Optical Focussing and Alignment of the Multi-Spectral Solar Telescope Array II Payload

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ABSTRACT

The Multi-Spectral Solar Telescope Array (MSSTA) is a sounding rocket borne observatory designed to image the sun at many spectral lines in soft x-ray, EUV and FUV wavelengths. Of the nineteen telescopes flown on November 3rd, 1994, the two Cassegrain telescopes and three of the six Ritchey-Crétien telescopes were focussed at NASA/Marshall Space Flight Center (MSFC) with a Zygo double-pass interferometer to determine the best position of back focus. The remaining three Ritchey-Crétien and eleven Herschellian telescopes were focussed in situ at White Sands Missile Range by magnifying the telescopic image through a Gaertner traveling microscope and recording the position of best focus. From the data obtained at visible wavelengths, it is not unreasonable to expect that many of our telescopes did attain the sub-arc second resolution for which they were designed.

Keywords: x-ray optics, focussing, alignment

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Table 1. MSSTA Two-Mirror Telescope Design Specifications[4–8]

	Ritchey-Crétien	Short Ritchey-Crétien	Cassegrain
Focal Length	350 cm	230 cm	200 cm
Mirror Seperation	80 cm	55 cm	42.3 cm
Primary Diameter	12.7 cm	12.7 cm	6.4 cm
Secondary Diameter	4.9 cm	5.7 cm	2.5 cm
Total Field of View	48 arc min	73 arc min	48 arc min

1 MSSTA CONFIGURATION

The Multi-Spectral Solar Telescope Array (MSSTA)[1] is a rocket borne observatory designed to image the sun in selected soft x-ray (44.1-93.9Å), Extreme Ultraviolet (EUV) [150-335Å], and Far Ultraviolet (FUV) [1215.6 and 1550Å] wavelengths. Its first flight, on May 13, 1991, brought back many images; some with sub-arc second resolution.[2] The MSSTA is a joint project of Stanford University, NASA/MSFC, and the Lawrence Livermore National Laboratory. Its telescopes use multilayer coated normal incidence optics in order to obtain greater collecting area and diffraction limited resolution not offered by grazing incidence systems. These telescopes can then be tested with standard interferometric and resolution target tests to determine optical performance. At soft x-ray wavelengths, the MSSTA utilizes single reflection Herschellian optics. For the longer wavelengths, the MSSTA employs doubly reflecting Ritchey-Crétien and Cassegrain telescopes. The Cassegrain telescopes are not true Cassegrains in the sense that the optical elements were fabricated as spheres. Conic elements of the smoothness required for the multilayer coatings were unavailiable at the time the Cassegrain optics were made. This second flight of the MSSTA on November 3, 1994 carried six Ritchey-Crétiens, two Cassegrains and eleven Herschellian telescopes.

The Ritchey-Crétien telescopes are two-mirrored telescopes with hyperboloid optical elements. These mirrors are held in place in their cells with a vacuum compatible Dow Corning Silastic RTV which also allows for slight motion during vibrational loading. To minimize changes in mirror separation, the optical benches were constructed of graphite fiber in an epoxy resin matrix.[4] Earlier theoretical studies revealed that the Ritchey-Crétien telescopes could obtain spatial resolutions of better than 0.3 arc sec over a 48 arc min field of view at 1216Å (with the best possible resolution of 0.03 arc sec occuring near the optical axis at a wavelength of 173Å).[3] This flight carried five Ritchey-Crétien telescopes with mirrors coated to image wavelengths of 150, 193, 284, 304, and 1550Å. A Short Ritchey-Crétien telescope was constructed and is capable of obtaining resolutions of 0.22 arc sec at its operating wavelength of 1216Å.[5]

The two Cassegrain telescopes (with coated optics designed to reflect wavelengths of 173 and 211Å) were both flown on the first MSSTA payload on May 13, 1991. The 173Å telescope was also flown on the Stanford-Marshall Space Flight Center Rocket Spectroheliograph sounding rocket payload on October 23, 1987. These Cassegrains are two-mirrored telescopes with spherical optical elements and were found to be diffraction limited in visible wavelengths. The maximum resolution, however, is limited to 0.5 arc sec due to abberations.[7]

The eleven Herschellian telescopes flown were of five different types and designed to operate at 44.2, 54.7, 93.9, 143, 150, 180, 193, 211, and 284Å. All were off-axis paraboloids except for the 180Å telescope which was a General Optics 1.5 inch concave sphere with a 2 meter radius of curvature. The multilayer coating for this optic was deposited at MSFC by Palmer Peters a few weeks before launch.[9]

Table 2. MSSTA Herschellian Specifications[1]

Wavelength	Diameter	Focal Length
44, 143Å	4.0 cm	1.4 m
54.7, 150, 284Å	4.0 cm	1.0 m
93.9Å	5.0 in	1.0 m
180Å	1.5 in	1.0 m
193, 211Å	4.0 in	1.4 m

2 PRE-FLIGHT FOCUSSING

The authors tested the two Cassegrain and three of the six Ritchey-Crétien telescopes interferometrically for position of best focus at MSFC. (The 284 and 1216Å telescopes were unavailiable for testing and the 1550Å telescope required special handling, described later in this section.) A Zygo PTI Fizeau interferometer, using a Helium-Neon laser (6328Å) as its coherent light source, produced interferograms which were captured with a frame grabber (installed in an IBM-AT equipped with an Intel Inboard 386 processor and an EGA monitor and video card). These interferograms were then analyzed by MicroFringe 3.1 code. Because of the existance of the central obscuration, spider mount and multilayer sector boundaries on these telescopes, the interferogram contained many artifacts which the code was unable to recognize so the interference patterns were digitized by hand. The entire set up was laid out on a 5'x9' Microflat granite table. The optical set-up is shown in Figure 1.

With a precision (1/20 wave) flat reference mirror reflecting the beam back through the optical system under test, each fringe in the interferogram represents 1/2 wave of wavefront deformation. After moving the flat mirror to the point where MicroFringe 3.1 reported the flattest wave front, that position was then used as the position of best focus and, therefore, the camera film plane. The position of best focus for any telescope was found repeatably to within 0.001 inch. The Modulation Transfer Function (MTF) of each of the five tested telescopes, as calculated from the interferograms, is shown in Figures 2 and 3. For the Ritchey-Crétien and Cassegrain telescopes, a normalized spatial frequency of unity represents a diffraction limited resolution of 1.25 arc sec and 2.5 arc sec (at 6328Å), respectively. Based on these results, we expect the telescopes to have achieved the sub-arc second resolution desired at their respective operational wavelengths.

The approximate visible-light resolutions of the telescopes are listed in Table 3. These calculations serve as a base-line for the photographic tests performed at the launch site and described later in the text. The resolutions are calcuated at an MTF of 0.4 because the detector (photographic film) requires this level of contrast to faithfully record an image.

The 1550Å Ritchey-Crétien telescope was coated by Acton Research Corp. with a dielectric layer stack that has such a low reflectivity at the red He-Ne laser line that the multi-pass interferometer was unable to record an interference pattern. The conventional knife-edge test was performed instead. This test has a somewhat lower accuracy in determining the position of best focus, however the 1550Å Ritchey-Crétien telescope operates at such a long wavelength that the depth of focus of the system is significantly greater than for the EUV instruments.[4]

3 IN-FIELD ALIGNMENT AND FOCUSSING

The telescopes were transported to White Sands Missile Range, placed into the MSSTA II payload, and mated with their cameras. To aid in aligning their optical axes, a 16 inch Schmidt-Cassegrain collimator with a 180

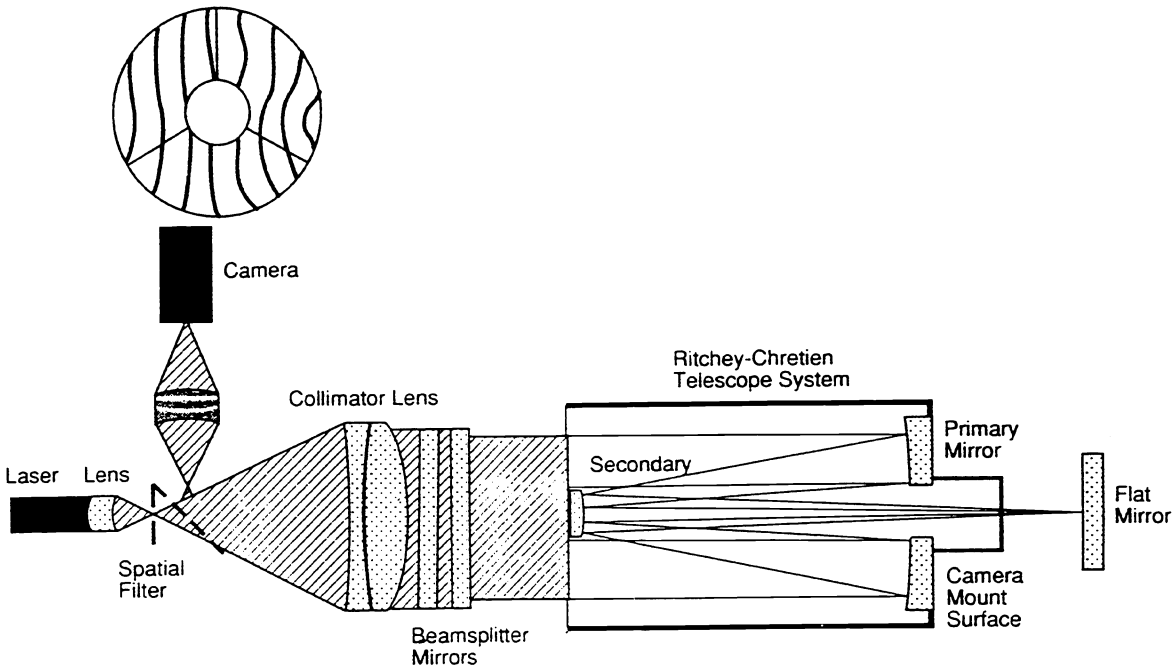


Fig 1. Determination of back focus position.

Table 3. Visible-Light Resolutions of the Two Mirrored Telescopes

Telescope	Resolution
150Å	7.1 arc sec
193Å	7.1 arc sec
304Å	7.1 arc sec
173Å	8.3 arc sec
211Å	6.7 arc sec

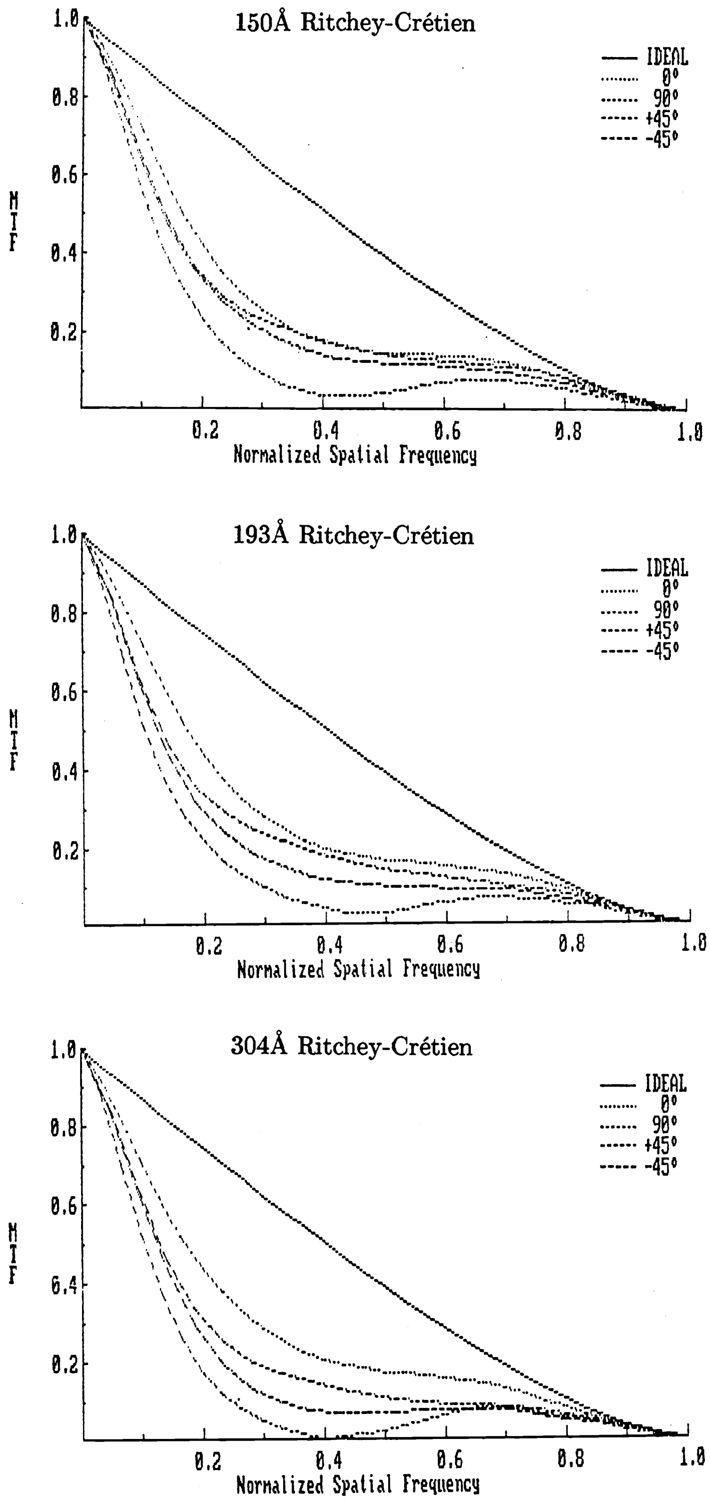


Fig 2. MTF for three of the Ritchey-Crétien telescopes.

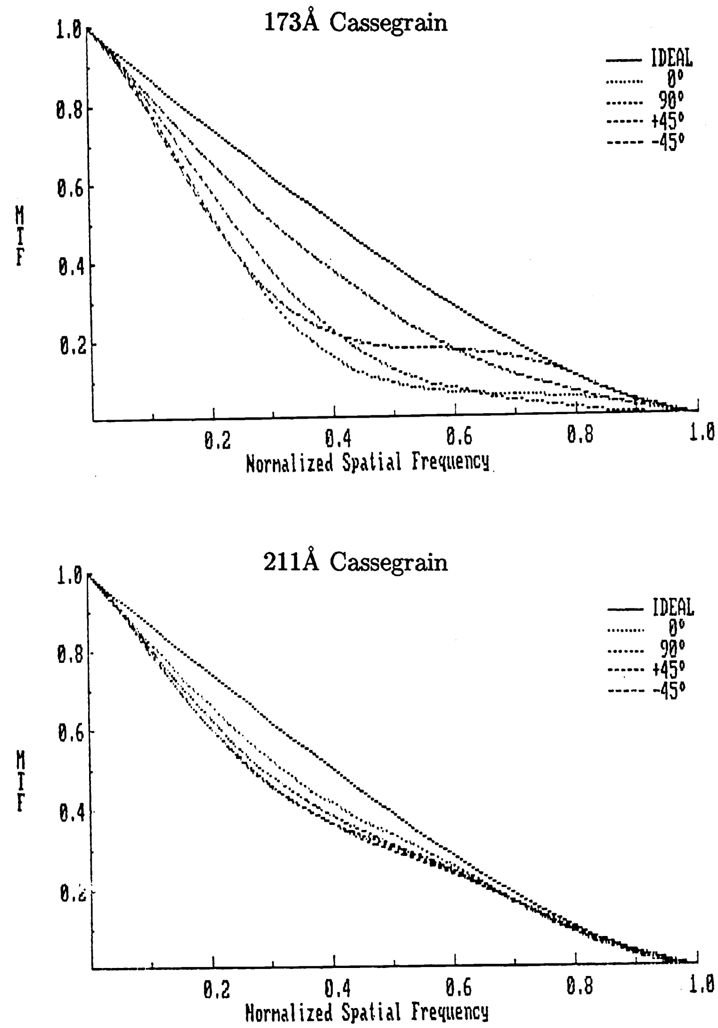
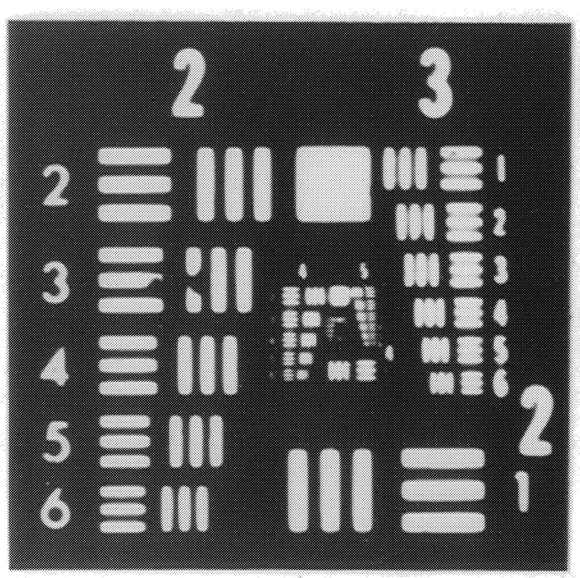


Fig 3. MTF for the two Cassegrain telescopes.

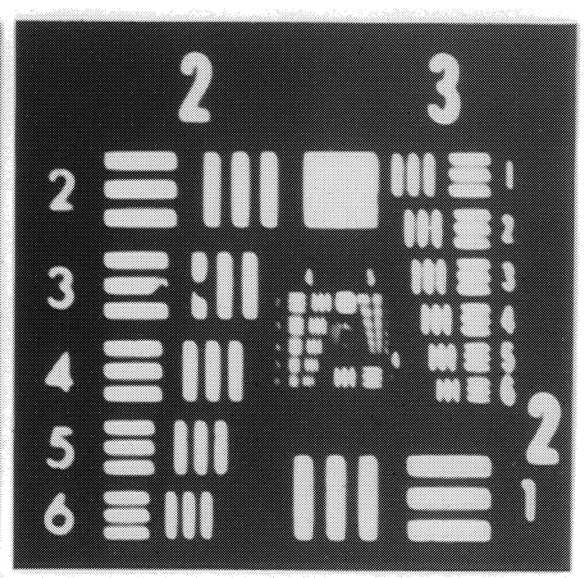
inch focal length (made by Diffraction Limited) was used to illuminate the payload. This collimator was aligned and focussed using a six inch cube's corner retro-reflector while a 10 arc second pinhole was placed in its object plane. After one of the Ritchey-Crétien telescopes was chosen as the "master" telescope and aligned visually to the axis of the payload, the collimater was aimed such that the pinhole was projected from the collimator and found exactly in the center of the "master" telescope's field of view. The remaining telescopes were subsequently aimed such that they were also imaging the pinhole in the center of their fields of view (for three cameras the pinhole was aligned elsewhere in the field of view due to the fact that these cameras were recording images from more than one Herschellian telescope on the same frame of film). This procedure aligned the telescopes to within a minute of arc.

To accurately point our payload to the sun, Lockheed Solar Pointing Attitude Rocket Control Systems (SPARCS) provided us with a Miniature Acquisition Sun Sensor (MASS) and two Lockheed Intermediate Sun Sensors (LISS). These sensors, combined, would send signals to the reaction control systems enabling our payload to aquire and track the sun with an accuracy of 0.1 seconds of arc. Because the LISS operates such that its entrance window is perpendicular to its optical axis, aligning it to our telescopes merely required centering the reflection of the pinhole from the sensor in the collimator while our "master" telescope also had the pinhole centered in its field of view. The MASS, however, required collimated sunlight to illuminate both types of sensors. When the LISS output a zero correction signal, the MASS was aligned by tilting it (using thin metal shims) until it also output a zero correction signal.

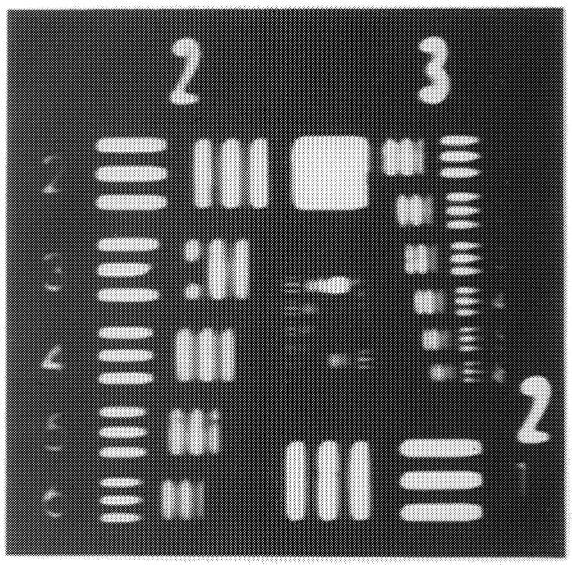
To perform the "in-the-field" focussing, a Standard 1951 Air Force High Resolution test target was placed in the object plane of the collimator. A Gaertner traveling microscope, fitted with a razor blade in its object plane obscuring part of its field of view, was then used to view the image of the resolution test target produced by each telescope. The position of best focus was chosen to be the location of the razor blade where the microscope showed the sharpest image. We were able to reproduce this position to within 0.04 inches. After the cameras were mounted with their film planes in the correct position, photographs were taken of the resolution test target. These images are shown in the following figures (bar group 3-1 represents a resolution of 5.6 arc sec) and a summary of the data is presented in Table 4. This data was determined from the negatives which these figures may not faithfully reproduce.



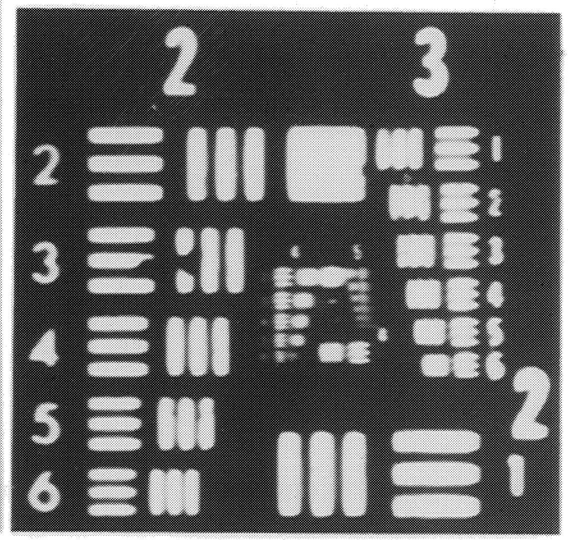
150Å Ritchey-Crétien



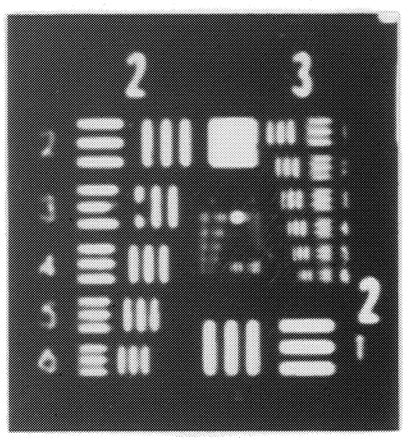
193Å Ritchey-Crétien



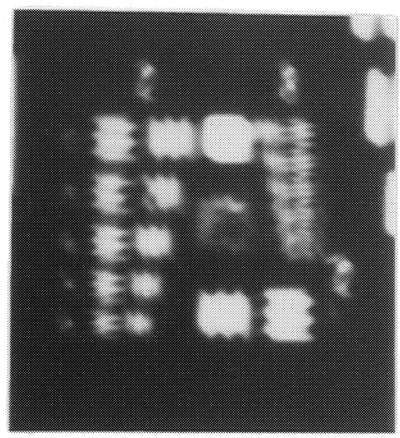
284Å Ritchey-Crétien



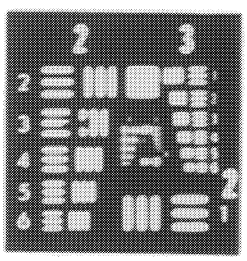
1550Å Ritchey-Crétien



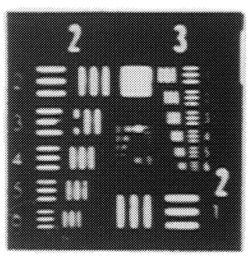
1216Å Short Ritchey-Crétien



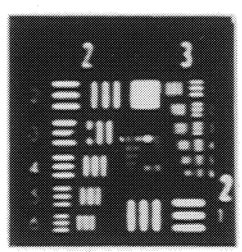
173Å Cassegrain



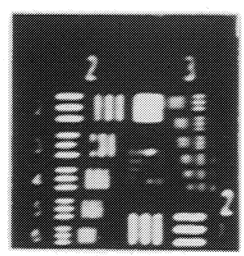
193Å Herschellian



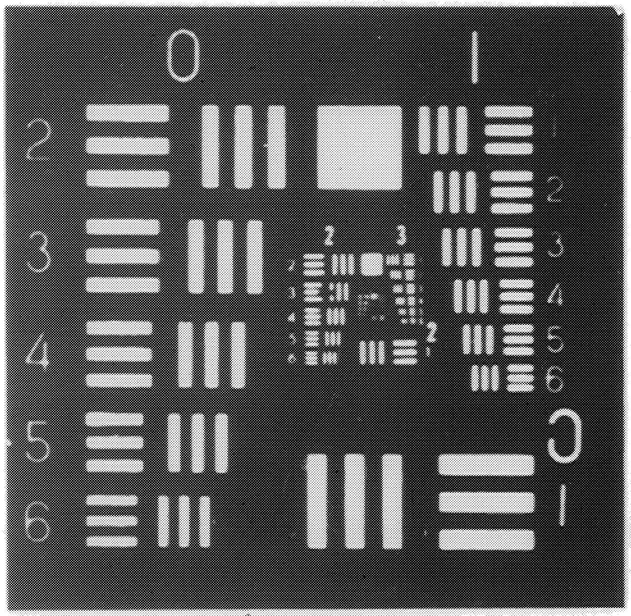
211Å Herschellian



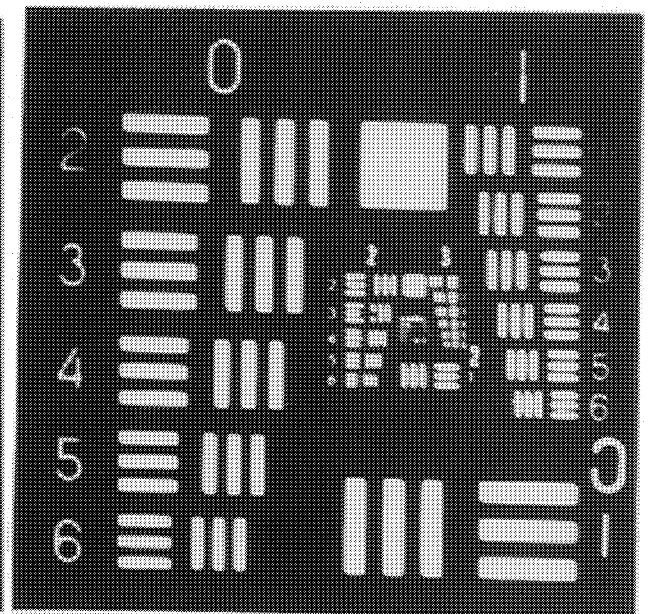
44Å Herschellian



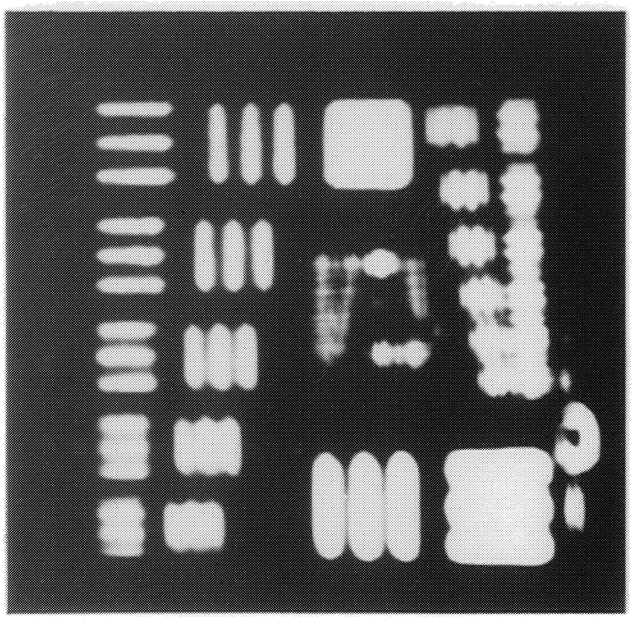
143Å Herschellian



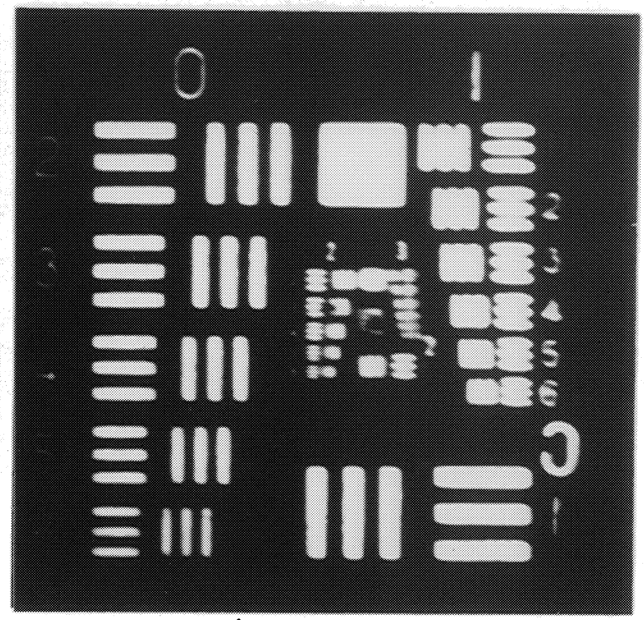
54.7Å (η) Herschellian



150Å (δ) Herschellian



180Å Spherical Herschellian



284Å Herschellian

Originally, due to the lower accuracy of this test, this method of focussing was only to be performed on the thirteen telescopes which were not or could not be interferometrically tested at MSFC. After the payload had been vibration tested, it was found that three of the secondary mirrors of the Ritchey-Crétiens had moved (those of the 193Å, 284Å and 304Å telescopes). The mirrors were repositioned manually and held in place with vacuum compatible Dow Corning Silastic RTV. These telescopes were then focussed with the traveling microscope.

In the case of the Ritchey-Crétiens, all telescopes were within about a factor of two of the diffraction limit. The Herschellians' resolutions varied widely due to some being used far off axis. This can be seen where one value of resolution is quite different than the value in the orthogonal direction. The 180Å Herschellian, being a

Table 4. Visible Light Resolution Test Results

Telescope	Horizontal (arc sec)	Vertical (arc sec)
Ritchey-Crétien (D.L. = 1.2 arc sec)		
150Å	1.2	1.4
193Å	2.8	1.4
284Å	1.3	3.2
1216Å	4.5	2.0
1550Å	1.3	3.6
Cassegrain (D.L. = 2.4 arc sec)		
173Å	8.0	6.3
4.0cm Herschellians (D.L. = 3.8 arc sec)		
44Å	4.0	5.6
54.7Å (β)	41.0	35.8
54.7Å (η)	3.2	4.0
143Å	4.5	8.0
150Å (δ)	5.6	4.0
150Å (ϵ)	18.0	6.3
284Å	4.5	8.0
4.0in Herschellians (D.L. = 1.5 arc sec)		
193Å	2.0	5.0
211Å	2.0	3.6
5.0in Herschellian (D.L. = 1.2 arc sec)		
93.9Å	12.7	3.6
1.5in Herschellian (D.L. = 4.0 arc sec)		
180Å	25.3	25.3

(D.L. = Diffraction Limit at 6328Å. Horizontal and Vertical resolutions are arbitrary, orthogonal directions in the image plane) spherical optic, performs worse off axis than the paraboloids.

4 SUMMARY AND CONCLUSIONS

The MSSTA II payload with its compliment of nineteen telescopes was assembled and optically tested in the visible wavelengths before flight. Five of the two-mirrored systems were focussed interferometrically. Analysis of their interferograms at the postion of best focus returned MTFs which indicate the ability to attain roughly half of their diffraction limited resolutions. Such resolution meets the mission objectives. The 1550Å Ritchey-Crétien was focussed using a conventional knife edge test due to the low reflectivity of the coating at 6328Å.

All telescopes were then aligned and checked for focus in situ at White Sands Missile Range using a Diffraction Limited 16 inch collimator which projected either a pinhole for alignment or a Standard 1951 Air Force High Resolution test target for resolution testing. All of the Ritchey-Crétien telescopes performed admirably as well as a number of the Herchellians.. The difference in calculated resolution versus observed resolution at visible wavelengths may stem from the fact that the flim used for the tests (SO-253) was able to record images at lower contrasts levels than expected. With these performances it is not unreasonable to expect that many of our telescopes attained the sub arc-second resolution for which they were designed.

Pictures taken on this flight are still being analyzed at the time of publication, but it appears as if the 1550Å Ritchey-Crétien did yeild sub-arc second resolution of structures in the chromosphere (Figure 4). The MSSTA was designed for rapid turn around and, with appropriate fixes to problems located during vibration testing, could be ready for re-flight in a matter of months.

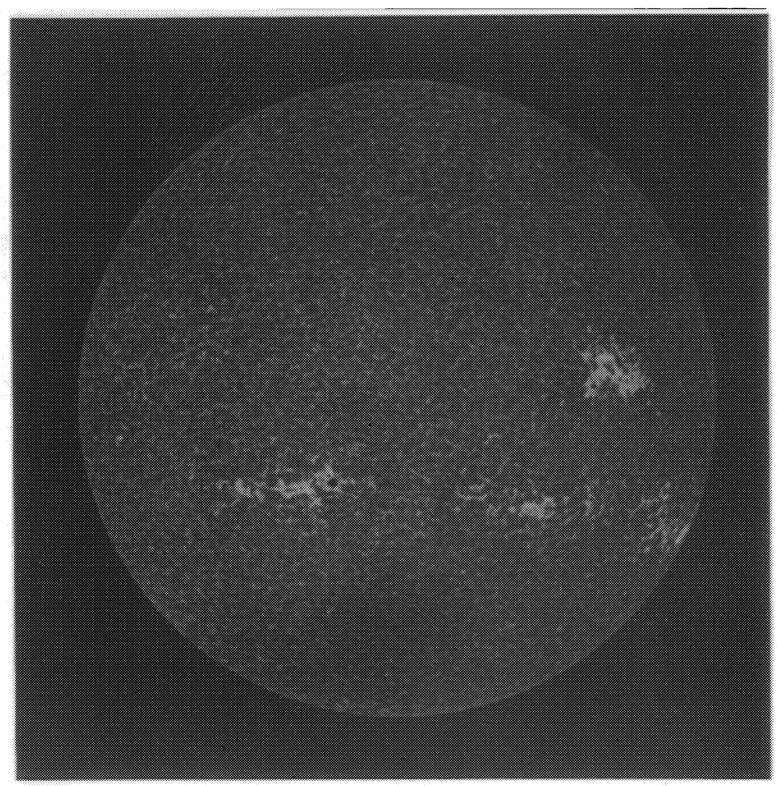


Fig 4. Image of the solar chromosphere taken with the 1550Å Ritchey-Crétien.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

[1] A.B.C. Walker, Jr., *et al.*, "Multi-Spectral Solar Telescope Array," *Optical Engineering*, **29**, pp. 581-591, 1990.

[2] R.B. Hoover *et al.*, "Solar Observations with the Multi-Spectral Solar Telescope Array," *SPIE Proc.*, **1546**, pp. 175-187, 1991.

[3] J.B. Hadaway, *et al.*, "Design and Analysis of Optical Systems for the Stanford/MSFC Multi-Spectral Solar Telescope Array," *SPIE Proc.*, **1160**, pp. 195-208, 1989.

[4] R.B. Hoover, *et al.*, "Performance of the Multi-Spectral Solar Telescope Array III. Optical Characteristics of the Ritchey-Chrétien and Cassegrain Telescopes," *SPIE Proc.*, **1343**, pp. 189-202, 1990.

[5] R.B. Hoover, *et al.*, "Design and Fabrication of the All-Reflecting H-Lyman α Coronograph/Polarimeter," *SPIE Proc.*, **1742**, pp. 439-451, 1992.

[6] Arthur B.C. Walker, Center for Space Science and Astrophysics, Stanford University Stanford, CA 94305, Private Communication.

[7] A.B.C. Walker, *et al.*, "Soft X-ray Images of the Solar Corona with a Normal-Incidence Cassegrain Mulilayer Telescope," *Science*, **241**, pp. 1725-1868, 30 Sep. 1998.

[8] D.L. Shealy, R.B. Hoover, D.R. Gabardi, "Multilayer X-Ray Imaging Systems," *SPIE Proc.*, **691**, pp 83, 1986.

[9] P.N. Peters, *et al.*, "Fabrication of Multilayer Optics by Sputtering: Application to EUV Optics with Greater Than 30% Normal Reflectance," to appear in *SPIE Proc.*, **2515**, 1995