}.

Internal telescope baffling is provided to assure a minimum of two scatterings before light from outside the FOV can reach the detector. An external, cylindrical Sun baffle mounted ahead of the telescope contains annular sub-baffles and a polished cone, oriented so as to efficiently reflect away light incident at greater than 51° to the telescope axis.

An Image Motion Compensation (IMC) system is provided to stabilize the UIT image at a finer level than possible with the IPS alone. Payload motion is sensed by two gyroscopes, which are updated by information from a CCD startracker. The gyros provide error signals to counteract the corresponding image motion in the UIT focal planes through a closed-loop servomechanism that controls small tilts of the UIT secondary mirror about two axes. Post-flight measurements on the *Astro-1* mission film show that the UIT jitter specification ($3\sigma = 1''.0$ peak to peak) was met or surpassed during all observations but one.

TABLE 1

TELESCOPE PARAMETERS

Parameter	Value
Clear aperture (cm)	38
Effective focal length (cm)	342.900
System focal ratio	f/9.0
Obscuration ratio	0.41
Field of view (arcmin)	40
Plate scale (arcsec mm^{-1})	56.8

3. DETECTORS AND ELECTRONIC SUBSYSTEMS

The UIT detector systems consist of MgF_2-windowed, dual-stage, magnetically focused image intensifiers. Detector system A uses a CsTe photocathode for the near ultraviolet and the grating. Detector system B is optimized for the far-ultraviolet and the grating with a CsI photocathode. The image intensifiers are focused with samarium-cobalt magnets arranged so that the magnetic poles are oriented radially in at one end and radially out at the other. The magnetic flux paths are united by a soft iron outer cylinder. The 165 gauss axial field causes the photoelectrons to follow one-turn helical paths when accelerated through 13 kV. Field uniformity is on the order of 1%. High-voltage power supplies are located in the film vaults, which are maintained at a pressure of 1 atm to prevent corona. The cathodes are at ground, with the high-voltage anode at 26 kV. Potentials of +700 volts and −100 volts are applied to a grid near the cathodes to serve as an electronic shutter. Each of the photocathode-window combinations provides good UV response and is insensitive to long-wavelength light: for CsTe, $\lambda > 3500$ Å, and for CsI, > 2000 Å. The first image intensifier stage in each detector has a P20 phosphor and is coupled through fiber optics to the second stage, which has a bialkali photocathode. The second-stage output is generated in a P11 phosphor and is transmitted by fiber optics to 70 mm Eastman Kodak IIa-O film, which has a conductive carbon backing.

Annotation devices controlled by the Dedicated Experiment Processor (DEP; see § 4) project the frame count, the exposure time, a 30 step gray scale and fiducial marks on each frame. The film transports each hold about 1200 frames. The film is advanced by stepper motors controlled by the DEP. A platen solenoid holds the film away from the fiber optic extenders during frame advances.

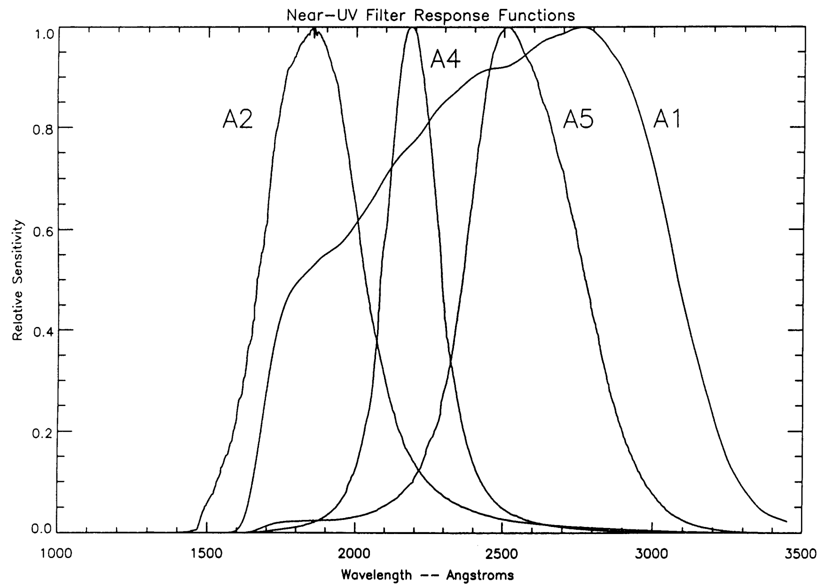

FIG. 3*a*

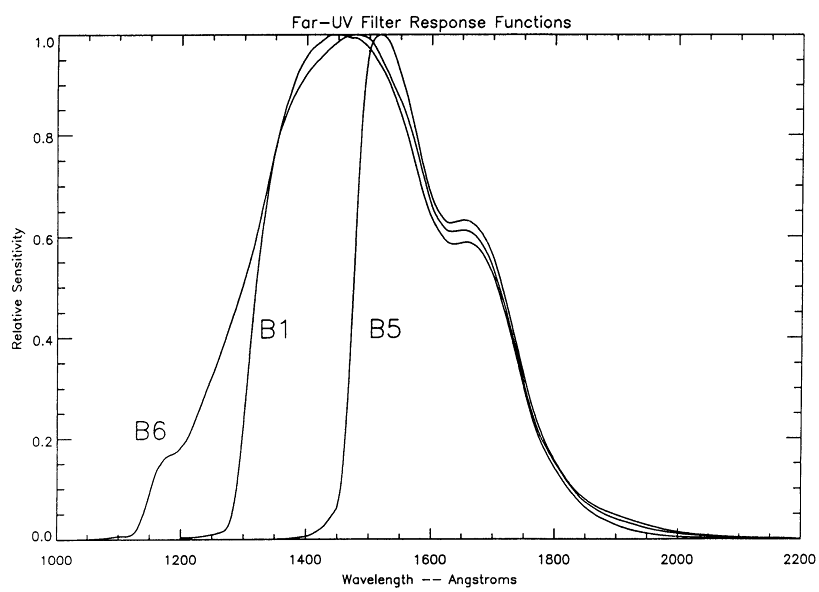

FIG. 3*b*

FIG. 3.—Total response curves for the UIT with the various filters employed with (*a*) detector system A and (*b*) detector system B

4. UIT COMPUTER AND FLIGHT OPERATIONS

The Dedicated Experiment Processor (DEP) controls the operations of the UIT and its interaction with the onboard and ground-based observers. It is operated by flight software and/or by real-time commands and consists of two identical Motorola M6800 microprocessor systems with memory, input/output, and dedicated function hardware. All UIT operations during *Astro-1* were to be conducted by astronaut Payload Specialists using two Data Display Unit (DDU) computer terminals, a controller for manual guiding, and optical information from the Hopkins Ultraviolet Telescope (HUT) and Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE). After failure of both DDU computer terminals three days into the mission, the Astro instruments were commanded from the Payload Operations Control Center (POCC) at the Marshall Space Flight Center. In the case of the UIT, which recorded its images on photographic film, the telemetry reported instrument status but did not provide information on the quality of scientific data. The Mission Control Center at the Johnson Space Center generated the IPS commands. The flight crew examined HUT acquisition images on a television monitor and conducted target acquisition and verification and manual telescope guiding.

5. CALIBRATION

The UIT was calibrated in the Laboratory for Astronomy and Solar Physics at Goddard Space Flight Center in 1985 February. The total response of the UIT was determined in a vacuum tank in each of 11 filter bandpasses and for the grating mode. The light source for this work was an auxiliary Cassegrain telescope equipped with a scanning monochromator with a hydrogen lamp at its focus. Photomultipliers were placed at the UIT image intensifier output and in the beam of the auxiliary telesope. As the monochromator scanned each filter bandpass, the ratio of the two signals provided the relative response of the UIT with wavelength. The results for each filter bandpass that was used is shown in Figure 3.

Flat-field exposures were made with the same hydrogen lamp, which illuminated a finely ground, aluminized, quartz flat positioned to obscure the auxiliary telescope secondary mirror and serve as a Lambert surface. These exposures were used to correct flight data for sensitivity variations over the FOV of up to 40% to less than 2% and were also used to determine the characteristic curve of the IIa-O film. For this purpose, a sequence of exposures was obtained with exposure times increasing by factors of 2 over a large range. The linearized scale of the characteristic curve for the IIa-O film is derived from this exposure sequence. The UIT has no reciprocity failure, because each detected photon is amplified sufficiently to register on film. The determination of the absolute sensitivity was tied to standard photodiodes from the National Bureau of Standards (now NIST).

Plans to calibrate the UIT in flight with flat-field exposures of the Earth and with observations of white dwarf fields over a wide range of exposure time were not successful due to the necessity of revising the observing schedule to make commanding from the POCC possible. Therefore, observations made for astronomical purposes are used to verify the laboratory calibration. The characteristic curve for the IIa-O film is confirmed by checking the densities of three images of each field with exposure times typically differing by factors of 5. The absolute calibration is verified and refined by comparing measured fluxes for appropriate sources in UIT flight films with results from 66 observations that are in common with the *IUE*, *OAO 2*, HUT, and *ANS* missions.

UIT noise characteristics are determined from repeated measurements of the laboratory flat-field source and stellar fluxes. Becauses the UIT records its images on film, its noise/signal ratio is small over the center of its dynamic range and increases at the extremes. The normal observational procedure is to make exposures of each field in each filter in time ratios of 1:5:25. Surface photometry of well-exposed sources over regions several arcseconds in extent is repeatable to 5%–10%. The uncertainty in the absolute calibration is estimated at 15%, which is slightly greater than the 10%–15% error assigned to the *IUE* stellar reference fluxes.

The faintest stellar images recorded in exposures of order 1000 s in the broad NUV bandpass correspond to $m_{\rm NUV} \sim 21.0$, or $V \sim 24.4$ for hot unreddened stars, where $m = -2.5 \log ({\rm flux}) - 21.1$. In the broad FUV bandpass, the corresponding limit is $m_{\rm FUV} \sim 19.3$, or $V \sim 24.0$. Photometry of the faintest sources and sky background suffers in accuracy because the measurements are made near film fog level. Effects of artifacts due to flat-fielding and other sources such as scratches introduced during film processing and microdensitometry compound this problem.

The UIT point spread function (PSF) is evaluated by measuring the sizes of stellar images on frames from each camera, which are specially digitized with 10 μm spacing. After correction for the finite digitization aperture, the mean full width at half-maximum (FWHM) of the (Gaussian) stellar profile is 2".3 in the near-ultraviolet (Detector System A) and 2".5 in the far-ultraviolet (Detector System B). These values represent the PSF under benign flight conditions, during which no unusual crew-induced transients occurred and after the IMC system was carefully tuned. The FWHM as measured directly from digital images with the usual 20μ digitization interval is 0".6 larger. These average values include the results of pointing error, the digitization process and coma, which increases the FWHM by about 20% over the outer 20% of the FOV. Stellar images have sharper cores than in a true Gaussian function.

6. DATA REDUCTION

The photographically recorded data from the *Astro-1* flight of the UIT were converted to digital form by scanning with the Perkin-Elmer Model 1010 m microdensitometers at GSFC. Fiducial marks exposed on the film in flight are used to align a frame with a repeatability of 20μ or better, which ensures consistent registration when the flat-field calibration is applied to the data. All frames are scanned with a 20μ square-aperture and a sample spacing of 20μ and some portions of some frames are also scanned with a 10μ spacing. The background fog is measured from unexposed film at the edge of the frame, which is not exposed to the sky. The digitized density data are reduced with a special purpose batch processing system on a mainframe computer. Sequentially, this software (1) corrects for background fog, linearizes the data, and applies the flat-field calibration; (2) performs point-source photometry and makes astrometric solutions for source positions using the *Hubble Space Telescope* Guide Star Selection System Catalog (Lasker et al. 1988); and (3) transforms each frame to a north-up, east-left orientation.

FITS image format is used for all data products, both intermediate and final. The standard data products that will be archived are 16-bit 2048 × 2048 pixel images. A density image, an intensity image in the original orientation, and a north-up, east-left rotated and resampled intensity image will be delivered to the NSSDC. A versatile interactive analysis system, based on the Interactive Data Language (IDL), has been developed for use on UIT images and is available to users of the UIT data set.

We gratefully acknowledge the dedicated work of the *Astro-1* flight crew, including Mission Specialists Jeffrey Hoffman and Robert Parker and Payload Specialist Sam Durrance. Thanks are due also to *Astro-1* Mission Scientist, Theodore R. Gull, the Mission Manager, Jack Jones, former Mission Manager Mickey Allen and the hundreds of other crucial staff members at the Goddard Space Flight Center, Johnson Space Center, and Marshall Space Flight Center who made the *Astro-1* mission a notable scientific success. We also thank the many officials at NASA Headquarters whose support for this mission brought it through a long and difficult gestation period. Co-author and Payload Specialist R. A. Parise thanks NASA for the opportunity to conduct this research program from the Space Shuttle *Columbia.* Funding for UIT project has been through the Spacelab Office at NASA Headquarters under Project number 440-51.

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