FINAL REPORT

X-RAY MICROSCOPE/TELESCOPE TEST AND ALIGNMENT

(NASA-CR-184258) X RAY MICROSCOPE/TELESCOPE TEST AND ALIGNMENT Final Report, 26 Jun. 1990 - 25 Jun. 1991 (Alabama Univ.) 49 p CSCL 20F N92-13782

Unclas G3/74 0052264

July 1991

Prepared for:

NASA/MSFC
Huntsville, AL

Under Contract Number:
NAS8-36955
Delivery Order Number:
91

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This report details the tasks performed by the Center for Applied Optics (CAO) in support of the Normal Incidence Multilayer X-Ray Optics program at NASA's Marshall Space Flight Center (MSFC). This is a continuation of work performed and documented under Delivery Orders 2 and 49.

The Multi-Spectral Solar Telescope Array, or MSSTA, was launched on a Terrier-boosted Black Brant sounding rocket from White Sands Missile Range, New Mexico on May 13 1991 at 1:05PM. High resolution images of the sun in the soft x-ray to extreme ultraviolet (EUV) regime were obtained with normal-incidence Cassegrain, Ritchey-Chretien, and Herschelian telescopes mounted in the sounding rocket. MSSTA represents the first use of multilayer optics to study a very broad range of x-ray and EUV solar emissions. Energy-selective properties of multilayer-coated optics allow distinct groups of emission lines to be isolated in the solar corona and transition region. Features of the near and far coronal structures including magnetic loops of plasmas, coronal plumes, coronal holes, faint structures, and cool prominences are visible in these images.

Without the use of multilayer optics, instrumentation limited by the low reflection efficiency of conventional mirrors at normal incidence for EUV and soft x-ray radiation has made it necessary for observers to compromise on observable characteristics including spatial resolution, temporal resolution, field of view, and temperature determination. Techniques such as grazing-incidence optics and mechanically collimated Bragg spectrometers are limited by low reflection efficiency at these wavelengths. The newer technique of normal incidence multilayer optics allows observers to achieve high angular resolution astronomical images with moderate spectral resolution in wavelengths from 30Å to 1550Å. MSSTA utilizes normal incidence multilayer telescopes.

The normal incidence multilayer technique allows soft x-ray and EUV images to be produced with spatial resolutions as low as 0.1 arc seconds. The MSSTA imaging detectors had to therefore be able to record extremely high contrast, high resolution images of the solar disk and corona associated with flares and active regions without saturating and while still maintaining the capability of capturing very faint, low contrast structures in coronal holes, polar coronal plumes, network structures and faint loops in the corona. Films selected for MSSTA had to be sensitive over a wide portion of the electromagnetic spectrum. The film had to also keep its integrity in an evacuated environment; it had to have low outgassing rates and the ability to be transported through a Pentax 645 camera while in dry vacuum conditions without electrostatic discharge or cracking. Characteristics of tabular grain Experimental XUV 100 film and uncoated Experimental Spectroscopic 649 emulsion were established and thoroughly investigated.

The Principle Investigator of this experiment was Arthur B. C. Walker of the Center for Space and Astrophysics at Stanford University. The Co-Investigator was Richard B. Hoover of the Space Science Laboratory at NASA's Marshall Space Flight Center (MSFC). Procedures initiated by A. B. C. Walker and R. B. Hoover and followed in the development of this project can be discussed in eleven steps:

1. Telescope Design. The design and analysis of the optical systems was carried out by James B. Hadaway and R. Barry Johnson of the Center for Applied Optics of UAH under a previous contract. See Hadaway et. al. "Design and Analysis of Optical Systems for the Stanford/MSFC Multi-Spectral Solar Telescope Array," Proc. SPIE 1160, pp.195-208, 1989.

2. Telescope Optical Performance Testing. These tests were necessary to determine the optimum focal plane for each telescope for precise positioning of the film plane. Equipment used for this process consisted of a Zygo interferometer from the CAO and software developed by Baker Consulting of Walnut Creek, CA. Performance of this task was carried out by James Hadaway and Cynthia Peterson from the CAO and Phil Baker of Baker Consulting.

3. Film Type and Development Process Analysis. To allow a large field for the image, 70mm format film was chosen. The cameras used to transport this film during flight were Pentax 645 models. A series of visible light tests were done on film to determine the resolution of the system and off axis effects. Tests were also performed using the synchrotron facility at the University of California, Berkeley and the NIST SURFII facility. These tests allowed insight into the performance of the films at soft x-ray to EUV wavelengths as well as operation in vacuum. It was decided that KODAK XUV-100 and Spectroscopic 649 film would be flown, spliced together, in each camera. The XUV-100 is extremely sensitive in visible light, whereas the 649

is nearly opaque to visible light. However, at x-ray wavelengths the two films are less than 3 f-stops apart.

Methods to splice the film had to be researched thoroughly as a faulty splice could disable a camera. A Metrologic film splicer gave very good results after a few modifications were made by the manufacturer to fit our needs.

Film characterization, establishment of experimental film handling procedures, data enhancement of the synchrotron tests and visible light tests were performed by Cynthia Peterson of the CAO in collaboration with Richard Hoover of NASA/MSFC. The synchrotron tests were performed by researchers from Stanford University.

4. Assembly and Alignment of Payload. The seven Ritchey-Chretien telescopes (150Å, 173Å, 193Å, 304Å, 335Å, 1216Å, 1548Å), two Cassegrain telescopes (173Å, 211Å) and a large Herschelian telescope (193Å) were mounted in the truss section at Stanford. The payload was then shipped to Marshall clean room facility in building 4705 where an array of four small Herschelian telescopes (143Å, 135Å, and two 44Å) were mounted and interferometric alignment testing was performed. Electronics were mounted, cameras were loaded with test film and mounted, and telescopes were shimmed to their proper alignment. The interferometric alignment testing was performed by Baker and Peterson. The electronics were designed and mounted by Max Allen of Stanford. Film handling and camera preparation was performed by Peterson. Mounting of devices was performed by Walker, Allen, and Deforest of Stanford and Peterson.

5. Vibration Testing. Shake testing of the payload to simulate vibrational stress during flight was performed at Marshall with horizontal and vertical sine and random wave patterns. Post inspection was performed in the Marshall clean room by Hoover, Peterson, and Deforest.

The payload was then shipped to White Sands Missile Range (WSMR) where delicate filters were mounted by the Stanford group including J. F. Lindblom and Ray O'Neal. Shake tests were again preformed at WSMR.

6. Flight Film Loading. Critical flight film was measured, cut and loaded into the cameras for flight. This procedure was performed by Hoover and Peterson. The work at White Sands was performed partially under this effort and partially under a new contract (Delivery Order #129).

7. Pre-Launch Preparation. Assembly of the rocket and boosters on the rail at Navy Launch Complex #36 and necessary pre-launch preparations were performed by SPARCS Lockheed and the Navy. Mounted on the rail inside a temperature controlled, sun shielding facility, vacuum pumping was performed on the payload. Launch preparations were carried out by all groups.

8. Launch. During the launch the film sequencing was monitored. A reset occurred in the system at T= +340 seconds, during an 80 second film exposure. Therefore, manual exposure sequencing was performed by Hoover and Peterson.

9. Recovery. Recovery by helicopter of the payload was performed by SPARCS, Deforest, O'Neal, and Hoover. Post flight inspections were performed by each group. Post flight camera tests were performed for each camera, the film was secured, and then taken to Sacramento Peak National Observatory (SacPeak) in Sun Spot, NM by Hoover and Peterson.

10. Film Processing. Development of the flight film was performed by Hoover and Peterson at SacPeak utilizing the expertise of Lou Gilliam and Todd Brown. Digitization of the images was performed by Larry November of SacPeak. Photographic printing of the images was performed by Peterson.

11. Data Analysis. Analysis and quality enhancement of the images continues.

A month-to-month breakdown detailing specific activities performed follows:

June 1990 Discussed visible light and UV testing method to be carried out to establish spatial resolution, depth of field, field curvature, optical vignetting effects, and off axis behavior of the telescopes. Began testing film characteristics to determine appropriate flight film.

July 1990 Set up optical table in preparation for optical characteristic testing. Included alignment of collimator with telescopes and appropriate mounts. Photographically reproduced resolution target to be used in testing. Continued film and development process testing to determine flight film and development techniques.

August 1990 Alignment of collimator to produce image of resolution target at infinity to be focused onto film by the telescopes. Multiple exposures of this test target were taken and recorded on KODAK 649 and XUV-100 film. These films were developed using various techniques including development in D-76, D-19, T-Max and Microdol-X to determine the best processing for highest resolution.

September 1990 A translation microscope was aligned with the telescopes and collimator to evaluate the image of a resolution target through the system. The microscope was then replaced by a Pentax 645 Camera with 70 mm film back to record images of the resolution target. Multiple exposures where taken at grid interval points on a single frame to determine off-axis effects. It was shown that resolution remained consistent across the field until vignetting effects occurred. This test was performed for the 173Å, 193Å, and 304Å telescopes. Double images or effects of defocus or vibration began to appear in each of the telescopes. To determine the cause and nature of this effect, a variety of tests was performed. It was decided to use a resolution target made from etched metal to eliminate the effect of internal reflections that may have been present in the glass targets.

October 1990 Filter images of the 173Å and 1550Å where recorded on XUV 100 and Spectroscopic 649 film. This film was analyzed to determine resolution at these wavelengths and best film characteristics. A microscope enlarger was used to enlarge the images to show the high resolution. A densitometer was also used to determine the density of the images on the film.

November 1990 Results from EUV and FUV tests conducted at the NIST SURFII synchrotron at wavelengths of 173Å, 211Å, 335Å, and 1550Å using XUV 100 and Spectroscopic 649 film were analyzed. The analysis of the resultant images indicated that the XUV 100 film was more sensitive at 1550Å than at EUV wavelengths. Long exposures were used to establish an H&D curve. It was also found that at 1550Å, photons penetrated through one layer of film and exposed an underlying piece of film. Tests were then conducted to determine if a second underlying piece of film should be flown for the 1550Å telescope.

It has thus far been found that the image on the second layer of film has lower integrity.

December 1990 Film tests were continued to establish H&D curves for the film of solar images previously recorded by the Cassegrain telescopes (1987 flight). Densitometry tests were also preformed on experiment film to be used on the upcoming flight. Spectroscopic 649 and XUV 100 film was developed with strict and varied processes to determine the development technique which yielded the best H&D curve.

January 1991 "Development of the Water Window Imaging X-Ray Microscope" and "Design and Analysis of a Water Window Imaging X-Ray Microscope" (Hoover et al.) were written. Peterson provided support in the formation of these papers by gathering and preparing data on the Multi Spectral Solar Telescope Array (MSSTA) to be applied to the topic of Water Window Microscopy.

February 1991 The telescopes were mounted in the truss structure. Film processing equipment was tested to standardize processing techniques and timing.

March 1991 The MSSTA payload was returned from Stanford to the clean room in building 4705 at MSFC. The outer skins of the payload were removed. The truss structure, with mounted telescopes, was placed on V blocks.

Alignment of the telescopes to the collimator was performed using a Michelson interferometer with video cameras, PC-eye, and Genera software, which Phil Baker supplied. The beam projected through each of the Ritchey-Chretien and Cassegrain telescopes was focused on a mock camera to allow viewing of the position of the spot at the focal plane of each telescope. This spot optimally belongs in the center. Telescopes whose spots were off axis were shimmed and realigned. A video camera was then installed in place of the mock camera. A frame grabber was used to capture and then digitize these images for comparison after the shake test. (It was later determined that this procedure would not be repeated after the shake test for comparison because of serious difficulties encountered in mounting the flight cameras.)

Small mirrors for the small Herschelian telescopes were epoxied in brackets then mounted on the truss and aligned using the above procedure.

The cameras were cleaned and prepared to be mounted on the truss structure. Camera mounting rings were assembled and mounted on the telescopes.

April 1991 The film was loaded for all cameras, electronics attached to the cameras, the cameras mounted to the telescopes, and the camera mounts were refabricated to fit the truss. The truss bumpers were mounted. Camera tests were performed indicating that one camera had failed. All telescopes were realigned to the collimator. Two electronic sequences were shot with all cameras, except the failed camera, to simulate flight. The first attempt to return the truss section into the outer skins showed that the bumpers did not fit into the skins. The bumpers were removed. A second attempt was made to put the truss section into the skins - the seal ring was machined too large and would not fit. The seal ring was machined to size, at Marshall, and the truss was put into the skins. The front door and rear bulkhead were attached. The payload was taken to the shake facility at Marshall. Vertical and horizontal tests were performed in both sine and random wave configurations. The payload was returned to the clean room. Post shake analysis was performed. One small Herschelian was chipped on the back surface. Alignment was examined (and found to have moved) and post shake film exposures were shot. The failed camera was then replaced with the now available working camera. The truss was returned to the skins. The payload was shipped to White Sands. The launch date was set for 13 May 1991 at 1:00pm (local).

May 1991 Final assembly of the MSSTA payload was completed at White Sands Missile Range. The flight film was precisely measured, spliced and loaded for all flight cameras. The payload was assembled on the rail by SPARCS to the Black Brant Terrier-boosted rocket. Vacuum pumping procedures were carried out for two days. Launch on 13 May at 1:05pm (five minute hold due to a road block violation) was successful. A timer glitch occurred at T= +340 seconds (during an 80 second exposure). Therefore, manual camera firing sequencing was performed. Recovery of the payload was successful. The instrumentation was inspected. It was found that the telescope mounts where not completely in tact. The helicoil inserts on the telescopes did not completely hold. This allowed the telescopes to move during flight. It was also found that the 150Å camera had not fired correctly due to a transport problem. Ground exposures were taken on all cameras before and after the flight.

The film was then taken to SacPeak National Observatory in Sun Spot, New Mexico to develop, digitize, and print flight data solar images. Development of most of the flight film was done using a Fulton automatic processing machine. Lou Gilliam and Todd Brown from the observatory aided in the film processing. Larry November performed the digitization of the images. Degradation of the XUV 100 flight film was discovered. Straight and parallel lines cross the image surface. It was determined that this effect was caused by cracking of the emulsion during film transport after having been in a vacuum for an extended amount of time. This theory has not yet been test proven.

June 1991 Data obtained on the MSSTA flight for the 44Å solar image on XUV 100 70mm film was very thin. Photographic techniques were employed to gain detail and density of the image so that it may be useable, printable data. The best technique was to make a copy of the negative on high speed direct positive duplicating film (4575). Color enhanced pictures of the 1216Å H Lyman alpha image were produced. Work was also performed on a proposal for a solar polarimeter to fly on the next MSSTA flight.

Evaluation of the images recorded shows that the best results of film processing were for 649 film developed in Dektol for 25 minutes. In all cases the film was underexposed. The data retrieved for 1550Å Carbon 4 was out of focus due to movement of the telescope resulting from a mounting problem. Excellent images were produced from the 1216Å H Lyman alpha, and 193Å Iron 12 cameras. The 304Å and 350Å results were not successful; it is suspected that the problems occurred due to their filters. The 44Å small Herschelian camera produced faint images. Data analysis and film improvement of image integrity is presently being continued.

In conclusion, MSSTA has successfully obtained unprecedented information regarding the structure and dynamics of the solar atmosphere in the temperature range of 10^4K to 10^7K. This project has yielded a very powerful experimental apparatus for the investigation of the thermal density of the corona and chromosphere. The performance of MSSTA has demonstrated a unique combination of ultra-high spatial resolution and spectral differentiation by use of multilayer optics.

Publications resulting from this effort include:

"Performance of the Multi-Spectral Solar Telescope Array III: Optical Characteristics of the Ritchey-Chretien and Cassegrain Telescopes," Richard B. Hoover, Phil Baker, James B. Hadaway, R. Barry Johnson, Cynthia M. Peterson, David Gabardi, Arthur B. C. Walker, Joakim F. Lindblom, Craig E. Deforest, and R. H. O'Neal, in X-Ray/EUV Optics for Astronomy, Microscopy and Projection Lithography, (Richard B. Hoover and Arthur B. C. Walker, eds.), Proc SPIE, 1343, (1990).

"Performance of the Multi-Spectral Solar Telescope Array VI: Performance and Characteristics of the Photographic Films," Richard B. Hoover, Arthur B. C. Walker, Craig E. Deforest, Maxwell J. Allen, and Joakim F. Lindblom, in X-Ray/EUV Optics for Astronomy, Microscopy and Projection Lithography, (Richard B. Hoover and Arthur B. C. Walker, eds.), Proc SPIE, 1343, (1990).

"Response Characteristics of the MSSTA Photographic Films at EUV and FUV Wavelengths," Richard B. Hoover, Arthur B. C. Walker, Craig E. Deforest, Joakim F. Lindblom, Maxwell J. Allen, and Cynthia M. Peterson, to be presented at SPIE 1991.

Performance of the Multi-Spectral Solar Telescope Array
III. Optical characteristics of the Ritchey-Chrétien and Cassegrain telescopes

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ABSTRACT

The Multi-Spectral Solar Telescope Array (MSSTA) is a sounding rocket borne observatory for investigations of the Sun in the soft x-ray/EUV and FUV regimes of the electromagnetic spectrum. At soft x-ray wavelengths (λλ < 100 Å), the MSSTA utilizes single reflection multilayer coated Herschelian telescopes. For selected wavelengths in the EUV (100 - 1000 Å) the MSSTA employs five doubly reflecting, multilayer coated Ritchey-Chrétien and two Cassegrain telescopes. In the FUV (λλ > 1000 Å) the MSSTA utilizes two Ritchey-Chrétien telescopes, with optics coated with thin film interference coatings. In this paper, we describe the interferometric alignment, testing, focusing, visible light testing, and optical performance characteristics of the Ritchey-Chrétien and Cassegrain telescopes.

1. INTRODUCTION AND THEORETICAL CHARACTERISTICS

The Multi-Spectral Solar Telescope Array (MSSTA)[1] is a rocket-borne observatory designed to obtain ultra-high resolution images of the Sun at selected soft x-ray (44.1-93.9 Å), Extreme Ultraviolet (EUV) [150-335 Å], and Far Ultraviolet (FUV) [1215.6 Å and 1550 Å] wavelengths. The MSSTA is an expansion of the Stanford/MSFC/LLNL Rocket X-Ray Spectroheliograph program which produced the first high resolution normal incidence x-ray images of the Sun with two doubly reflecting "Cassegrain" multilayer telescope on October 23, 1987.[2,3] These small (6.35 cm diameter primary) telescopes will be reflown as part of the MSSTA payload. The 173 Å telescope, which produced images with spatial resolution of 1.2 - 1.5 arc sec, will be reflown with no optical changes, but with a 70 mm camera rather than the 35 mm camera used on the prior flight. The other Cassegrain will also be reflown, but the 256 Å mirrors will be replaced with new optics which have been coated for peak reflectivity at 211 Å. These telescopes are not true Cassegrains in that the primary and secondary mirrors were fabricated as spheres. At the time these optics were made, conic elements of the smoothness required as substrates for the multilayer coatings could not be obtained.

During the initial design of the optical systems for the MSSTA, we theoretically analyzed a number of optical systems, including sphere-sphere, ellipsoid-sphere (Dall-Kirkham), paraboloid-hyperboloid (Cassegrain), and hyperboloid-hyperboloid (Ritchey-Chrétien) configurations. Hadaway et al.[4] described the results of these studies in some detail. In order to improve the performance over that achieved during the October 1987 flight, we sought a faster optical system with enhanced plate scale and superior optical properties. To increase the plate scale, the focal length of the telescope was increased from 2 meters to 3.5 meters. This yields a larger image of the Sun and improved spatial resolution even when photographic film of identical grain characteristics is used as the detector.

We had already established that the spatial resolution during the prior flight was limited by the film grain characteristics rather than the optics or pointing. To acccommodate the larger image size, while still permitting each system to record images of the entire solar disk and corona out to 1.5 solar radii, the 35 mm format film cameras were replaced with 70 mm format Pentax 645 cameras. To further improve the spatial resolution and sensitivity, the diameter of the primary mirror was doubled, which both reduces the level at which Fraunhoffer diffraction limits the spatial resolution and yields a faster optical system that is capable of utilizing lower sensitivity (but much finer grain) photographic emulsions. In order to fully utilize these improved aspects of the instrument, conic mirrors were required with optical characteristics which could permit ultra-high spatial resolution to be realized over the entire field of view of the telescope. In Table 1, we summarize the final design parameters of the MSSTA flight Ritchey-Chrétien telescopes.

TABLE 1.

MSSTA Telescope Design Specifications

RITCHEY-CHRÉTIEN	
Focal Length	350 cm
Overall Length	100 cm
Mirror Separation	80 cm
Primary Diameter	12.7 cm
Secondary Diameter	4.9 cm
Total Field of View	48 arc min
F-Number	28
Primary Curvature	-0.004464 cm^{-1}
Secondary Curvature	-0.010625 cm^{-1}
Conic Constants	-1.08192, -4.68042

It is well known that improved performance over a much wider field of view can be achieved with aplanatic telescopes for which (to third order at least) coma is zero and spherical aberration is absent. The Ritchey-Chrétien telescope, which is an aplanatic form of the Cassegrain configuration, utilizes hyperboloidal primary and secondary mirrors. The conic constant for the Ritchey-Chrétien secondary mirror is more negative than for the classical Cassegrain, which has a concave paraboloidal primary and a convex hyperboloidal secondary. Since the mirrors were to be used as substrates for multilayer x-ray coatings it was essential that they have an rms smoothness of less than 5 Å. Based upon prior work which had been performed for the Space Sciences Laboratory of the University of California, Berkeley,[5] it was established that the Advanced Flow Polishing methods developed at Baker Consulting[6] were capable of producing hyperboloidal mirrors to the required surface figure and rms surface smoothness such that they could serve as substrates for normal

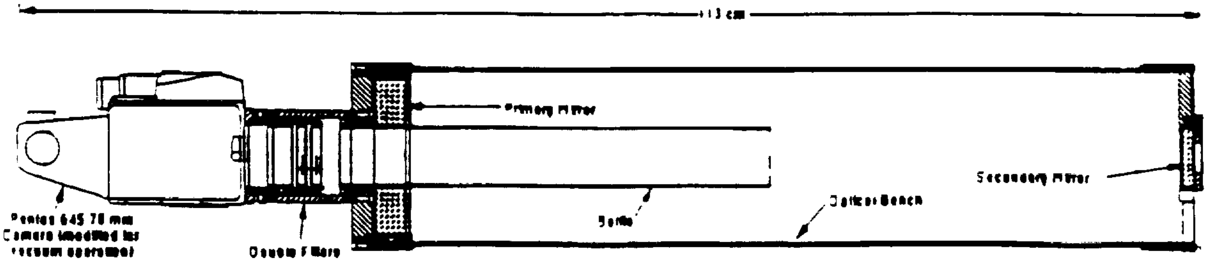

Fig. 1. Schematic layout of the MSSTA Ritchey-Chrétien Telescope.

incidence multilayer x-ray optics. Consequently, the Ritchey-Chrétien design was selected as the optical configuration for the large MSSTA telescopes (**Fig. 1**).

This provides an aplanatic system with excellent performance over a wide field of view. Our theoretical studies revealed that the MSSTA Ritchey-Chrétien telescopes were optically capable of yielding spatial resolution better than 0.3 arc sec over a 48 arc min field of view, which corresponds to 200 line pair/mm spatial resolution at the film plane. It further established that a spatial resolution of 0.03 arc sec (2000 line pair/mm) was theoretically possible near the optical axis at a wavelength of 173 Å, with resolution of the order of 0.1 arc sec out to 10 arc min off axis. Obviously, the 0.03 arc sec limiting values significantly exceed the pointing and control capabilities of the Terrier-boosted Black Brant vehicle and the Lockheed attitude control system. However, it is hoped that quiescent periods will exist during the flight which may permit images to be recorded at 0.1 arc sec spatial resolution.

Ray trace analysis shows that over the central 20 arc minute region, the predicted resolution is approximately 0.1 arc sec as shown in **Fig. 2**. Only a very slight (fraction of an arc second) degradation in resolution occurs over the central 50 arc minute field of view **Fig. 3** offered by the current telescope configuration. The maximum off-axis field angle is limited by vignetting imposed by the a central hole of 2.54 cm radius in the primary mirror. Even though only a very slight degradation in resolution results from increasing the size of the hole in the primary to permit observations over a wider field of view, a somewhat significant loss in throughput is experienced due to the vignetting effects.

The field limit for high resolution images produced by aplanatic telescopes such as the Ritchey-Chrétien is essentially constrained by astigmatism and field curvature. Although systems with focal planes curved to precisely match the Petzval surface are conceivable, and some solid state devices have been made with precisely that objective in mind, the difficulties in general outweigh the benefits obtained in image quality improvements. For photographic systems where film transport is desired from long rolls in systems which must operate in a vacuum, significant technological difficulties exist in attempting to use image planes curved to match the contour of the Petzval surface. Hence, an alternate approach that is very frequently used is to focus the system in such a manner as to achieve balanced resolution over the entire field. Moving the flat image plane toward the telescope primary by 0.04 cm. degrades the on-axis resolution to 0.3 arc sec but 0.1 arc sec resolution is achievable at the limb **Fig. 4**. The resolution remains better than 0.5 arc sec over a 50 arc min full field of view, which would allow high resolution observations of the solar corona out to 1.6 $R_{\odot}$.

Since these Ritchey-Chrétien telescopes are aplanats, the primary image degradation arises from curvature of field and astigmatism. At the edge of the usable field of aplanatic telescopes the distortion is usually only a few hundredths of an arc sec. Image blur due to astigmatism is symmetric and therefore the center of the point spread function can be very precisely located. The optical elements were polioshed to the required figure from Zerodur blanks by Baker Consulting. Polishing of the mirrors by Advanced Flow Polishing methods resulted in a surface smoothness accuracy of 1-2 Å rms as measured using a Zygo profilometer.

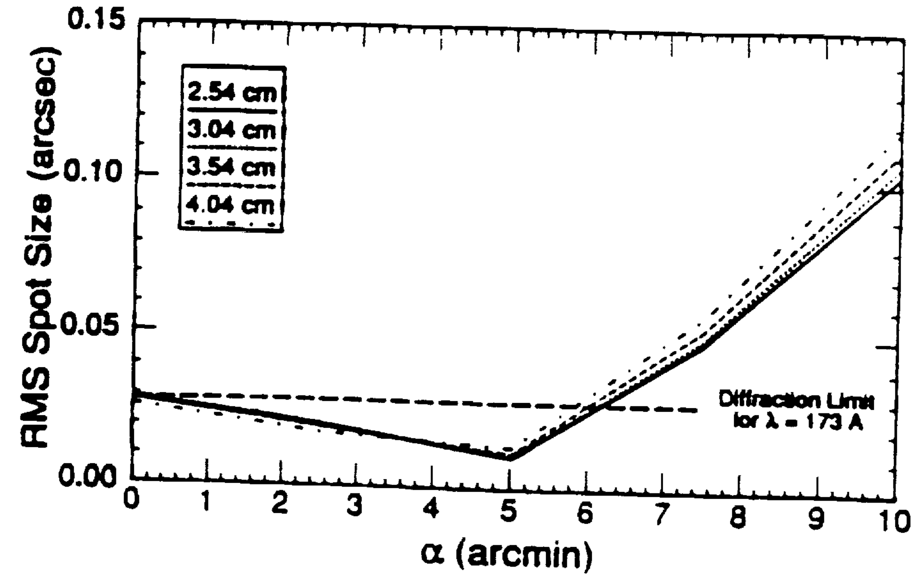

Fig. 2. Theoretical performance of the MSSTA Ritchey-Chrétien telescopes over the central 20 arc minute field. The theoretical diffraction limit for the 173 Å telescope is shown as the dashed line. The curves show the effect of increasing the size of the hole in the primary mirror.

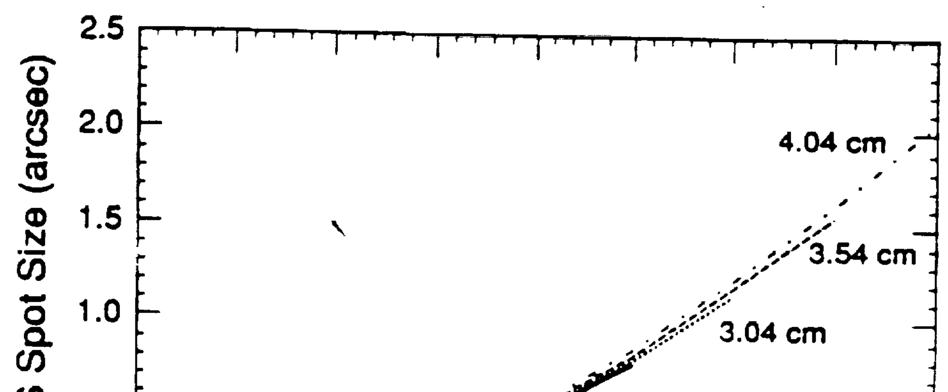

Fig. 3. Resolution of the MSSTA Telescopes over a wide field of view with system focused for optimal performance on-axis. The current telescope has a central hole in the primary of 2.54 cm radius which limits the full field of view to 50 arc minutes.

2. TELESCOPE ASSEMBLY AND INTERFEROMETRIC ALIGNMENT

In order to realize sub-arc second resolution with these systems, the optical alignment and focusing of each telescope must be accomplished with extreme accuracy. To insure that the system alignment could be achieved and maintained during flight, great care was taken in the design and fabrication of the mirror mounts and optical bench. The primary mirrors are mounted in an optical bench of specialized design to allow the primary and secondary mirrors to be accurately maintained in the same relation after the rocket

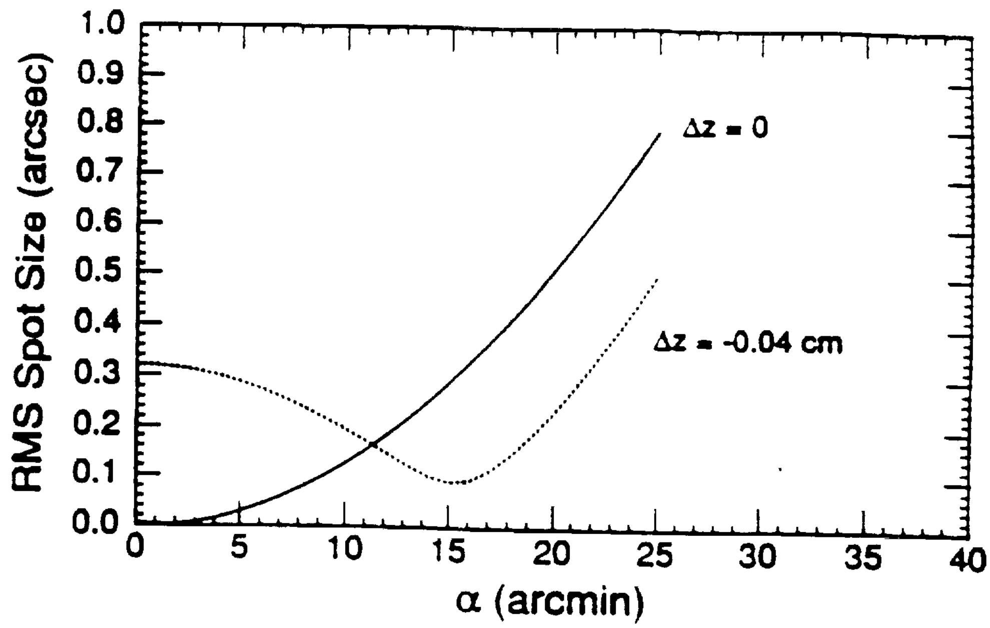

Figure 4. Improvement in spatial resolution of the MSSTA telescopes that can be achieved by moving the flat film plane toward the telescope primary mirror by 0.04 cm.

launch load vibrations. The primary mirrors are mounted in mirror cells with proper centering achieved by means of eight accurate spacer rods which separated the perimeter of the optic from the inner wall of the cell as described in detail by Hoover et al.[7]

The mounting of the primary and secondary elements and the assembly and alignment of the completed systems was carried out by the MSSTA team using the optical facilities available at the Applied Optics Corporation in Walnut Creek, CA. The mirrors were assembled into the cells using a $\lambda/20$ optical flat of 20 inch diameter. Precision spacers were used to support the primary mirrors at a precisely defined position above the flat, and a Vacuum Compatible Dow Corning Silastic RTV 90-00602 was injected into the eight ports around the mirror cell. The RTV was then allowed to cure at 75 °F for 72 hours. This low outgassing, silastic RTV permits each mirror to be firmly held in place, but allows slight movements during vibrational loadings. After the RTV had cured, pressure plates and three solid torsion springs were inserted into the base plates. The mirror cells, containing the primary optics were then assembled to the base plates. Three set screws were inserted into the base plates and torqued to 40 inch ounces to provide a uniform loading on the solid torsion springs (which lie between the pressure plates in the aft mount plate and the rear suface of the primary optic).

The secondary mirrors are mounted in a precisely machined cell, with a Zytel 159 nylon spacer used for accurate centering of the optic. There is a strong amplification factor in this system and slight changes in the separation of the primary and secondary mirror can result in large changes in the location of the position of best focus. Consequently, every effort has been made to prevent changes in primary to secondary separation from occurring after focusing. The optical benches were fabricated as filament wound tubes constructed at MSFC by Morton Thiokol. A special AS4-12k graphite fiber with an HBRF55A epoxy resin matrix was used. Longitudinal fibers were applied to increase the stiffness and yield optical benches with near-zero coefficient of thermal expansion. The tubes were also coated to minimize the effects of length changes due to moisture absorption. In addition, the telescopes are kept stored in dry nitrogen at all times except when they must be exposed for optical testing. Dehumidifiers were used in the optics test laboratory to minimize the relative humidity during all alignment and focusing work. The telescopes will be flown in a dry condition in an evacuated payload and this precaution was taken to minimize tube length shifts as a result of moisture absorption and release during evacuation. Prior to final assembly, all structures were cleaned and subjected to thermal vacuum baking in accordance with the methods and techniques developed for the Hubble Space Telescope optical systems.

The initial assembly and optical alignments were carried out at Applied Optics Corporation using a

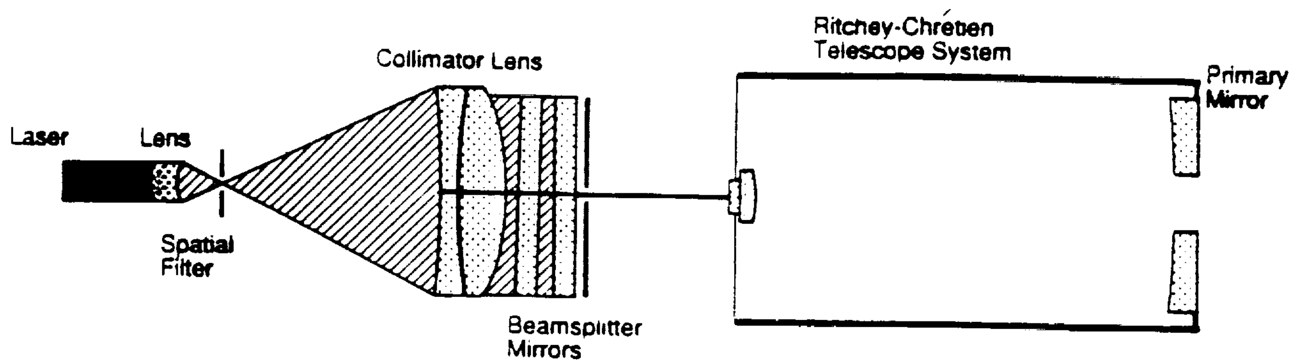

Fig. 5. Initial autocollimation of telescope in Multi-Pass Fizeau Interferometer. The small flat is mounted on the rear surface of the secondary optic.

Zygo interferometer. For all Ritchey-Chrétien telescopes (except the 1550 Å system) the resultant fringe pattern was manually digitized and analyzed using the MicroFringe code.

3. INTERFEROMETRIC TESTING OF RITCHEY-CHRÉTIEN TELESCOPES

Interferometric techniques were used in the Space Science Laboratory of NASA/MSFC to test and focus the two Cassegrains and six Ritchey-Chrétien telescopes (five with EUV multilayer coatings and one Ritchey-Chrétien telescope system with the FUV coating operating at Hydrogen I Lyman α). (The seventh Ritchey-Chrétien telescope, designed to operate at 1550 Å, had a coating which precluded the use of interferometric methods.) The interferometer used was a Zygo PTI Fizeau type instrument operating at a wavelength of 6328 Å. The 4 inch aperture instrument was equipped with a 4% reflecting transmission flat and a 90% reflecting reference flat in a 5 degree of freedom mount. The resultant interferograms were captured with a frame grabber installed in an IBM-AT equipped with an Intel Inboard 386 and an EGA monitor and video card. A precision V-Block with tip and tilt adjustments was used to hold the telescopes on the interferometer optical axis, and the entire optical setup was mounted on a 5' X 9' Microflat Granite table.

The initial alignment was achieved by means of a small optical flat which was placed on the rear surface of the secondary mirror (**Fig. 5**). The rear surface of the secondary was fabricated to be orthogonal to the optical axis of the system to a precision of 10 arc seconds. The reflections from this surface were viewed on the interferometer monitor as they were superimposed with the reference reflection. After coarse alignment was accomplished by autocollimation from the small flat, a large flat was placed at the rear surface of the camera mount (**Fig. 6**). This flat mirror intercepted the converging beam and returned a de-focused converging beam that interfered with the reference arm of the Fizeau causing a set of circular fringes that could be viewed on the interferometer monitor. The interference pattern was then used to check the front-to-back alignment of the telescope.

The collimation of the interferometer was measured by placing a high quality ($\lambda/50$) flat reference mirror approximately 1.2 meters from the output beamsplitter mirror. This mirror was then replaced with a concave, spherical, retro-reflector mirror, which was situated just aft of the prime focus of the Ritchey-Chrétien telescope under test (**Fig. 7**). The interferometer beamsplitter mirror is tilted to pass second-order reflection and improve system sensitivity. The beam was reflected twice off the retro-mirror, resulting in a four-fold increase in the sensitivity of the test. The optical path differences were stored in an OPD file for comparison of the reference tests to the system tests in order to extract the actual system performance. By

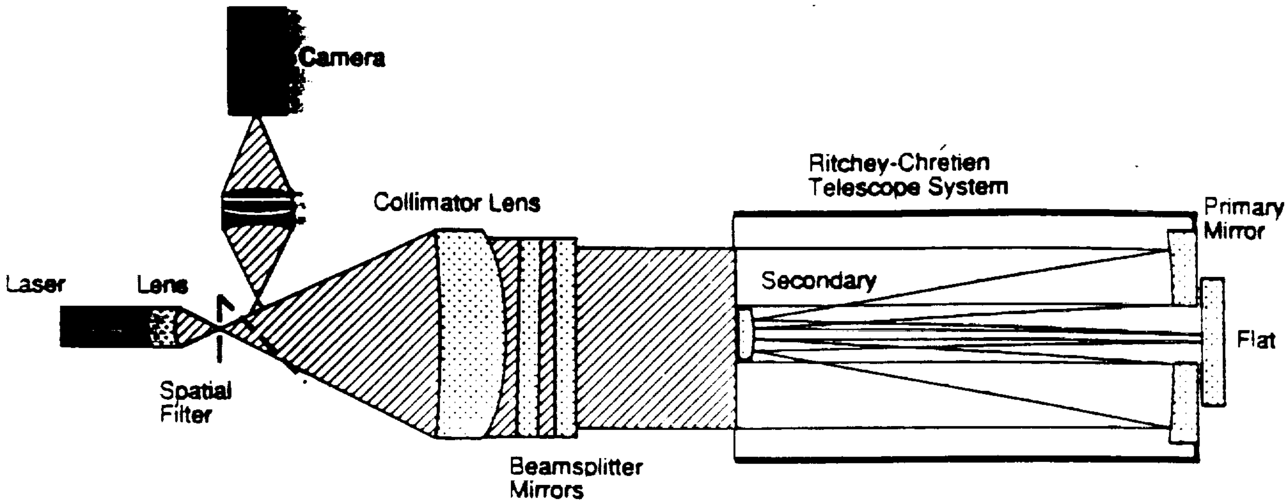

Fig. 6. System autocollimation test. The flat mirror is mounted at the aft camera mounting flange.

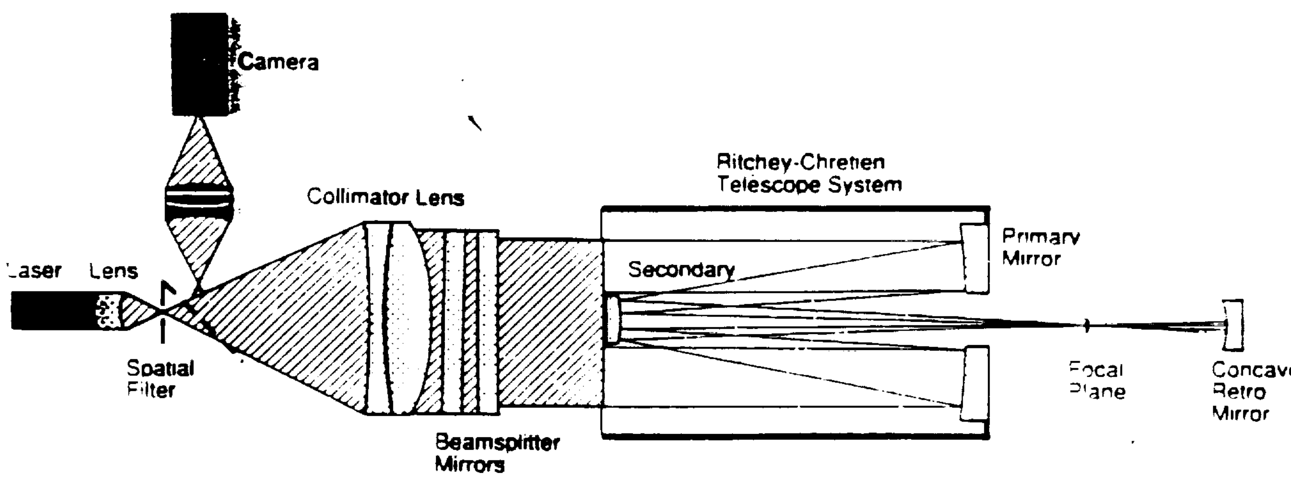

Fig. 7. Test configuration for the Multi-Pass Fizeau Interferometer. The beamsplitter mirror is tilted to pass second-order reflection to improve sensitivity to $\lambda/8$ per fringe.

using the Fizeau interferometer in this multi-pass test configuration, a sensitivity of 1/8 wave per fringe at $\lambda = 6328$ Å is realized.

For all telescopes except the 1550 Å instrument, the multi-pass optical test was possible due to the high reflectivity of the optical coatings at this wavelength. This permitted several reflections to occur before the intensity dropped below the level that was required for acceptable contrast of the fringes. The 1550 Å telescope was coated by Acton Research Corp., of Acton, Mass. with a special "black" coating. This coating results in such low reflectivity at visible wavelengths that the multi-pass interferometer could not be used. Hence, the conventional knife-edge test was utilized for the testing and focusing of that telescope,

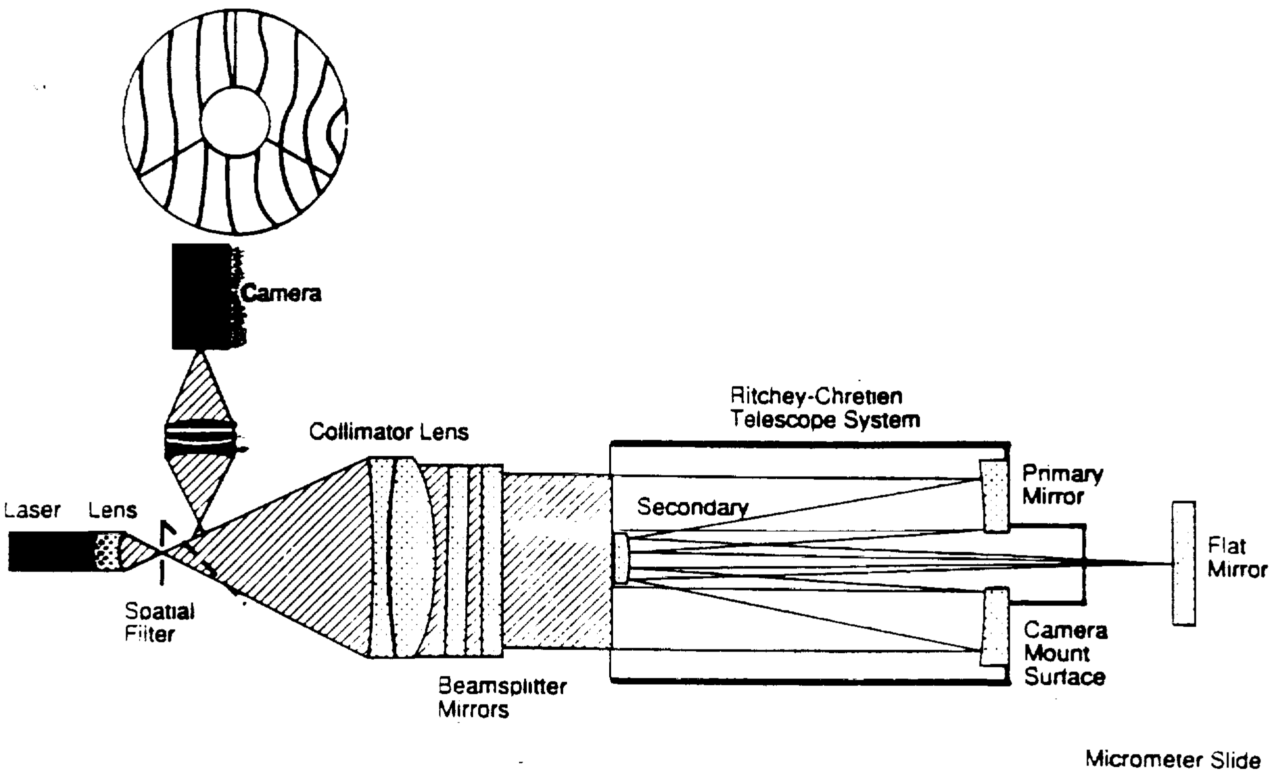

Fig. 8. Determination of the back focal position. The interference pattern of the return focal spot is analyzed for only the focus term to establish the position of best focus. Repeatability to 0.001 inch was accomplished.

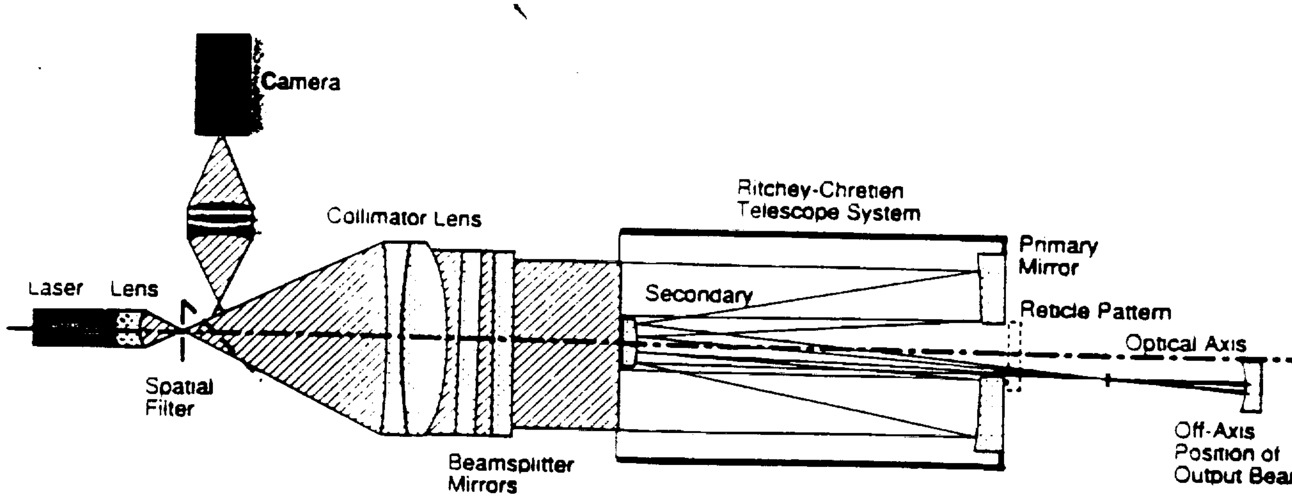

Fig. 9. Off-Axis test of the Ritchey-Chrétien Telescope using the multi-pass configuration

with somewhat lower accuracy in the determination of the position of best focus than is achieved by the interferometric methods. However, this telescope is operating at such a long wavelength that the depth of field of the system is significantly greater than for the EUV instruments, and the position of best focus is not nearly as critical for diffraction limited performance to be realized in flight.

The focal spot was viewed on a screen placed forward of the focal plane in order to measure the centration of the converging beam with respect to the camera mount. This permitted the detection of slight mirror tilts or decentrations as evidenced by the decenter of the focal spot on the screen. Slight adjustments were made when necessary. The final system tests and focus adjustments were performed for each telescope following this alignment procedure. The results of the system wavefront analyses confirmed the validity of this alignment procedure. The off-axis tests were carried out using the position of the focal spot on a reticle screen placed at the camera film plane position. As the input beam was tilted, the focal spot was moved to pre-determined off-axis positions and the field angle calculated in accordance with the telescope plate scale. Interferometric analysis was then carried out to establish the off-axis performance of each telescope at the selected field angles (**Fig. 9**).

The multi-pass configuration of the interferometer was also employed to establish the position of best focus for each telescope. A precision reference flat was mounted near the position of best focus of the telescope under test. The return beam sent back through the optical system then interfered with the transmission flat to yield fringes. These fringe patterns were then digitized manually. The MicroFringe Code permits automatic digitization of fringes, but it was discovered that the optical system central obscuration, spiders and alterations to the fringe patterns which occurred at the sector boundaries of the multilayer coatings significantly disturbed the algorithms used for the automatic digitization and hence manual digitization proved to be the better method for all fringe patterns. After analysis with all aberration terms removed, except the focus term, the back focal position was determined to a very high degree of precison. The digitized fringe pattern was analyzed and the rms and peak-to-valley errors were noted as well as the contour (concave or convex) nature of the wavefront. The reference mirror would then be moved in precision increments, and the interferometric pattern re-analyzed. When minimum rms and peak-to-valley errors were observed and the displayed contour had both convex and concave characteristics simultaneously, the flat was taken to be in the position of best focus for the telescope under test. Precision Guage Blocks were then used to measure the distance from the rear surface of the camera mount tube to the telescope position of best focus to an accuracy of 0.001 inch. Several telescopes were measured more than once and it was found that this technique afforded excellent repeatability.

When the position of best focus was found to lie outside of the desired range, precision stainless steel shims were employed between the mirror base plate and the mount cell to alter the primary/secondary separation. A change of 0.001 inch in primary to secondary separation results in a change in the position of best focus of about 0.014 inch. The focal plane moves aft as the primary to secondary separation is diminished.

4. POINT SPREAD FUNCTIONS

The MicroFringe 3.1 Code was used to analyze the fringes produced when the optical flat is situated in the position of best focus of each telescope. All Ritchey-Chrétien telescopes with the exception of the 1550 Å instrument were tested interferometrically. The geometrical zonal spot diagrams obtained from analysis of the interferogram at the position of best focus for the Ritchey-Chrétien telescopes designed to operate at 150 Å, 173 Å, 193 Å, 304 Å, 335 Å, and 1216 Å are shown in (**Fig. 10.**) These are extremely tight spot distributions, ranging in size from 0.01 to 0.03 Airy radii. Three-dimensional point spread functions for these six telescopes are shown in (**Fig. 11**). The two small Cassegrain telescopes were also tested in the same manner. **Fig. 12** shows the three dimensional PSF and the zonal spot diagrams for the 173 Å and the 211 Å 6.35 cm Cassegrain telescopes. The performance of all the MSSTA telescopes is clearly seen to be essentially diffraction-limited. Table 2 shows the computed diffraction limit (Airy Disk radius) for the MSSTA Ritchey-Chrétien telescopes.

5. VISIBLE LIGHT RESOLUTION TESTS

Visible light resolution studies were also carried out on the telescope systems. A 12 inch diameter clear aperture Ritchey-Chrétien collimator, designed and fabricated by Goerz Optics, was used. The collimator was initially aligned and focused by placing it in autocollimation with a 20 inch diameter $\lambda/20$ optical flat manufactured by the Perkin Elmer Corp., Norwalk. Conn. Using this technique the Standard 1951 Air Force High Resolution Test target, manufactured by Buckbee Mears. was situated with the smallest bar groups on the optical axis of the collimator and accurately in the prime focus of the collimator. A fiber optic system, including a diverging optic and diffuser screen was then used to uniformly illuminate the target with light from the Ealing Fiber Source or a mercury arc source. Preliminary testing consisted of observing the highly magnified image through a Gaertner Traveling Microscope as a function of position along the optical axis. This allowed the depth of field to be examined and provided a direct visual confirmation of the accuracy of the interferometric focusing method.

TABLE 2.

Diffraction Limit of MSSTA Telescopes

RITCHEY-CHRÉTIEN TELESCOPE	
Wavelength λ,	Airy Disk Radius
150 Å	0.03 arc sec
173 Å	0.034 arc sec
193 Å	0.038 arc sec
304 Å	0.06 arc sec
335 Å	0.066 arc sec
1216 Å	0.24 arc sec
1550 Å	0.30 arc sec

Final testing inolved photographic documantation of images which were recorded on the MSSTA flight films. including both the Kodak XUV 100 film and the uncoated Spectroscopic 649 film. The photographic tests were carried out by mounting a Pentax 645 camera on the telescope in the flight configuration and exposing the film. A shutter mounted on the Goerz Collimator allowed several images to be recorded on a single piece of flight film. By moving the collimator between each exposure it was possible to map out the image plane in a grid of resolution target images. The quality of the images was so high that the target was masked to allow only the smallest (4 to 7) bar groups to be imaged. The images on the processed films were observed with an Olympus BHN Microscope under a magnification of 50 diameters to determine the smallest bar elements that were resolvable. Although some variability occurred as a result of vibrational and seeing conditions within the laboratory, the best resolution obtained was generally at the diffraction limit. For example, the 193 Å Ritchey-Chretien telescope produced a repeated series of images showing resolution down to the 6-3 bar group level across the entire 48 arc minute field of view, when the images were recorded on the 649 emulsion. That corresponds to a spatial resolution of 0.5 arc sec in visible light (diffraction-limited performance) over the entire field of view of the telescope. This suggests that our goal of ultra-high resolution images in the 0.1 to 0.3 arc second range may well be realized when these instruments are used in flight at EUV and FUV wavelengths.

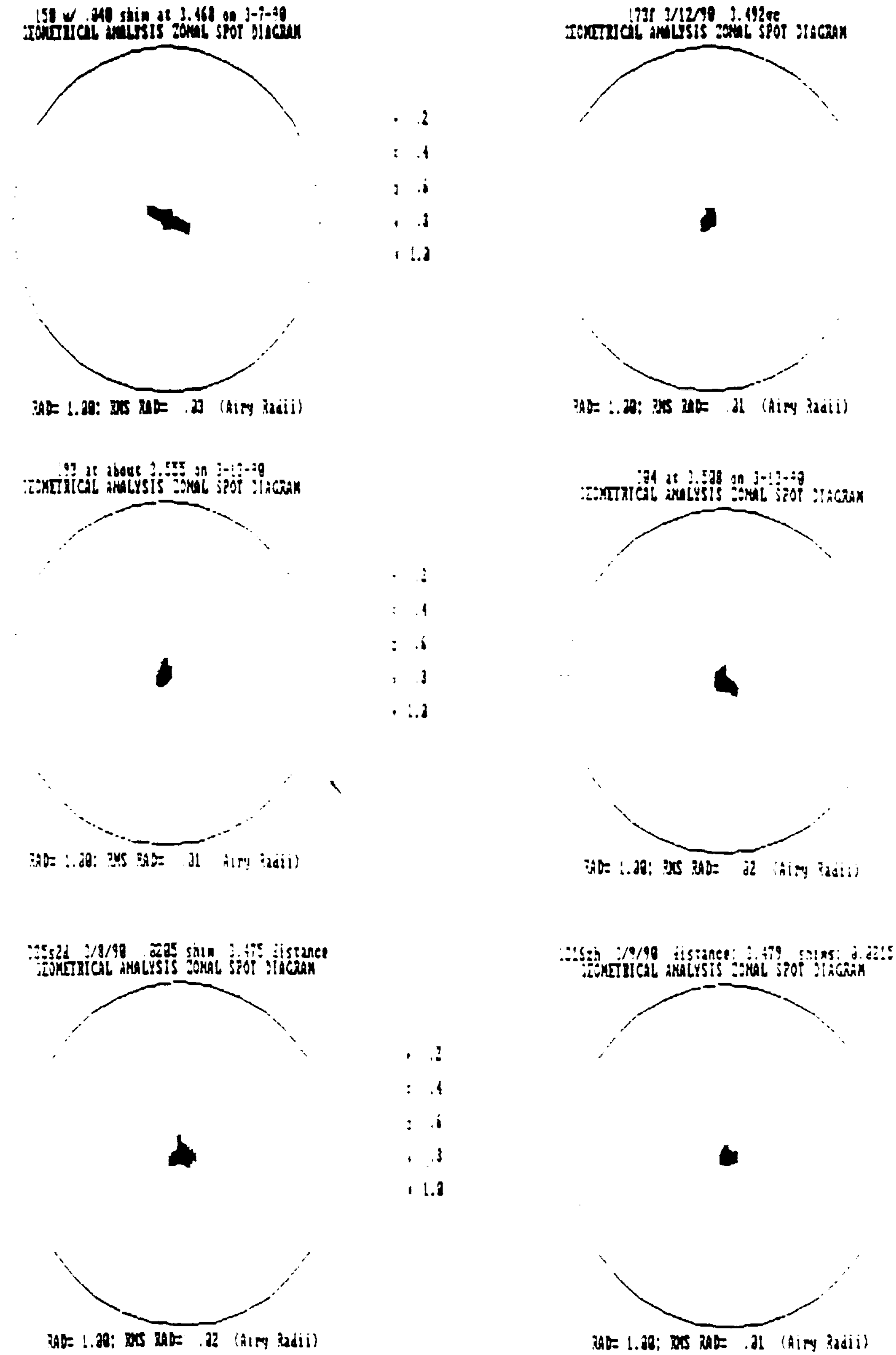

Fig. 10. Geometrical zonal spot diagram obtained from analysis of the interferogram at the position of best focus for the six MSSTA Ritchey-Chrétien telescopes.

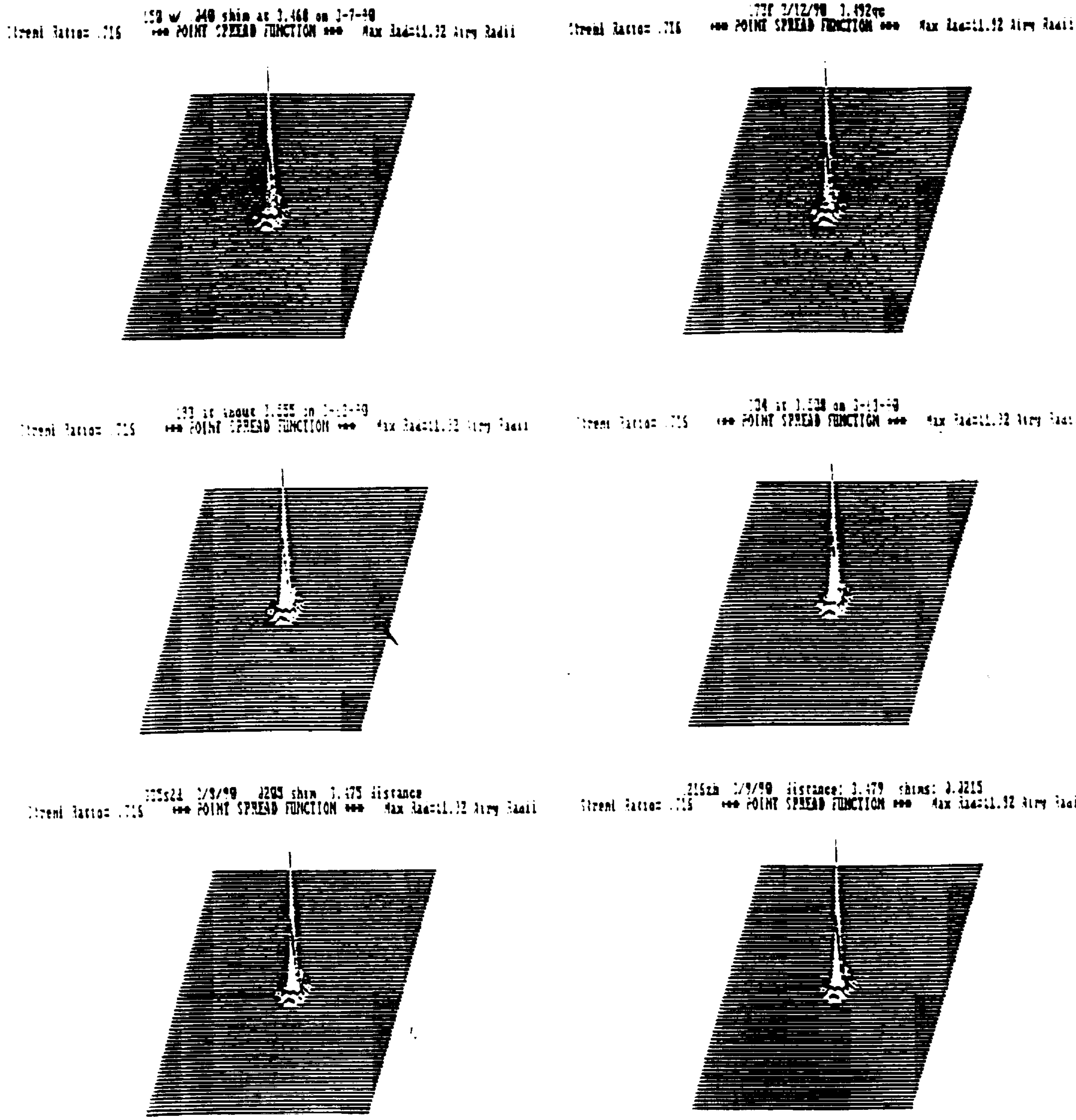

Fig. 11. Three-dimensional point spread functions obtained from analysis of the interferogram at the position of best focus for the six MSSTA Ritchey-Chrétien telescopes.

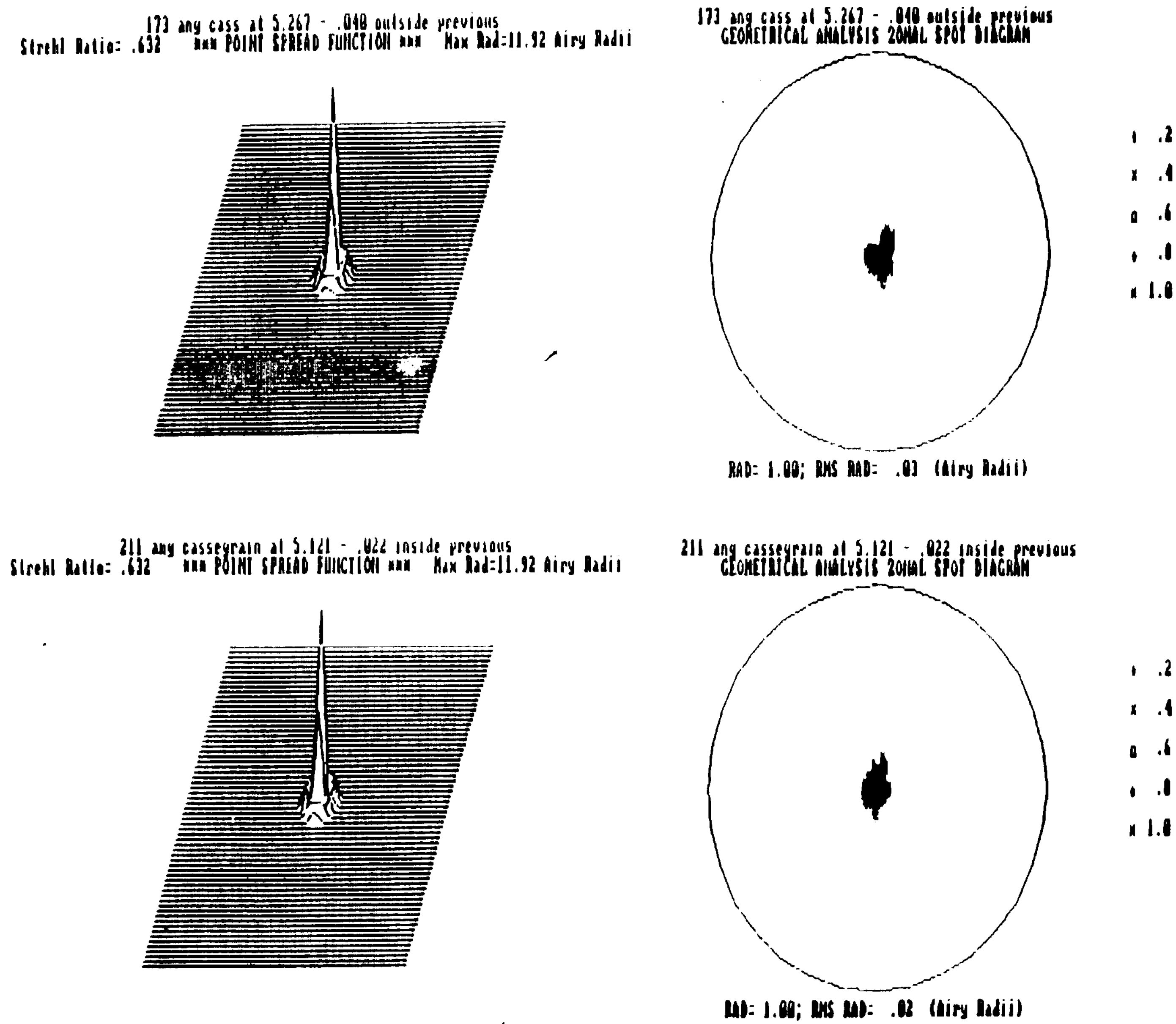

Fig. 12. Geometrical zonal spot diagrams and three-dimensional point spread functions obtained from analysis of the interferogram at the position of best focus for the two small MSSTA Cassegrain telescopes.

6. SUMMARY AND CONCLUSIONS

The MSSTA Cassegrain and Ritchey-Chrétien telescopes have been assembled and aligned using a multi-pass Fizeau interferometric method. The interferometer was also used to analyze the optical performance of the telescopes and to perform the critical focusing of the flight instruments in visible light. Precision focusing of the 150 Å, 173 Å, 193 Å, 304 Å, 335 Å, and 1216 Å Ritchey-Chrétien and the 173 Å and 211 Å Cassegrain telescopes was achieved by these interferometric methods. The position of best focus was established with repeatability to a precision of 0.001 inch. The 1550 Å telescope coating precluded testing and focusing with the interferometer, so this instrument was focused using a conventional knife edge test. The interferometric tests indicated rms wavefront errors typically of the order of $\lambda/100$.

The optical performance of the telescopes was also evaluated by imaging a Standard Air Force High Resolution Test Target projected by a Ritchey-Chrétien collimator as though they were situated at infinity. Images of this target were recorded on the flight emulsions in the flight cameras, and have revealed diffraction limited performance at the 0.5 arc second resolution level over the entire field of view of the MSSTA instrument. These results indicate that the Ritchey-Chrétien telescopes should be capable of producing ultra-high resolution images during the MSSTA flight.

7. ACKNOWLEDGEMENTS

This project was funded by NASA Grant NSG-5131 at Stanford University. Additional support has been received through the NASA/MSFC Center Director's Discretionary Fund. We would like to express our gratitude to Joe Linke and Gerhardt Koch of Applied Optics, Inc., Pleasant Hill, CA, for their support and assistance during the assembly and initial interferometric testing of the MSSTA telescopes.

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Performance of the Multi-Spectral Solar Telescope Array
VI. Performance and Characteristics of the Photographic Films

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ABSTRACT

The Multi-Spectral Solar Telescope Array (MSSTA) is a sounding rocket-borne observatory designed to produce ultra-high resolution full-disk images of the Sun. The MSSTA utilizes an array of Ritchey-Chrétien, Cassegrain, and Herschelian normal incidence multilayer x-ray/EUV telescopes and thin film interference-coated FUV telescopes to produce narrow band solar images at selected wavelengths in this broad region of the electromagnetic spectrum. This mission places extremely strenuous requirements upon the imaging detector. The desire for ultra-high resolution images of the solar disk and corona out to 1.5 $R_\odot$ demands an information storage capacity which can at the present time be met only by the highest quality photographic emulsions. Furthermore, there exists a tremendous range in intensity levels and contrast of solar x-ray/EUV/FUV emission features. The MSSTA imaging detectors must have the ability to record extremely bright, high contrast features associated with flares and active regions without saturating, whicle still maintaining the capability of capturing very faint, low contrast structures in coronal holes, polar coronal plumes, network structures and faint loops in the corona. This very difficult requirement established the need for very wide latitude photographic emulsions so that these diverse features can be imaged at appropriate density levels within the range of exposure times that can be accommodated on a sounding rocket mission.

Furthermore, the films selected for the MSSTA flight must be sensitive over a very broad and difficult portion of the electromagnetic spectrum. The payload must be evacuated prior to launch to preserve the integrity of the delicate EUV filters. Hence, the films chosen must also have low-outgassing rates and possess the ability to be unspooled from the reel and transported through conventional film cameras while dry, after exposure to high vacuum, without experiencing the degradation to the images which can result from electrostatic discharges. In this paper we describe the performance and characteristics required of photographic films for solar observations in the soft x-ray/EUV and FUV wavelength regimes. We discuss the properties of the important new emulsions that have been selected for flight on the Multi-Spectral Solar Telescope Array. We also present exciting and important new data on the response characteristics of a tabular grain Experimental XUV 100 film and an uncoated Experimental Spectroscopic 649 emulsion based upon measurements of these films at the SURF II synchrotron facility of the National Institute of Standards and Technology and at the Space Sciences Laboratory of the University of California, Berkeley.

1. INTRODUCTION AND HISTORICAL BACKGROUND

On October 23, 1987 a Nike-boosted Black Brant sounding rocket was launched from the White Sands Missile Range, New Mexico carrying the Stanford/MSFC/LLNL Rocket X-Ray Spectroheliograph.[1] This flight produced not only the first high resolution image of the Sun with a normal incidence multilayer x-ray telescope (**Fig.** 1), it also produced the first astronomical images ever recorded on a new and exciting tabular grain (T-grain) photographic emulsion produced by the Eastman Kodak Company. Our flight film was a specially-coated version of KODAK T-MAX film, which yielded excellent sensitivity and high spatial resolution at the selected wavelengths ranging from 44 Å to 250 Å. This T-grain film also demonstrated a very wide latitude with measurable diffuse densities ranging from a base fog density of 0.03 to a D_{max} in excess of 3.1.

This maximum density far exceeded that which has typically been obtained with the Schumann type photographic emulsions that had previously been used for astronomical research in this portion of the spectrum. In the soft x-ray/EUV portion of the electromagnetic spectrum the sensitivity of photographic films suffers significantly due to absorption within the gelatin which is used to hold the silver halide grains in place. This phenomenon has been well known for a very long time. It was first recognized by Victor Schumann, who was responsible for the discovery of the Extreme Ultraviolet (EUV) portion of the electromagnetic spectrum. To provide a film with improved sensitivity in this regime, he invented Schumann emulsion in 1892 and perfected it by 1901.[2] The Schumann emulsion has a monolayer of silver halide crystals deposited on a 12 micron thick gelatin pad. Halation effects at wavelengths for which the gelatin is transparent were reduced by adding a yellow dye to the gelatin pad. Since the invention of Schumann emulsions they have served as the primary film of choice for solar EUV photography. (We consider the soft x-ray regime to span the 1-100 Å wavelength range, the Extreme Ultraviolet (EUV) to extend from 100 to 1000 Å and the Far Ultraviolet (FUV) to span the range from 1000-2000 Å. The Extreme Ultraviolet is also called XUV, which is the designation used by Kodak in referring to some of their films configured for use in this region of the spectrum.)

Fig. 1. First high [illegible] 173 Å image of the Sun produced with a doubly reflecting Cassegrain multilayer [illegible] telescope operating at normal incidence on Kodak T-grain 100 photographic film.

The method of fabricating Schumann plates was described by Lyman in 1928, and for many years Schumann films were made by hand in extremely limited quantities. In 1967 the Eastman Kodak Company started producing them by a machine coating process.[3] Extensive utilization of Schumann emulsions was made by the Naval Research Laboratory group during Skylab with the Extreme Ultraviolet Spectroheliograph (ATM Experiment S-082A).[4] This instrument used a concave imaging diffraction grating to produce multiple overlapping images of the Sun in dispersed solar emission lines in the spectral range from 171-630 Å. Schumann film types 101 and 104 were also used by the NRL Extreme Ultraviolet Spectrograph (ATM Experiment S-082B)[5] to perform solar spectroscopy in the 970-3940 Å region, which they refer to as the the XUV (but which we refer to as the FUV and UV portions of the spectrum).

Since Schumann film has no protective gelatin overcoat, it is extremely susceptible to abrasion, scratching, and fogging from environmental effects of all kinds. It is so sensitive to pressure-induced fogging that special "bead rails" are usually deposited at the edges of the film to prevent the emulsion surface from making any contact with the back surface of the film immediately adjacent to it on the roll. VanHoosier et al.[6] have described in detail the intricate care and precautions taken to allow this film to be used in the NRL experiments aboard Skylab. This care included the use of a specially designed and highly complex camera, that accommodates only single strips of film. Despite these intricate precautions, many of the flight exposures were damaged by pressure marks and other types of fogging. Furthermore, the Skylab flight film (type 104-06-05) exhibited a marked change in characteristics of the H&D curve as compared with the ground control samples. Although the laboratory samples reached a $D_{max}=1.2$, the flight film suffered a significant loss in both D_{max} and contrast as compared to the identical emulsion batch that remained in the laboratory. The maximum diffuse density of the film which was flown reached a value of only 0.8 and after a flat plateau at that level diminished abruptly as the exposure level increased. This solarization effect is extremely detrimental to the analysis of solar EUV data, as the same measured diffuse density can be produced by vastly different photon fluxes incident upon the film. Problems such as this, coupled with the extreme difficulty in the manufacture, cost, film transport problems, and various unpredictable appearances of fog and blemishes in images recorded on the Schumann emulsions have resulted in these films being regarded as difficult, both by the user and by Eastman Kodak Company. Furthermore, since Al DeWan (the individual most knowledgeable about the manufacture of the Schumann emulsions at Eastman Kodak) retired from the company almost a year ago, it may become impossible to obtain Type 104, 101-07 and the other types of Schumann emulsions that Kodak has produced as a service to the scientific community for several years. Although this does not pose a difficulty for experiments such as the MSSTA, which uses relatively fast imaging systems with high reflection efficiency optics, it could be a serious problem for those interested in EUV spectroscopy of the Sun, laser fusion plasmas, or imaging of faint EUV/FUV sources.

Kodak had also produced other specialized films for use at soft x-ray wavelengths. The soft x-rays in the 6-49 Å bandpass regime, covered by our ATM Experiment S-056 x-ray telescope that was flown on Skylab,[7] are not nearly as strongly absorbed by gelatin as are the photons of longer wavelengths. Nevertheless, the flight film we utilized with this instrument to take almost 25,000 x-ray images of the Sun was a specially prepared Kodak S0-212 emulsion. (Some images were also recorded on a color emulsion, Kodak Aerial Color Film S0-242, which resulted in slightly higher spatial resolution but at significantly lower x-ray sensitivity.) The SO-212 is a Kodak Panatomic-X Aerial film 3400 with the protective gelatin overcoat removed to reduce soft x-ray absorption effects. The emulsion was de[illegible] on a thin (63.5 micron) Estar base. The Estar base films have considerably higher dimens[illegible] stability than the cellulose acetate butyrate base films.

Since EUV and FUV [illegible] st be transported on rolls after exposure to high vacuum, a

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conductive Rem-Jet backing was applied to the film. This prevents image degradation due to electrostatic discharges that occur when the film is unwound after drying as a result of exposure to high vacuum. However, Rem-Jet coatings are difficult to remove and great care must be exercised to prevent debris (in the form of tiny black particulates) from contaminating the emulsion surface of the film during the removal process. Any Rem-Jet particles on the emulsion side when the film dries have a tendency to become permanently affixed to the film. Kodak has recently solved this problem by developing a conductive Estar base. All of the newer EUV sensitive films which Kodak has provided us have been on this conductive Estar base. Extensive vacuum tests have produced excellent results. No degradation has ever been observed as a result of electrostatic discharges resulting from unspooling the dry conductive Estar base film, even after prolonged exposure to ultra-high vacuum conditions. Furthermore, there exist none of the problems associated with Rem-Jet removal, so this technological development is very much appreciated.

The limitations of the Skylab films flown on S-056, S-082A and S-082B led us to be extremely concerned about photographic emulsons for use at wavelengths longward of 60 Å. Indeed, the EUV wavelength regime was particularly demanding. When Skylab was launched only the very difficult Schumann emulsions were known with certainty to be sensitive in this regime. The Stanford/MSFC/LLNL Rocket X-Ray Spectroheliograph was designed to obtain images at selected wavelengths ranging from 8 Å at the prime focus of the grazing incidence Wolter-Schwarzschild telescope to 44 Å, 173 Å and 256 Å for the Herschelian and Cassegrain telescopes. To obtain suitable photographic films (which could be transported in conventional cameras) for use in this region, assistance was sought from Al DeWan, Gordon Brown, and others at Eastman Kodak. Kodak provided several experimental tabular grain emulsions in 35 mm format on Estar base with Rem-Jet anti-static coated backing for our investigations and flight.

Tests which were conducted at MSFC and at the Los Alamos National Laboratory revealed that these T-grain emulsions[3] have significantly higher sensitivity in the desired regime than the S0-212 films which we had maintained in cold storage since the Skylab mission. The Kodak tabular grain films represented a revolutionary breakthrough, in that the silver halide grains are in the form of flat, triangular or truncated triangular crystals. The grains tend to lie flat on the base, which yields a film which has higher sensitivity and enhanced spatial resolution simultaneously. The experimental emulsion which we selected for flight on the Stanford/MSFC/LLNL Rocket X-Ray Spectroheliograph is now marketed commercially as KODAK T-MAX 100 film. On this flight, the T-grain 100 film proved itself to be an excellent detector for high resolution imaging of the Sun in the wavelength regime from 8 Å-256 Å. Hoover and Lindblom processed the flight film, by hand, at the White Sands Missile Range. Hoover et al.[9] have described details of film processing and experiences with this emulsion on the rocket flight.

2. MSSTA PHOTOGRAPHIC FILM REQUIREMENTS

The Multi-Spectral Solar Telescope Array utilizes Ritchey-Chrétien (**Fig. 2**) telescopes (as well as Herschelians and Cassegrains) designed to image the Sun over a much broader region of the electromagnetic spectrum than our previous payload. Walker et al.[10] have provided a detailed description of this payload.

The MSSTA telescopes are also designed to achieve a much higher spatial resolution than those flown on the Stanford/MSFC/LLNL Rocket X-Ray Spectroheliograph. Consequently, the MSSTA poses some of the most strenuous demands upon the imaging detector ever imposed by a single spaceflight payload. The MSSTA requires detectors capable of providing full disk images of the Sun (including the corona out to 1.5 solar radii) with spatial resolution up to 0.1 arc second. The usable field of view of each of the Ritchey-Chrétien telescopes is ≈ 25 arc minutes, which is an

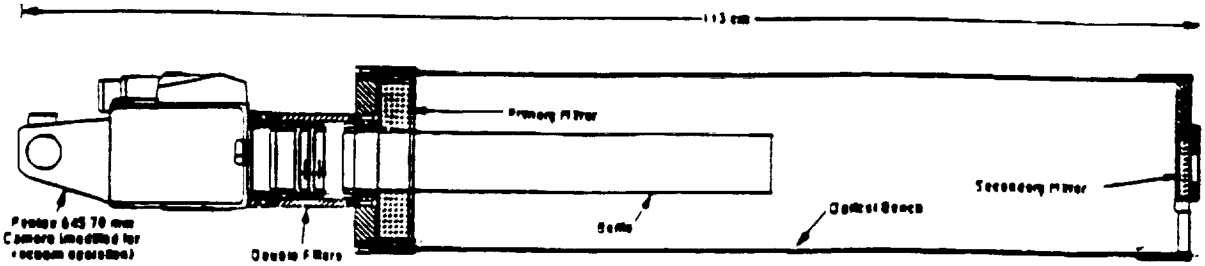

Fig. 2. Schematic of a MSSTA Ritchey-Chrétien multilayer telescopes. The solar EUV/FUV images are recorded on photographic film carried in conventional 70 mm Pentax 645 cameras.

area of 3000X3000 arc seconds. In accordance with the Nyquist limit, to achieve spatial resolution of 0.1 arc second over this field of view with a CCD, we would require a detector with 60,000 X 60,000 pixels. Since the MSSTA Ritchey-Chrétiens have a focal length of 3.5 meters, their plate scale is such that 1 arc second is 17 microns in the detector plane. Hence, to achieve the desired ultra-high resolution of 0.1 arc second, a CCD type imaging detector would require pixels of 0.85 micron dimension. These requirements are clearly far beyond the capabilities of currently available solid state detectors and consequently ultra-high resolution photographic emulsions afford the only solution. The information storage capacity of photographic films is indeed phenomenal, ranging from 10^7 to 10^9 bits cm^{-2}. Even if a CCD with these characteristics could be produced, the data rates produced by such an array of ultra-high resolution instruments taking full disk solar images simultaneously would far exceed the limitations of telemetry technologies now available.

The MSSTA requires detectors capable of operating over a very wide and difficult portion of the electromagnetic spectrum, ranging from the soft x-ray (44-100 Å) through the Extreme Ultraviolet (100-335 Å) and into the Far Ultraviolet (1215.6 Å and 1550 Å). Photographic films constitute the only detectors capable of meeting these requirements. The films must be capable of functioning after days of exposure to high vacuum without degrading the images due to sparks from electrostatic discharges and they must be capable of being transported through ordinary film cameras. Furthermore, to permit observations of faint features in the far corona and quiet Sun as well as to allow rapidly varying transient features to be studied during the limited time (300-400 seconds) available on a sounding rocket flight, high sensitivity at these diverse wavelengths is needed. To accommodate the extreme variations of brightness that can occur in single image of the Sun (such as between the brightness levels of coronal holes and the faint corona as compared to that of an active region or flare), emulsions with the greatest possible latitude, which are capable of reaching extremely high D_{max} diffuse density values before solarizing, are needed. In order to adequately take advantage of extremely high spatial resolution made possible by the Ritchey-Chrétien multilayer x-ray telescopes aboard the MSSTA payload, photographic emulsions from high (200 lines/mm) to ultra-high (2000 lines/mm) spatial resolution are required. We report here on the initial results of our synchrotron studies of several exciting new photographic emulsions which were developed by Eastman Kodak Company and which meet these demanding requirements of the MSSTA program.

Kodak had provided several batches of experimental tabular grain film in 70 mm format with

Type II perforations, including Experimental XUV-100, Experimental XUV-400, Experimental XUV-3200, and Spectroscopic 649. Visible light testing and evaluation of these films was carried out within the Space Science Laboratory at MSFC. Soft x-ray/EUV tests of the T-grain 100 film that was flown on the Stanford/MSFC/LLNL Rocket X-Ray Spectroheliograph were carried out at MSFC and at the Los Alamos National Laboratory. We conducted measurements of the EUV sensitivity of this film as well as investigated the EUV response characteristics of the new MSSTA candidate emulsions at the Stanford Synchrotron Radiation Laboratory (SSRL). We also performed evaluations of these films at EUV and FUV wavelengths at the University of California, Berkeley and at the Synchrotron Ultraviolet Radiation Facility (SURF II) of the National Institute of Standards and Technology (NIST). We report here on the performance of different emulsions and batches at selected wavelengths in the EUV and FUV that are of importance to the MSSTA program, based primarily upon the data obtained at NIST and the University of California, Berkeley.

3. EUV/FUV RESPONSE OF MSSTA FLIGHT FILMS

Based upon our prior observations of base film fog, resolution and x-ray/EUV sensitivity characteristics we had observed in prior studies, the choices of flight emulsions was narrowed to the Experimental XUV 100 tabular grain film, very similar to the T-grain 100 film used on the last flight, and Spectroscopic 649 film. During our prior studies we had rejected the Experimental XUV 400 and Experimental XUV 3200 films in that they exhibited higher base fog densities and lower spatial resolution than the Experimental XUV 100 films, although exhibiting appreciably higher sensitivity at EUV wavelengths. We had also rejected certain batches of XUV 100, such as J4-2726, due to the presence of scratches in the film batch. Our tests at Los Alamos and SSRL had also established that the Experimental XUV 100 film batches were slightly more responsive at 173 Å than the T-grain 100 emulsion which was used as the flight film on our prior mission.

These investigations, coupled with imaging tests using the flight Ritchey-Chrétien telescopes at MSFC, had resulted in the reduction of the candidate films for the MSSTA flight to two batches of Experimental XUV 100 film and two batches of Spectroscopic 649 film. Both of these emulsions were available in 70 mm format with minimum gelatin overcoat on a conductive Estar base. The XUV 100 and Spectroscopic 649 films are fundamentally very different. The XUV 100 has high sensitivity and very good spatial resolution (200 lines/mm). This film is ideal for recording faint solar features and rapidly varying transient events which require numerous short exposures. The Spectroscopic 649 film is a super-fine grain film capable of higher spatial resolution than any other film produced by Kodak. It affords even significantly higher resolution than the Kodak Technical Pan 2415 emulsion which has been used for solar x-ray imagery. Therefore, the Spectroscopic 649 film was considered ideal for use as a flight emulsion on the MSSTA payload, provided it could be shown to have adequate sensitivity at the wavelengths of interest. The 649 emulsion is vastly less sensitive than the XUV 100 at visible wavelengths, but offers significantly higher spatial resolution (2000 lines/mm). Consequently, this is a most important film, as it alone offers the capability of achieving the ultimate 0.1 arc second spatial resolution capabilities to which the instrument has been designed. However, prior to our tests absolutely nothing was known about the sensitivity of this film at EUV/FUV wavelengths.

The EUV tests carried out at the NIST SURF II synchrotron made use of a 2 Å bandpass 2.2 meter grazing incidence McPherson Monochromator. The tests were conducted at three wavelengths of importance to the MSSTA instrumentation: 173 Å, 211 Å and 335 Å. We have assumed that no significant variation [illegible] beam strength occurs over the small bandwidth of the monochromator. We have also assumed that the beam power is directly proportional to the beam current.

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The film was contained in a specially constructed, all aluminum, light tight camera of our own design, which had outgassing properties suitable for use in ultra-high vacuum systems. This film holder was equipped with double filters, each of 1500 Å aluminum foil on a nickel mesh. The filters were fabricated by LUXEL Corp. of Friday Harbor, Washington. We have designated as f the transmission of the filter pair. A calibrated United Detector Technology (UDT Model: XUV 100) photodiode was placed in the beam prior to any exposures being recorded. The diode current $I_{D_\circ}$ was measured for a particular beam current $I_{B_\circ}$. Then for any subsequent beam current I_B we should have:

$$I_D = \frac{I_B}{I_{B_\circ}} I_{D_\circ}. \tag{1}$$

The exposures were made by opening the beam shutter for time t which allowed the beam to pass through the filters and expose the film. A precision two-axis translation stage within the ultra-high vacuum chamber of the monochromator was then advanced to the next X and Y position to permit the next spot on the film to be exposed. Typical operational chamber pressures were in the range of 10^{-8} Torr. Since we know the diode quantum efficiency Q, the photon flux at the filter is QI_D. After passing through the filter pair, the flux is fQI_D. During exposure time t, the total number of photons hitting the film is fQI_Dt. In an image spot of area A, the photon density is:

$$\frac{\text{photons}}{\text{cm}^{-2}} = \frac{fQI_Dt}{A} = \frac{fQI_BI_{D_\circ}t}{AI_{B_\circ}}. \tag{2}$$

At the NIST facility, we measured the quantities $I_{D_\circ}$ and $I_{B_\circ}$ initially and I_B, t and A for each spot recorded on the film. The energy density is obtained by multiplying the photon density by $h\nu$.

The SURF II facility was also used to test the MSSTA candidate films in the Far Ultraviolet (FUV) at 1550 Å. Since this wavelength was beyond the spectral range that could be selected with the monochromator, the flight 1550 Å filters produced by Acton Research were used to select the radiation range which struck the film. The monochromator was placed in zero order, and the direct synchrotron beam allowed to transmit through both FUV filters before striking the film. To carry out the analysis properly, all quantities should be convolved as functions of λ. However, since the diode quantum efficiency Q is constant to within 10 % over the range of wavelengths within the 100 Å bandpass of the filter pair, the analysis simplifies to the EUV case where Q is replaced with its average.

After exposure to the synchrotron beam, the film camera was removed from the monochromator chamber and transferred to the darkroom. The camera was unloaded in total darkness and the film processed by hand in Kodak D-19 developer at 70 °F for 9 minutes. It was then submerged in Kodak indicator stop bath at 70 °F for 30 seconds and fixed in Kodak Rapid Fixer at the same temperature for 4 minutes. The film was then washed in a flowing water bath at 70 °F for 30 minutes, treated with Kodak photo-flo and allowed to dry in air. The diffuse density measurements were performed at MSFC using a MacBeth Model TD-504 densitometer. Prior to each run, a calibrated Kodak step wedge was used to verify that the densitometer was in proper calibration.

The resultant images consist of a small dark square (2.2 mm X 2.2 mm) on top of a lighter and larger rectangle (2.2 mm X 12 mm), due to the properties of the monochromator grazing incidence optic and grating. The monochromator is properly focussed for radiation at 130 Å wavelength, but becomes progressively more de-focussed at longer wavelengths. At 173 Å most of the radiation falls within the confines of the small square and only a small fraction of the flux is in the large rectangle. At 335 Å the small square has merged completely with the large rectangle and is no

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longer apparent. The diode is large enough to receive all radiation within both the large rectangle and the inscribed smaller square. This aspect of the data complicates the analysis. If the density of only the small square is considered, photons in the rectangle are being missed. To establish the relative photon flux onto the small square and the large rectangle requires knowledge of the H&D curve, which is the subject of the measurement. However, this analysis problem has been approached by means of a recursive procedure to determine how much flux fell on the small square and the larger rectangle:

a) Assume all flux falls on the small square
b) Determine the H&D curve
c) Use H&D curve to determine flux onto large rectangle
d) Adjust flux into small square accordingly
e) Determine new H&D curve
f) Recursively loop through b-e until the solution becomes stable.

Two primary batches of Experimental XUV 100 film were evaluated at NIST as the prime candidates for the flight. These were batch J4-6569 and batch J4-320201. **Figure 3a shows a** composite of the data compiled on these two film batches at the test wavelengths investigated at the SURF II facility It can be seen that for comparable photon fluxes, slightly lower densities are obtained at 211 Å with respect to the 173 Å and 335 Å photons. There is virtually no difference in the performance of the two film batches at 211 Å. However, at 173 Å, 335 Å, and 1550 Å emulsion batch J4-6569 is slightly more sensitive. The relatively flat aspect of the H&D curve for the EUV wavelengths at the photon flux levels available within the short exposure times obtained is probably an effect of absorption of the EUV photons within the gelatin. It should however be noted that we have previously established that the Experimental XUV 100 emulsion batch J4-320201 is more responsive at 173 Å than the Experimental T-grain 100 film (Batch J4-994203) which was flown on the Stanford/MSFC/LLNL Rocket X-Ray Spectroheliograph.

Since the MSSTA telescopes are photographically faster than the 173 Å telescope flown on the Stanford/MSFC/LLNL Rocket Spectroheliograph, and the MSSTA mirrors have a reflectivity that is considerably higher, comparable densities on this film should be obtained in exposure times which are shorter by a factor of 6. The great surprise in the measured response data lies in the fact that the Experimental XUV 100 film is remarkably more sensitive at 1550 Å than at the EUV wavelengths. This is probably the result of lower absorption by the gelatin of the FUV photons. It can be seen that at 1550 Å diffuse densities as high as 3.7 were recorded on the Experimental XUV 100 film batch J4-6569. It is also extremely important that even at these high densities, the data points still lie on the linear portion of the H&D curve with no appearance of the shoulder yet appearing. This indicates the tremendous dynamic range of this emulsion. Future tests are planned which will allow exposures sufficiently long to establish the shoulder of the curve, and if possible to determine what photon fluxes would be required in the FUV to initiate film solarization. An exciting and potentially important discovery of these tests was that the 1550 Å photons are capable of penetrating completely through the top layer of film and exposing the underlying piece of film of the other batch being tested.

This result was obtained because of the fact that adhesives commonly used to splice the film were not acceptable due to the ultra-high vacuum requirements of the test. The Metric Splicer Ultrasonic Film Splicer which we plan to use for the flight emulsions was still being fabricated. Consequently, to evaluate two different film batches in a single run, one piece was cut to 70 mm X 70 mm format and a 35 mm X 70 mm format piece of film of a different batch placed so as to cover half of the underlying film. This allowed two batches to be tested for each pump-down. When the top piece was exposed for 30 minutes and received a density of 3.7, the bottom piece of film was found to have been exposed to a density of 1.8 *with photons which had penetrated the*

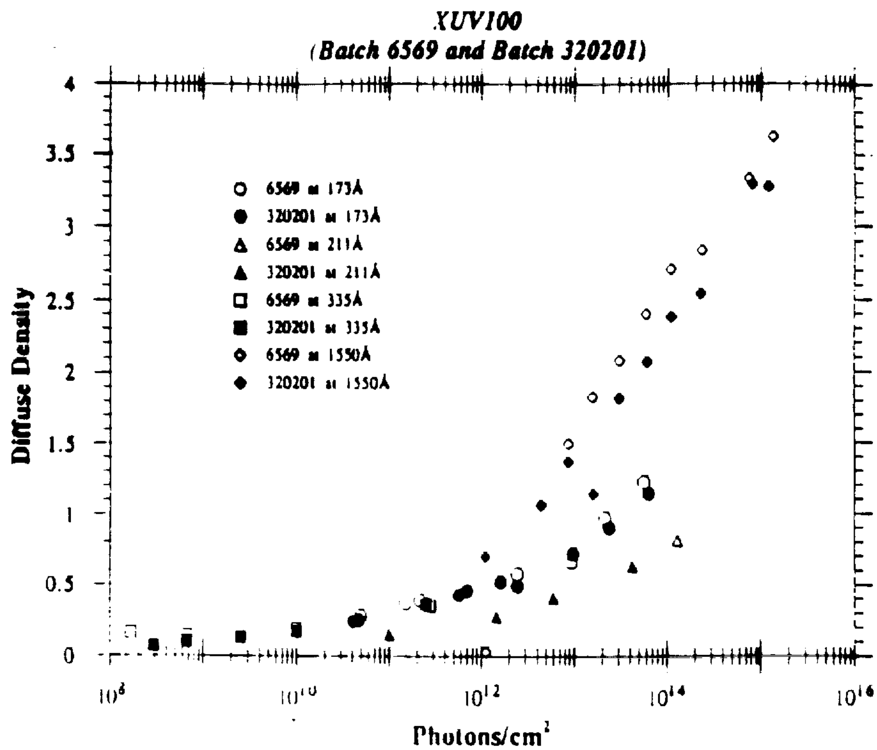

Fig. 3a. Measurements at SURF II of the response characteristics of two different batches of Experimental XUV 100 film for MSSTA flight film selection. Results are shown for measurements at 173 Å, 211 Å, 335 Å, and 1550 Å with diffuse density plotted vs. photons/cm^2.

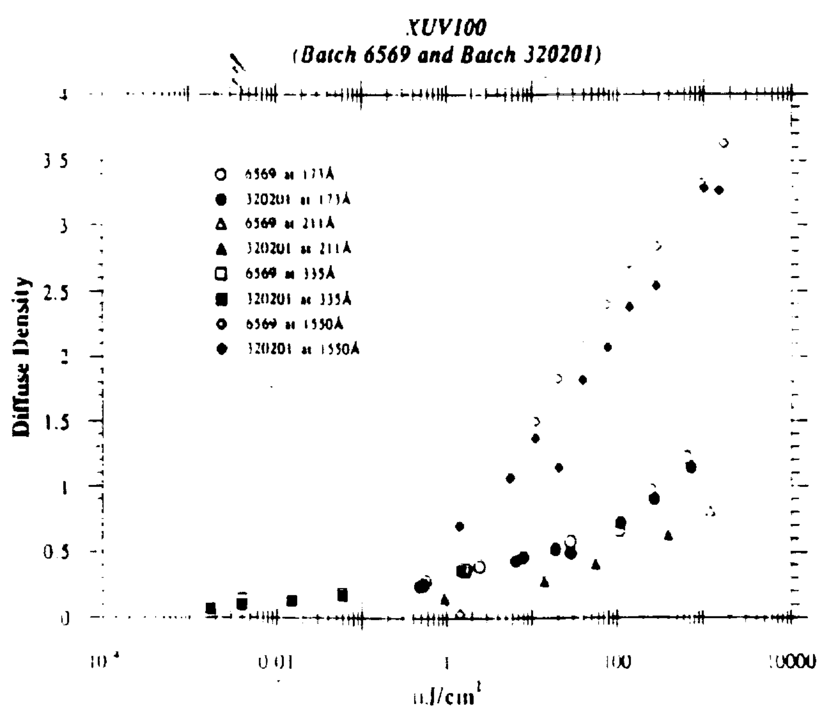

Fig. 3b. Response characteristics of XUV 100 film with diffuse density plotted against energy density in μJ/cm^2.

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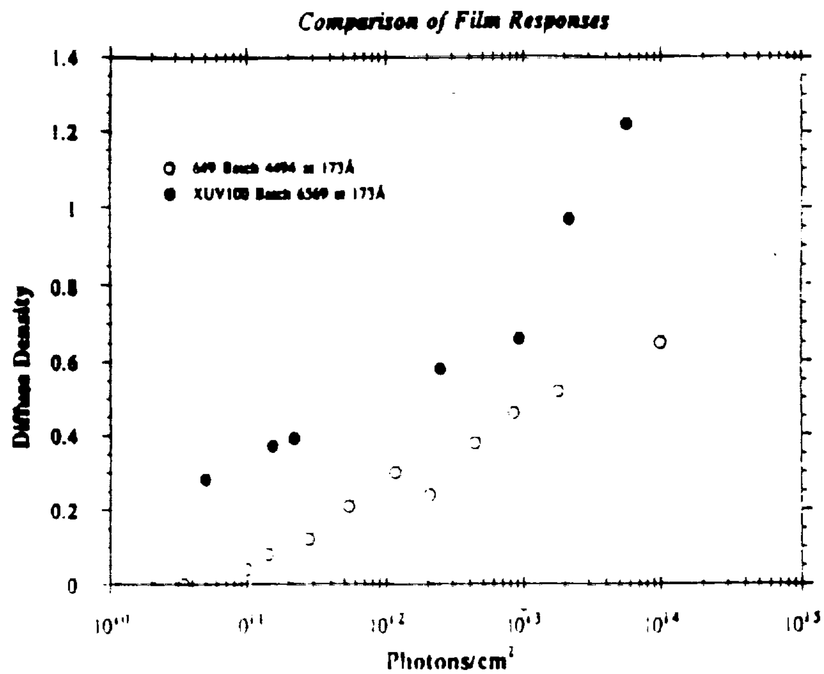

Fig. 4a. Comparison of the response characterisics of the Spectroscopic 649 film (batch J4-4494) with the response of the Experimental XUV 100 film (batch J4-6569) at 173 Å. The 649 is remarkably sensitive at this wavelength when one considers that it offers spatial resolution an order of magnitude higher than the XUV 100.

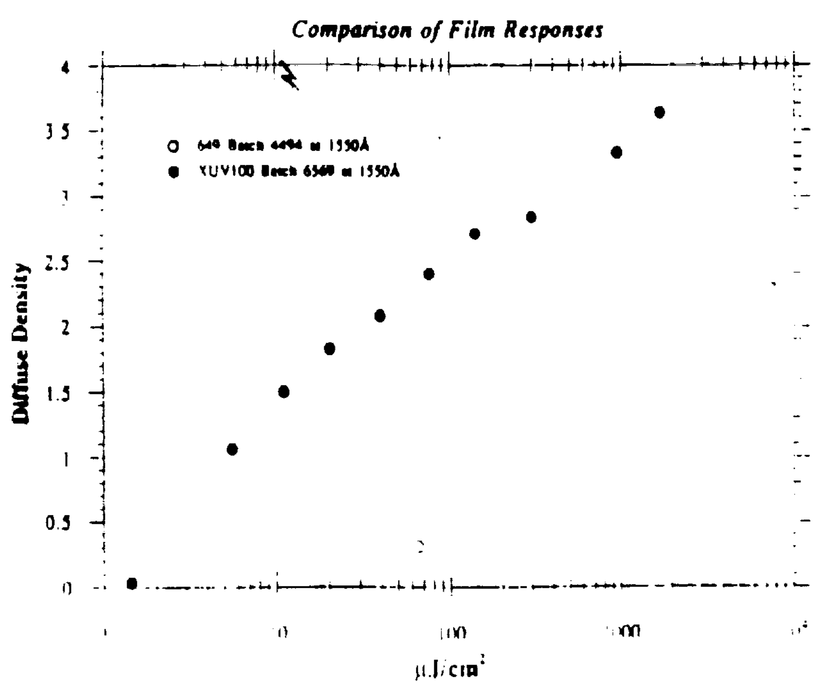

Fig. 4b. Comparison of the response of the two films compared at 1550 Å. The incredibly high density reached by the XUV 100 tends to exaggerate the difference in response characteristics in this plot.

entire emulsion and Estar base of the uppermost piece of film. The effect of the gelatin absorption is even more clearly seen when the data are shown as in **Fig. 3b** where the energy of the incident photons is included to calculate the incident energy density on the film.

The ultra-high resolution Spectroscopic 649 film was also tested and the results were very exciting. The Spectroscopic 649 proved to be very much more sensitive in the EUV than we had anticipated based upon the relative sensitivity of 649 as compared to the XUV 100 at visible wavelengths. During resolution tests of the MSSTA telescope in white light, exposures of 30 seconds were required to produce densities on the film similar to that obtained on XUV 100 in 1/500 of a second, a difference of some 14 f/stops, which is equivalent to exposures some 16,000 times longer.

Even though at these exposure times reciprocity failure might play some role in the observed 649 density levels, it is clear the the 649 is very much less responsive at visible wavelengths as compared to the XUV 100. The response characteristics of the Spectroscopic 649 emulsion as compared to the Experimental XUV 100 are shown in **Fig. 4a** for 173 Å and in **Fig. 4b** for 1550 Å. The Spectroscopic 649 film is astonishingly sensitive at 173 Å. Indeed, even at 1550 Å it is responsive, although much slower than the XUV 100. These results are of the utmost imortance to the MSSTA program. They show that the ultra-fine grain Spectroscopic 649 emulsion can be used for the Herschelian and Ritchey-Chrétien telescopes in the EUV. Consequently, our ultimate goal of achieving solar images with 0.1 arc second spatial resolution on the MSSTA flight may be achieved, providing the pointing system delivers sufficient stability during at least some of the exposures. They also indicate that the Spectroscopic 649 emulsion may even be of value in the FUV. At Hydrogen I Lymanα (1216 Å) the Sun emits more radiation than at all other FUV lines combined. Consequently, even though the film is notably less responsive, sufficient solar flux at this wvelength should be available to permit images with a spatial resolution in the range of 0.3 arc second, which corresponds to the diffraction limit of the telescope at 1216 Å.

The response of the two candidate batches of Spectroscopic Film 649 (J4-4494 and J4-318801) in **Fig. 5a** is plotted as diffuse density vs. Photons/cm^{-2}. Data are shown for 173 Å, 335 Å, and 1550 Å. Virtually no difference is observed in the response of the two batches at 173 Å and 335 Å. However, approximately 100 times more photons/cm^2 is required at 1550 Å to achieve the same density as produced at 173 Å. However, the sensitivity differences do not appear nearly so great when the difuse density is plotted against energy density as is shown in **Fig. 5b** Apparently somewhere between 335 Å and 1550 Å the film makes the transition from being a quantum detector where a single photon can render a grain developable to being an integrating detector, where multiple photons are required to render a photon developable. It is also seen that there is virtually no difference in the response characteristics of the two film batches. Consequently, batch J4-4494 of the Spectroscopic 649 film has been selected as the flight film, solely because we have a larger amount of this emulsion batch available for the flight.

At the Space Science Laboratory of the University of California, Berkeley we obtained only a single data point at 1216 Å for the Spectroscopic 649 emulsion due to the low flux levels available. However, this did establish that the film is responsive at this wavelength. More tests are planned to be carried out at this wavelength at the SURF II facility, and absolute calibration must await these studies. At the UC Berkeley facility we also obtained 1216 Å data on the Schumann emulsion type 101-07. The film was processed using a 4-minute pre-soak in distilled water at 68 °F and developed for 4 minutes in Kodak D-19 developer at 68 °F. This was followed by a 30-second stop bath and a 30-minute wash at the same temperature as the developer.

It can clearly be seen (Fig. 6) that this film is phenomenally sensitive at this wavelength. For solar observations with an imaging instrument such as MSSTA, where large photon fluxes are available, the additional problems of film handling, transport, fogging, and solarization at levels expected within solar active regions makes this film less than ideal for our applications. However,

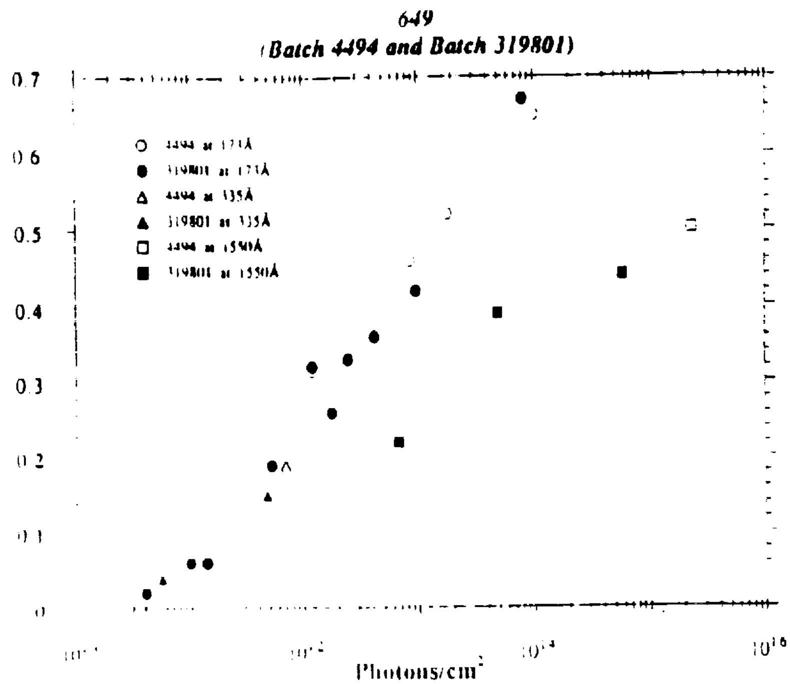

Fig. 5a. Response characterisics of Spectroscopic 649 film batches J4-4494 and J4-319801 at 173 Å, 335 Å, and 1550 Å shown with measured diffuse density plotted against photons/cm^2.

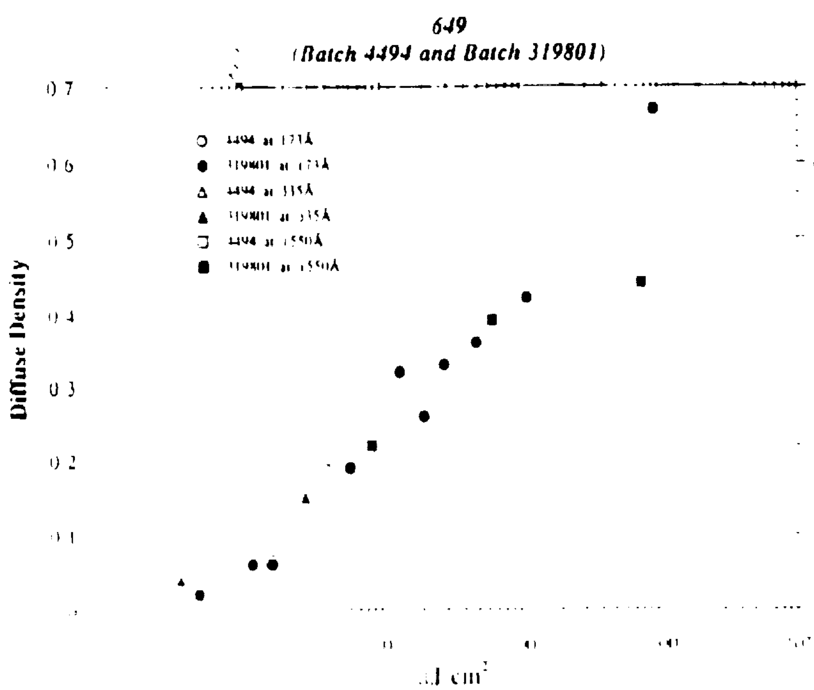

Fig. 5b. Response of the Spectroscopic 649 film batches J4-4494 and J4-319801 at 173 Å, 335 Å, and 1550 Å shown with measured diffuse density plotted against energy density.

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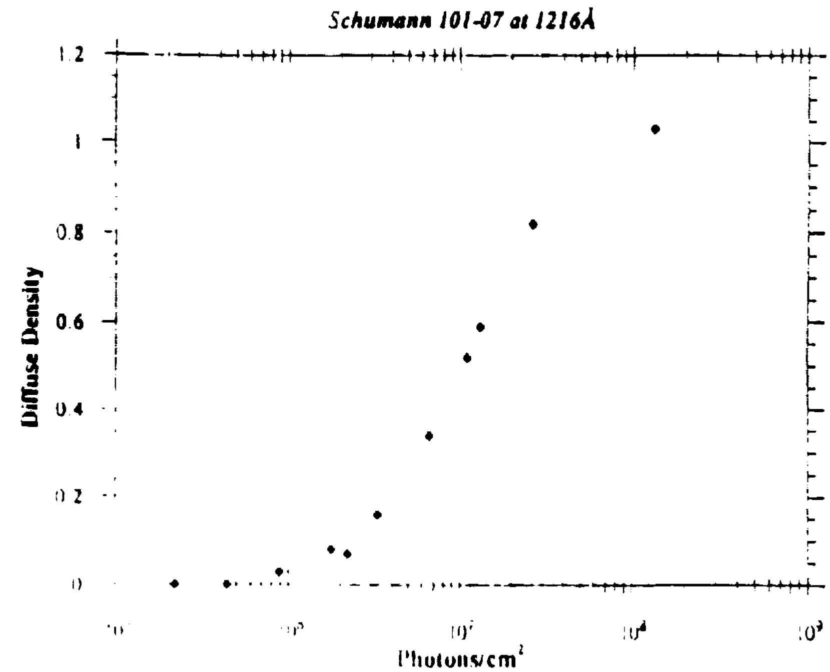

Fig. 6. Response characterisics at 1216 Å of the Schumann emulsion type 101-07. It can be seen that this film responds at significantly lower photon fluxes. The shoulder at the top of the H&D curve is appearing at a diffuse density of approximately 1.

for spectroscopy of faint EUV/FUV sources for laboratory or astronomical applications, it is clear that the Schumann emulsions still have advantages to offer.

5. SUMMARY AND CONCLUSIONS

We have conducted tests at the Los Alamos National Laboratory, the Space Science Laboratory of the University of California, Berkeley, the Stanford Synchrotron Radiation Laboratory, and the SURF II synchrotron of the National Institute of Standards and Technology to establish the response characteristics of photographic emulsions at selected EUV and FUV wavelengths. These tests were performed both to calibrate the T-grain film flown of the Stanford/MSFC/LLNL Rocket X-Ray Spectroheliograph, and to select the flight films which will be used as the primary imaging detectors for the upcoming launch of the Multi-Spectral Solar Telescope Array (MSSTA).

We have presented the results of our measurements at the NIST SURF II synchrotron of the response characteristics of the two candidate MSSTA flight film batches of the Experimental XUV 100 emulsion and the two candidate batches of the Spectroscopic 649 film. Tests were conducted in the EUV at 173 Å, 211 Å, 335 Å, and in the FUV at 1550 Å. Several astonishing observations were made during the course of this research. By far the most important is the observation that the Spectroscopic 649 emulsion is a suitable film for solar observations in the EUV. Although its sensitivity is lower than that of the Experimental XUV 100, it is only lower by 2 to 4 f/stops at 173 Å while its visible light sensitivity is some 14 f/stops below that of XUV 100 emulsion. However, this film has significantly higher spatial resolution than the XUV 100, so it will be the film of choice for obtaining the ultra-high resolution images of the Sun at EUV wavelengths, and even at FUV wavelengths in lines such as hydrogen I Lyman α (1216 Å) where the solar intensity is extremely high.

It was also exciting [illegible] that the Experimental XUV 100 is notably more sensitive at

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1550 Å than at the EUV wavelengths. The 1550 Å radiation was found to be capable of penetrating both the emulsion and film base to produce high density exposures on an underlying piece of film. Our prior measurements at Los Alamos National Laboratory and SSRL had established that the Experimental XUV 100 film batches tested are more responsive than the T-grain 100 emulsion which was successfully flown on the Stanford/MSFC/LLNL Rocket X-Ray Spectroheliograph. Since high density/high resolution images of the Sun were obtained with the small Herschelian mirrors and Cassegrain telescopes on this flight, we are confident that superior images will be produced with the significantly larger and superior Herschelian telescopes and Ritchey-Chrétien instruments which will be flown on the MSSTA.

6. ACKNOWLEDGEMENTS

We wish to express our gratitude to Al DeWan, Gordon Brown, Martin L. Scott, Paul B. Gilman, Seth Gaugh, Joe Maskaskey, Sally Robson, Silvia Zawadzki and all others at Eastman Kodak whose assistance and knowledge have been of tremendous value to this research. We also wish to thank Bill Priedorhsky and Frank Ameduri of the Los Alamos National Laboratory for assistance with calibration of the T-Grain 100 and XUV 100 films at their facility, and to Barry Welsh, Jim Gibson, and C. Stuart Bowyer of the Space Science Laboratory of the University of California, Berkeley, for their assistance in performing EUV/FUV calibrations at their facility. We are also grateful to Troy Barbee, Pierro Pianetta, and Efim Gluskin for their support during testing of the films at the Stanford Synchrotron Radiation Laboratory. We are deeply indebted to Richard Watts, Mitch Furst, Robert Madden, Randy Canfield, Bill Wooden, Lanny Hughey, Bill Graves, and Andrew Hamilton for their assistance in the calibration of the flight emulsions at EUV and FUV wavelengths at the NIST SURF II facility.

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Response Characteristics of the MSSTA Photographic Films at EUV and FUV Wavelengths

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ABSTRACT

The Multi-Spectral Solar Telescope Array (MSSTA) employs an array of Ritchey-Chrétien, Cassegrain, and Herschelian normal incidence telescopes to produce high resolution solar images in the soft x-ray (44-100 Å), Extreme Ultraviolet (EUV – $\lambda\lambda \sim 100 - 1000$ Å) and Far Ultraviolet (FUV – $\lambda\lambda \sim 1000 - 2000$ Å) portions of the electromagnetic spectrum. These normal incidence multilayer and thin film interference coated optical systems are designed to produce narrow band solar images at selected wavelengths within this very broad spectral regime. The MSSTA mission places extremely strenuous requirements upon the imaging detector. The desire for ultra-high resolution (~ 0.1-0.3 arc-second) images of the solar disk and corona out to 1.5 $R_{\odot}$ demands an information storage capacity which can at the present time be met only by the highest quality photographic emulsions. Since a tremendous range exists in the intensity levels and contrast characteristics of solar x-ray/EUV/FUV emission features, the MSSTA photographic films must have a wide latitude to allow extremely bright, high contrast features associated with flares and active regions to be recorded without saturating, while maintaining the ability to capture the faint, low contrast structures in coronal holes, polar coronal plumes, network structures and coronal loops.

The MSSTA flight films must have high to ultra-high resolution and be sensitive over this very broad and difficult portion of the electromagnetic spectrum. The gelatin overcoat of the film must be maintained at a minimum, while the 70 mm film must retain the ability to be transported through conventional Pentax 645 cameras with minimum degradation due to scratches in the delicate emulsion. Furthermore, since the payload must be evacuated to prevent the delicate EUV and soft x-ray filters from failing due to acoustic vibrational stresses during launch, the MSSTA flight films must also have low-outgassing rates. These films must also be provided with anti-static backing to prevent electrostatic sparks from degrading the images as the dry film is unspooled through the cameras.

We present the results of synchrotron beam line studies to establish the EUV and FUV response characteristics of photographic emulsions which will be flown on MSSTA for solar observations. We discuss the properties of the important new emulsions that have been selected for flight

and present data on the response characteristics of a tabular grain Experimental XUV 100 film and an uncoated Experimental Spectroscopic 649 emulsion. These data are based upon our measurements of these films at EUV and FUV radiation from sources at the SURF II synchrotron facility of the National Institute of Standards and Technology (NIST) and the Space Sciences Laboratory of the University of California, Berkeley.

1. INTRODUCTION.

The October 23, 1987 flight of the Stanford/MSFC/LLNL Rocket X-Ray Spectroheliograph [1] on Nike-boosted Black Brant sounding rocket was launched from the White Sands Missile Range, New Mexico produced the first high resolution image of the Sun with a normal incidence multilayer x-ray telescope and the first astronomical soft x-ray/EUV images ever recorded on tabular grain (T-grain) photographic emulsions. The flight film was a specially-coated version of KODAK T-MAX film, which yielded excellent sensitivity and high spatial resolution at the selected wavelengths between 44 Å and 256 Å. It also demonstrated a very wide latitude, with measurable diffuse densities ranging from a base fog density of 0.03 to a D_{max} in excess of 3.1.

This maximum density far exceeded that which has typically been obtained with the Schumann type photographic emulsions that had previously been used for astronomical research in this portion of the spectrum. In the soft x-ray/EUV portion of the electromagnetic spectrum the sensitivity of photographic films suffers significantly due to absorption within the gelatin which is used to hold the silver halide grains in place. This phenomenon was first observed by Victor Schumann, who was responsible for the discovery of the Extreme Ultraviolet (EUV) portion of the electromagnetic spectrum. To improve the EUV sensitivity of photographic film, Schumann[2] invented in 1892 an emulsion with a monolayer of silver halide crystals deposited on a 12 micron thick gelatin pad. In modern Schumann films, the halation effects at wavelengths for which the gelatin is transparent are reduced by the addition a yellow dye to the gelatin pad. Schumann emulsions have subsequently served as the primary film of choice for solar EUV photography.

The method of fabricating Schumann plates was described by Lyman in 1928, and for many years Schumann films were made by hand in extremely limited quantities. In 1967, the Eastman Kodak Company started producing them by a machine coating process.[3] Extensive use of Schumann emulsions was made by the Naval Research Laboratory group during Skylab with the Extreme Ultraviolet Spectroheliograph (ATM Experiment S-082A).[4] This instrument used a concave imaging diffraction grating to produce multiple overlapping images of the Sun in dispersed solar emission lines, in the spectral range from 171-630 Å. Schumann film types 101 and 104 were also used by the NRL Extreme Ultraviolet Spectrograph (ATM Experiment S-082B)[5] to perform solar spectroscopy in the 970-3940 Å region, which they designated as the the XUV (but which we refer to herein as the FUV and UV portions of the spectrum).

Since Schumann film has no protective gelatin overcoat, it is extremely susceptible to abrasion, scratching, and fogging from environmental effects of all kinds. It is so sensitive to pressure-induced fogging that special "bead rails" are usually deposited at the edges of the film to prevent the emulsion surface from making any contact with the back surface of the film immediately adjacent to it on the roll. VanHoosier et al.[6] have described in detail the intricate care and precautions that were taken to allow this film to be used in the NRL experiments aboard Skylab. This care included the use of a specially designed and highly complex camera, that accommodates only single strips of film. Despite these intricate precautions, many of the flight exposures were damaged by pressure marks and other types of fogging. Furthermore, the Skylab flight film (type 104-06-05) exhibited a marked change in characteristics of the H&D curve as compared with the ground control samples. Although the laboratory samples reached a D_{max}=1.2, the flight film suffered a significant loss in both D_{max} and contrast as compared to the identical emulsion batch that remained in the laboratory. The maximum diffuse density of the film which was flown reached a value of only 0.8, and after a flat plateau at that level diminished abruptly as the exposure level increased. This solarization effect is extremely detrimental to the analysis of solar EUV data, as the same measured diffuse density can be produced by vastly different photon fluxes incident upon the film. These problems, coupled with the extreme difficulty in the manufacture, cost, film transport, and with the various unpredictable appearances of fog and blemishes in images recorded on the Schumann emulsions, have resulted in these films being regarded as difficult, both by the astronomers who use the film and by Eastman Kodak Company who manufacture the film. Furthermore, since Al DeWan (the Eastman Kodak expert in the methods used to manufacture these emulsions) has retired, it may become impossible to obtain Type 104, 101-07 and the other types of Schumann emulsions, which for several years Eastman Kodak has produced as a service to the scientific community. Although the unavailability of 101-07 film does not pose a great difficulty for experiments such as the MSSTA, which uses relatively fast imaging systems with high reflection efficiency optics, it could be a serious problem for those interested in EUV spectroscopy of the Sun, laser fusion plasmas, or imaging of faint EUV/FUV sources.

Kodak had also produced other specialized films for use at soft x-ray wavelengths. The soft x-rays in the 6-49 Å bandpass regime, covered by our ATM Experiment S-056 x-ray telescope that was flown on Skylab,[7] are not nearly as strongly absorbed by gelatin as are the photons of longer wavelengths. Nevertheless, the flight film we used with this instrument to take almost 25,000 x-ray images of the Sun was a specially prepared Kodak S0-212 emulsion. (Some images were also recorded on a color emulsion, Kodak Aerial Color Film S0-242, which resulted in slightly higher spatial resolution but at significantly lower x-ray sensitivity.) The SO-212 is a Kodak Panatomic-X Aerial film 3400 with the protective gelatin overcoat removed to reduce soft x-ray absorption effects. The emulsion was deposited on a thin (63.5 micron) Estar base. The Estar base films have considerably higher dimensional stability than the cellulose acetate butyrate base films.

Since this soft x-ray had to be transported on rolls after exposure to high vacuum, a conductive Rem-Jet backing was applied to the film. This prevented image degradation due to electrostatic discharges that occur when the film is unwound after it has been dried by exposure to high vacuum. However, Rem-Jet coatings are difficult to remove, and great care must be exercised to prevent debris (in the form of tiny black particulates) from contaminating the emulsion surface of the film during the removal process. Any Rem-Jet particles on the emulsion side when the film dries have a tendency to become permanently affixed to the film. Kodak has recently solved this problem by developing a conductive Estar base. All of the newer EUV sensitive films which Kodak has provided to us have been on this conductive Estar base. Extensive vacuum tests have produced excellent results. No degradation has ever been observed as a result of electrostatic discharges resulting from unspooling the dry conductive Estar base film, even after prolonged exposure to ultra-high vacuum conditions. Furthermore, there exist none of the problems associated with Rem-Jet removal, so this technological development is very much appreciated.

The limitations of the Skylab films flown on S-056, S-082A and S-082B led us to be extremely concerned about photographic films for use at wavelengths longward of 100 Å. Indeed, the EUV wavelength regime was particularly demanding. When Skylab was launched, only the very difficult Schumann emulsions were known with certainty to be sensitive in this regime. The Stanford/MSFC/LLNL Rocket X-Ray Spectroheliograph was designed to obtain images at selected wavelengths ranging from 8 Å at the prime focus of the grazing incidence Wolter-Schwarzschild telescope to 44 Å, 173 Å and 256 Å for the Herschelian and Cassegrain telescopes. To obtain suitable photographic films (which could be transported in conventional cameras) for use in this region, assistance was sought from Al DeWan, Gordon Brown, Martin Scott, Paul Gilman and others at Eastman Kodak. Kodak provided several experimental tabular grain emulsions in 35 mm format on Estar base with Rem-Jet anti-static coated backing for our investigations and flight.

Tests which were conducted at MSFC and at the Los Alamos National Laboratory revealed that these T-grain emulsions[3] have significantly higher sensitivity in the desired regime than the S0-212 films which we had maintained in cold storage since the Skylab mission. The Kodak tabular grain films represent a revolutionary breakthrough, in that the silver halide grains are in the form of flat, triangular or truncated triangular crystals.[9] The grains tend to lie flat on the base, which yields a film which has higher sensitivity and enhanced spatial resolution simultaneously. The experimental emulsion which we selected for flight on the Stanford/MSFC/LLNL Rocket X-Ray Spectroheliograph is now marketed commercially as KODAK T-MAX 100 film. On this flight, the T-grain 100 film proved itself to be an excellent detector for high resolution imaging of the Sun in the wavelength regime from 8 Å-256 Å. Hoover and Lindblom processed the flight film, by hand, at the White Sands Missile Range. Hoover et al.[8] have described the film processing details and experiences with this excellent emulsion on the rocket flight.

2. MSSTA PHOTOGRAPHIC FILM REQUIREMENTS

The Multi-Spectral Solar Telescope Array includes two Cassegrain, seven Ritchey-Chrétien and five Herschelian telescopes to image the Sun over a much broader region of the electromagnetic spectrum than our previous payload. Walker et al.[10] have provided a detailed description of this payload. The completed payload is shown in Figure 1, undergoing final assembly and testing at MSFC prior to shipment to the White Sands Missile Range for launch.

It is also planned for the MSSTA telescopes to achieve a much higher spatial resolution than those flown on the Stanford/MSFC/LLNL Rocket X-Ray Spectroheliograph. Consequently, the MSSTA poses perhaps the most strenuous demands upon the imaging detector ever imposed by a single spaceflight payload.

The MSSTA requires detectors capable of providing full disk images of the Sun (including the corona out to 1.5 solar radii) with spatial resolution up to 0.1 arc second. The usable field of view of each of the Ritchey-Chrétien telescopes is ± 25 arc minutes, which is an area of 3000X3000 arc seconds. In accordance with the Nyquist limit, to achieve spatial resolution of 0.1 arc second over this field of view with a CCD, we would require a detector with 60.000 X 60.000 pixels. Since the MSSTA Ritchey-Chrétiens have a focal length of 3.5 meters, their plate scale is such that 1 arc second is 17 microns in the detector plane. Hence, to achieve the desired ultra-high resolution of 0.1 arc second, a CCD type imaging detector would require pixels of 0.85 micron dimension. These requirements are clearly far beyond the capabilities of currently available solid state detectors; consequently, ultra-high resolution photographic emulsions afford the only solution. The information storage capacity of photographic films is indeed phenomenal, ranging from 10^7 to 10^9 bits cm^{-2}. Even if a CCD with these characteristics could be produced, the data rates produced by such an array of ultra-high resolution instruments taking full disk solar images simultaneously would far exceed the limitations of telemetry technologies now available.

The MSSTA detectors must also operate over a very wide and difficult portion of the electromagnetic spectrum, ranging from the soft x-ray (44-100 Å) through the Extreme Ultraviolet (100-335 Å) and into the Far Ultraviolet (1215.6 Å and 1550 Å). Photographic films constitute the only detectors capable of meeting these requirements. The films must be capable of functioning after days of exposure to high vacuum, without degrading the images due to sparks from electrostatic discharges; and they must be capable of being transported through ordinary film cameras. Furthermore, to permit observations of faint features in the far corona and quiet Sun, as well as to allow rapidly varying transient features to be studied during the limited time (300-400 seconds) available on a sounding rocket flight, high sensitivity at these diverse wavelengths is needed. To accommodate the extreme variations of brightness that can occur in a single image of the Sun (such as between the brightness levels of coronal holes and the faint corona as compared to that of an active region or flare), emulsions with the greatest possible latitude, which are capable of reaching extremely high D_{max} diffuse density values before solarizing, are needed. In order to adequately take advantage of the extremely high spatial resolution made possible by the Ritchey-Chrétien multilayer x-ray telescopes aboard the MSSTA payload, photographic emulsions from high (200 lines/mm) to ultra-high (2000 lines/mm) spatial resolution are required. We report here on the initial results of our synchrotron studies of several exciting new photographic emulsions which were developed by Eastman Kodak Company, and which meet these demanding requirements of the MSSTA program.

Kodak had provided several batches of experimental tabular grain film in 70 mm format with Type II perforations, including Experimental XUV-100, Experimental XUV-400, Experimental XUV-3200, and Spectroscopic 649. Visible light testing and evaluation of these films was carried out within the Space Science Laboratory at MSFC. Soft x-ray/EUV tests of the T-grain 100 film that was flown on the Stanford/MSFC/LLNL Rocket X-Ray Spectroheliograph were carried out at MSFC and at the Los Alamos National Laboratory. We conducted measurements of the EUV sensitivity of this film as well as investigated the EUV response characteristics of the new MSSTA candidate emulsions at the Stanford Synchrotron Radiation Laboratory (SSRL). We also performed evaluations of these films at EUV and FUV wavelengths at the University of California, Berkeley and at the Synchrotron Ultraviolet Radiation Facility (SURF II) of the National Institute of Standards and Technology (NIST). We report here on the performance of different emulsions and batches at selected wavelengths in the EUV and FUV that are of importance to the MSSTA program, based primarily upon the data obtained at NIST and the University of California, Berkeley.

3. EUV/FUV RESPONSE OF MSSTA FLIGHT FILMS

In accordance with our prior observations of base film fog, resolution, and x-ray/EUV sensitivity characteristics, the choices of emulsions for the MSSTA mission had been narrowed to the Experimental XUV 100 tabular grain film, (which was very similar to the T-grain 100 film used on the last flight) and to the Spectroscopic 649 film. During our earlier studies we had rejected the Experimental XUV 400 and Experimental XUV 3200 films in that they exhibited higher base fog densities and lower spatial resolution than the Experimental XUV 100 films, although exhibiting somewhat higher sensitivity at EUV wavelengths. We had also rejected some XUV 100 batches (e.g. J4-2726) due to the presence of scratches in the film batch. Our tests at Los Alamos and SSRL had also established that the Experimental XUV 100 film batches were slightly more responsive at 173 Å than was the T-grain 100 emulsion which was used as the flight film on our prior mission.

These investigations, coupled with imaging tests using the flight Ritchey-Chrétien telescopes at MSFC, had resulted in the reduction of the candidate films for the MSSTA flight to two batches of Experimental XUV 100 film and two batches of Spectroscopic 649 film. Both of these emulsions were available in 70 mm format with minimum gelatin overcoat on a conductive Estar base. The XUV 100 and Spectroscopic 649 films are fundamentally very different. The XUV 100 has high sensitivity and very good spatial resolution (200 lines/mm). This film is ideal for recording faint solar features and rapidly varying transient events which require numerous short exposures. The Spectroscopic 649 film is a super-fine grain film capable of higher spatial resolution than any other film produced by Kodak. It affords significantly higher resolution than even the Kodak Technical Pan 2415. This is the photographic emulsion which was used by Golub et al.[11] to produce excellent solar x-ray images at 63.5 Å with a large Herschelian telescope. Spiller et al.[12] have provided calibration data on the response characteristics at 67.7 Å of standard Technical Pan film with gelatin overcoat (which is commercially available) and the special Technical Pan emulsion which was provided to them in 1985 without a gelatin overcoat. At 67.7 Å it is clear that absorption within the gelatin is a minimal effect, whereas it is highly significant in the EUV at wavelengths longer than 150 Å. Technical Pan has lower inherent spatial resolution than the the Spectroscopic 649 film, which was considered ideal for use as a flight emulsion on the MSSTA payload, provided it could be shown to have adequate sensitivity at the wavelengths of interest. The Spectroscopic 649 emulsion is vastly less sensitive than the XUV 100 at visible wavelengths, but offers significantly higher spatial resolution (2000 lines/mm). Consequently, this is a most important film, as it alone offers the capability of achieving the ultimate 0.1 arc second spatial resolution capabilities to which the instrument has been designed. However, prior to our tests, nothing was known about the sensitivity of this film at EUV/FUV wavelengths.

The EUV tests carried out at the NIST SURF II synchrotron made use of a 2 Å bandpass 2.2 meter grazing incidence McPherson Monochromator. The tests were conducted at three wavelengths of importance to the MSSTA instrumentation: 173 Å, 211 Å and 335 Å. We have assumed that no significant variation in beam strength occurs over the small bandwidth of the monochromator. We have also assumed that the EUV beam power is directly proportional to the synchrotron beam current. The film was contained in a specially constructed, all aluminum, light tight camera of our own design, which had outgassing properties suitable for use in ultra-high vacuum systems. This film holder was equipped with double filters, each of 1500 Å aluminum foil on a nickel mesh. The filters were fabricated by LUXEL Corp. of Friday Harbor, Washington. We have designated as f the transmission of the filter pair. A calibrated United Detector Technology (UDT Model: XUV 100) photodiode was placed in the beam prior to any exposures being recorded. The diode current $I_{D_\circ}$ was measured for a particular beam current $I_{B_\circ}$. Then for any subsequent beam current I_B we should have:

$$I_D = \frac{I_B}{I_{B_\circ}} I_{D_\circ}. \tag{1}$$

The exposures were made by opening the beam shutter for time t which allowed the beam to pass through the filters and expose the film. A precision two-axis translation stage within the ultra-high vacuum chamber of the monochromator was then advanced to the next X and Y position to permit the next spot on the film to be exposed. Typical operational chamber pressures were in the range of 10^{-8} Torr. Since we know the diode quantum efficiency Q, the photon flux at the filter is QI_D. After passing through the filter pair, the flux is fQI_D. During exposure time t, the total number of photons hitting the film is fQI_Dt. In an image spot of area A, the photon density is:

$$\frac{\text{photons}}{\text{cm}^{-2}} = \frac{fQI_Dt}{A} = \frac{fQI_BI_{D_\circ}t}{AI_{B_\circ}}. \tag{2}$$

At the NIST facility, we measured the quantities $I_{D_\circ}$ and $I_{B_\circ}$ initially and I_B, t and A for each spot recorded on the film. The energy density is obtained by multiplying the photon density by $h\nu$.

The NIST SURF II facility was also used to test the MSSTA candidate films in the Far Ultraviolet (FUV) at 1550 Å. Since this wavelength was beyond the spectral range that could be selected with the monochromator, the flight 1550 Å filters produced by Acton Research were used to select the radiation range which struck the film. The monochromator was placed in zero order, and the direct synchrotron beam allowed to transmit through both FUV filters before striking the film. To carry out the analysis properly, all quantities should be convolved as functions of

λ. However, since the diode quantum efficiency Q is constant to within 10 % over the range of wavelengths within the 100 Å bandpass of the filter pair, the analysis simplifies to the EUV case where Q is replaced with its average.

After exposure to the synchrotron beam, the film camera was removed from the monochromator chamber and transferred to the darkroom. The camera was unloaded in total darkness and the film processed by hand in Kodak D-19 developer at 70 °F for 9 minutes. It was then submerged in Kodak indicator stop bath at 70 °F for 30 seconds and fixed in Kodak Rapid Fixer at the same temperature for 4 minutes. The film was then washed in a flowing water bath at 70 °F for 30 minutes, treated with Kodak photo-flo and allowed to dry in air. The diffuse density measurements were performed at MSFC using a MacBeth Model TD-504 densitometer. Prior to each run, a calibrated Kodak step wedge was used to verify that the densitometer was in proper calibration.

The resultant images, as seen in **Fig. 3a.** consist of a small dark square (2.2 mm X 2.2 mm) on top of a lighter and larger rectangle (2.2 mm X 12 mm), due to the properties of the monochromator grazing incidence optic and grating. (**Fig. 3a.**) The monochromator is properly focussed for radiation at 130 Å wavelength, but becomes progressively more de-focussed at longer wavelengths. (**Fig. 3b.**) At 173 Å most of the radiation falls within the confines of the small square and only a small fraction of the flux is in the large rectangle. At 335 Å the small square has merged completely with the large rectangle and is no longer apparent. The diode is large enough to receive all radiation within both the large rectangle and the inscribed smaller square. This aspect of the data complicates the analysis. If the density of only the small square is considered, photons in the rectangle are being missed. To establish the relative photon flux onto the small square and the large rectangle requires knowledge of the H&D curve, which is the subject of the measurement. However, this analysis problem has been approached by means of a recursive procedure to determine how much flux fell on the small square and the larger rectangle:

a) Assume all flux falls on the small square
b) Determine the H&D curve
c) Use H&D curve to determine flux onto large rectangle
d) Adjust flux into small square accordingly
e) Determine new H&D curve
f) Recursively loop through b-e until the solution becomes stable.

Two primary batches of Experimental XUV 100 film were evaluated at NIST as the prime candidates for the flight. These were designated by Eastman Kodak as batches J4-6569 and J4-320201. **Figure 4a** shows a composite of the data compiled on these two film batches at the test wavelengths investigated at the SURF II facility. It can be seen that, for comparable photon fluxes, slightly lower densities are obtained at 211 Å than with the 173 Å and 335 Å photons. There is virtually no difference in the performance of the two film batches at 211 Å. However, at 173 Å, 335 Å, and 1550 Å emulsion batch J4-6569 is slightly more sensitive. The relatively flat aspect of the H&D curve for the EUV wavelengths at the photon flux levels available within the short exposure times obtained is probably an effect of absorption of the EUV photons within the gelatin. The effect of the gelatin absorption is even more clearly seen when the data are shown as in **Fig. 4b** where the energy of the incident photons is included to calculate the incident energy density on the film. It should however be noted that we have previously established that the Experimental XUV 100 emulsion (J4-320201) is more responsive at 173 Å than the Experimental T-grain 100 film (J4-994203) which was flown on the Stanford/MSFC/LLNL Rocket X-Ray Spectroheliograph.

Since the MSSTA telescopes are photographically faster than the 173 Å telescope flown on the Stanford/MSFC/LLNL Rocket Spectroheliograph, and the MSSTA mirrors have a reflectivity that is considerably higher, comparable densities on this film should be obtained in exposure times which are shorter by a factor of 6. The great surprise in the measured response data lies in the fact that the Experimental XUV 100 film is remarkably more sensitive at 1550 Å than at the EUV wavelengths. This is probably the result of lower absorption by the gelatin of the FUV photons. It can be seen that at 1550 Å diffuse densities as high as 3.7 were recorded on the Experimental XUV 100 film (J4-6569). It is also extremely important that even at these high densities, the data points still lie on the linear portion of the H&D curve with no appearance of the shoulder yet appearing. This indicates the tremendous dynamic range of this emulsion. Future tests are planned which will allow exposures sufficiently long to establish the shoulder of the curve, and if possible to determine what photon fluxes would be required in the FUV to initiate film solarization. An exciting and potentially important discovery of these tests was that the 1550 Å photons are capable of penetrating completely through the top layer of film and exposing the underlying piece of film of the other batch being tested.

This result was obtained because of the fact that adhesives commonly used to splice the film were not acceptable due to the ultra-high vacuum requirements of the test. The Metric Splicer Ultrasonic Film Splicer which we plan to use for the flight emulsions was unavailable. Consequently, to evaluate two different film batches in a single run, one piece was cut to 70 mm X 70 mm format, and another of a different batch was cut to a 35 mm X 70 mm format and placed so as to cover half of the larger piece of film. This allowed two batches to be tested for each vacuum pump-down. When the top piece was exposed for 30 minutes and processed, it exhibited a maximum density of 3.7. However, the bottom piece of film was found to have been exposed to a density of 1.8 with photons which had penetrated the emulsion and Estar base of the uppermost piece of film.

The ultra-high resolution Spectroscopic 649 film was also tested and the results were very exciting. The Spectroscopic 649 proved to be very much more sensitive in the EUV than we had anticipated based upon its relative sensitivity, as compared to the XUV 100, at visible wavelengths. During resolution tests of the MSSTA telescope in white light, exposures of 30 seconds were required to produce densities on the film similar to that obtained on XUV 100 in 1/500 of a second, a difference of some 14 f/stops, which is equivalent to exposures some 16,000 times longer.

Even though at these exposure times reciprocity failure might play some role in the observed 649 density levels, it is clear that the 649 is vastly less responsive at visible wavelengths as compared to the XUV 100. The response characteristics of the Spectroscopic 649 emulsion as compared to the Experimental XUV 100 are shown in **Fig. 5a** for 173 Å and in **Fig. 5b** for 1550 Å. The Spectroscopic 649 film is astonishingly sensitive at 173 Å. Indeed, even at 1550 Å it is responsive, although much slower than the XUV 100. These results are of the utmost importance to the MSSTA program. They show that the ultra-fine grain Spectroscopic 649 emulsion can be used for the Herschelian and Ritchey-Chrétien telescopes in the EUV. Consequently, our ultimate goal of achieving solar images with 0.1 arc second spatial resolution on the MSSTA flight may be achieved, providing the pointing system delivers sufficient stability during at least some of the exposures. They also indicate that the Spectroscopic 649 emulsion may even be of value in the FUV. At Hydrogen I Lyman α (1216 Å) the Sun emits more radiation than at all other FUV lines combined. Consequently, even though the film is notably less responsive, sufficient solar flux at this wavelength should be available to permit images with a spatial resolution in the range of 0.3 arc second, which corresponds to the diffraction limit of the telescope at 1216 Å.

The response of the two candidate Spectroscopic Film 649 batches (J4-4494 and J4-318801) in **Fig. 6a** is plotted as diffuse density vs. Photons/cm^{-2}. Data are shown for 173 Å, 335 Å, and 1550 Å. Virtually no difference is observed in the response of the two batches at 173 Å and 335 Å. However, approximately 100 times more photons/cm^2 is required at 1550 Å to achieve the same density as produced at 173 Å. However, the sensitivity differences do not appear nearly so great when the difuse density is plotted against energy density as is shown in **Fig. 6b** Apparently somewhere between 335 Å and 1550 Å the film makes the transition from being a quantum detector. where a single photon can render a grain developable. to being an integrating detector, where multiple photons are required to render a photon developable. It is also seen that there is virtually no difference in the response characteristics of the two film batches. Consequently, batch J4-4494 of the Spectroscopic 649 film has been selected as the flight film, solely because we have a larger amount available for the flight.

At the Space Science Laboratory of the University of California, Berkeley, we obtained a single data point at 1216 Å for the Spectroscopic 649 emulsion, due to the low flux levels available. However, this did establish that the film is responsive at this wavelength. More tests are planned to be carried out at this wavelength at the SURF II facility, and absolute calibration must await these studies. At the UC Berkeley facility we also obtained 1216 Å data on the Schumann emulsion type 101-07. The 101-07 film was processed using a 4-minute pre-soak in distilled water at 68 °F and developed for 4 minutes in Kodak D-19 developer at 68 °F. This was followed by a 30-second stop bath and a 30-minute wash at the same temperature as the developer.

It can clearly be seen (**Figs. 7a.** and **7b.**) that this film is phenomenally sensitive at this wavelength. For solar observations with an imaging instrument such as MSSTA, where large photon fluxes are available, the additional problems of film handling, transport, fogging, and solarization at levels expected within solar active regions, makes this film less than ideal for our applications. However, for spectroscopy of faint EUV/FUV sources for laboratory or astronomical applications, it is clear that the Schumann emulsions still have advantages to offer.

5. CONCLUSIONS

We have conducted tests at the Los Alamos National Laboratory, the Space Science Laboratory of the University of California, Berkeley, the Stanford Synchrotron Radiation Laboratory, and the SURF II synchrotron of the National Institute of Standards and Technology (NIST) to establish the response characteristics of photographic emulsions at selected EUV and FUV wavelengths. These tests were performed both to calibrate the T-grain film flown on the Stanford/MSFC/LLNL Rocket X-Ray Spectroheliograph, and to select the flight films which will be used as the primary imaging detectors for the May 16, 1991 launch of the Multi-Spectral Solar Telescope Array (MSSTA).

We have presented the results of our measurements at the NIST SURF II synchrotron of the response characteristics of the two candidate MSSTA flight film batches of the Experimental XUV 100 emulsion and the two candidate batches of the Spectroscopic 649 film. Tests were conducted in the EUV at 173 Å, 211 Å, 335 Å, and in the FUV at 1550 Å. Several astonishing observations were made during the course of this research. By far the most important is the observation that the Spectroscopic 649 emulsion is a suitable film for solar observations in the EUV. Although its sensitivity is lower than that of the Experimental XUV 100, it is only lower by 2 to 4 f/stops at 173 Å while its visible light sensitivity is some 14 f/stops below that of XUV 100 emulsion. This dramatic difference between visible light and EUV sensitivity is extremely valuable for solar research, as it results in greatly relaxed requirements for the visible light rejection characteristics of the EUV filters. The results of the MSSTA flight will reveal the extent to which this property can be utilized in future filter design considerations. Furthermore, the Spectroscopic 649 film has significantly higher spatial resolution than the XUV 100, so it is the film of choice for obtaining the ultra-high resolution images of the Sun at EUV wavelengths, and even at FUV wavelengths in lines such as Hydrogen I Lyman α (1216 Å) where the solar intensity is extremely high.

It was also exciting to discover that the Experimental XUV 100 is notably more sensitive at 1550 Å than at the EUV wavelengths. The 1550 Å radiation was found to be capable of penetrating both the emulsion and film base to produce high density exposures on an underlying piece of film. Our prior measurements at Los Alamos National Laboratory and SSRL had established that the Experimental XUV 100 film batches tested are more responsive than the T-grain 100 emulsion which was successfully flown on the Stanford/MSFC/LLNL Rocket X-Ray Spectroheliograph. Since high density/high resolution images of the Sun were obtained with the small Herschelian mirrors and Cassegrain telescopes on this flight, we are confident that superior images will be produced with the significantly larger and faster Herschelian and Ritchey-Chrétien telescopes which will be flown on the MSSTA.

6. ACKNOWLEDGEMENTS

We wish to express our gratitude to Al DeWan, Gordon Brown, Martin L. Scott, Paul B. Gilman, Seth Gaugh, Joe Maskaskey, Sally Robson, Silvia Zawadzki and all others at Eastman Kodak whose assistance and knowledge have been of tremendous value to this research. We also wish to thank Bill Priedorhsky and Frank Ameduri of the Los Alamos National Laboratory for assistance with calibration of the T-Grain 100 and XUV 100 films at their facility, and to Barry Welsh, Jim Gibson, and C. Stuart Bowyer of the Space Science Laboratory of the University of California, Berkeley, for their assistance in performing EUV/FUV calibrations at their facility. We are also grateful to Troy W. Barbee, Jr., Pierro Pianetta, and Efim Gluskin for their support during testing of the films at the Stanford Synchrotron Radiation Laboratory. We are deeply indebted to Richard Watts, Mitch Furst, Robert Madden, Randy Canfield, Bill Wooden, Lanny Hughey, Bill Graves, and Andrew Hamilton for their assistance in the calibration of the flight emulsions at EUV and FUV wavelengths at the NIST SURF II facility.

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