Performance of the Multilayer Coated Mirrors for the Multi Spectral Solar Telescope Array

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ABSTRACT

The *Multi-Spectral Solar Telescope Array (MSSTA)*, a rocket-borne solar observatory, was successfully flown in May, 1991, obtaining solar images in eight XUV and FUV bands with 12 compact multilayer telescopes. We report on recent measurements of the performance of multilayer coated mirrors for the *Multi Spectral Solar Telescope Array*, carried out at the Stanford Synchrotron Radiation Laboratory.

1. INTRODUCTION

We report here on recent (March-May 1993) measurements of the performance of multilayer mirrors and thin film filters developed for the *Multi-Spectral Solar Telescope Array*[1] *(MSSTA)*. The *MSSTA* is a comprehensive rocket-borne solar observatory capable of obtaining narrow-band images of chromospheric, transition region, and coronal structures with very high angular resolution (0.3 - 1.0 arc sec). We have described the optical design of the double reflection Ritchey-Chrétien [2] and Cassegrain [3] telescopes and the single reflection Herschelian [1] telescopes previously as well as the arrangement of all telescopes [1] within the 22 inch rocket shroud. The capabilities of the payload are described in Walker *et al*[1]. The first flight of the *MSSTA* occurred on May 13, 1991[4]. The payload consisted of two Cassegrain, seven Ritchey-Chrétien, one large Herschelian and four small Herschelian telescopes. Each of the large systems had its own 70 mm camera with a pair of thin film filters mounted at the aperture. The small Herschelians utilized a single camera but with a specialized split filter. Previous measurements of the performance of the multilayer optics and filters for *MSSTA* are described by Allen *et al*[5]. We report here on additional calibration of the *MSSTA* instruments which are critical to the analysis of the flight data. The extraction of absolute flux measurements from the images necessitates accurate data on the absolute multilayer reflectivities, the throughputs of the XUV thin film filters used, and the response of the photographic films. Calibration of the films used to record the *MSSTA* images is described by Hoover *et al.*[6]. These additional reflectivity measurements will be used to facilitate the calculation of electron temperatures and densities of the many features of interest in the images obtained. An important characteristic of the *MSSTA* payload is its ability to provide spatially resolved temperature information by its imaging of specific spectral lines. The temperature responses of the telescopes are quite sensitive to telescope bandpass because of the high density of lines in the coronal spectrum. Calculations of temperature responses for the various systems based on previous measurements of telescopes and theoretical filter data are reported in DeForest *et al*[7]. High resolution measurements of telescope bandpasses will enable us to improve our temperature response calculations, improving the capabilities of the *MSSTA* as a powerful temperature diagnostic tool.

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2. REVIEW OF PREVIOUS MEASUREMENTS

The reflection efficiency of the Cassegrain IV-a (central wavelength λ_o ~ 173 Å) telescope was initially measured in 1988 at the Space Sciences Laboratory of the University of California, Berkeley, using the EUVE calibration chamber, and the shape of the single-mirror reflectivity curve was measured at Stanford. The integrated reflectivities of the λ_o 173Å, 193 Å, 304 Å and 335 Å Ritchey-Chrétien telescope mirrors were measured at the National Institute of Standards (NIST) using the SURF II synchrotron[8] in 1989. The peak reflectivities and central wavelengths of the above mentioned Cassegrain and Ritchey-Chrétien telescopes in addition to the λ_o 211 Å Cassegrain and the λ_o 150 Å Ritchey-Chrétien telescopes were all measured at SSRL in March 1990 [9]. Unfortunately, this calibration was not of high enough resolution to accurately determine the shape of the reflectivity curves. The mirror reflectivity functions of the far-ultraviolet mirror coatings (λ_o ~1216 Å and λ_o ~1550Å) and the throughput functions of the FUV filters have been measured by Acton Research in 1989, and by our consortium at the University of California, Berkeley in 1990.

During March, April and May of 1992, a comprehensive calibration of the optical elements of the *MSSTA* payload was carried out at the Stanford Synchrotron Radiation Laboratory (SSRL) on beam line 1-2. Summaries of these earlier (pre-1993) results are shown in tables 1 and 2. The measured filter transmissions in Table 2 are compared with theoretical calculations of filter transmission by Lindblom *et al*[10].

The beamline 1-2 monochromator[11] has a high energy limit of approximately 250 eV (~50 Å), making it impossible to make measurements in the bandpass of the 44.1 Å Herschelian pair. These telescopes will have to be calibrated elsewhere. Although the monochromator on beamline 1-2 does produce light at FUV wavelengths, the combined problems of low flux, limited time and beam contamination by monochromator higher orders did not allow us to analyze the FUV telescopes in 1992. During March to May of 1993, further work was performed both in redoing difficult measurements with an improved setup and also in studying newly fabricated mirrors and filters. In addition, we obtained results on film exposure responses[11].

Table 1. Telescope mirror efficiencies and bandpasses.

System	Mirror Materials	Expected λ_o* (Å)	Expected FWHM§ (Å)	Expected R_o• %	Measured λ_o*(Å) (±0.2Å)	Measured FWHM§ (Å)	Measured R_o• %
Cassegrain VI-a	Mo/Si	172.5 ± 5^P	10^T	6 ± 1^P	168.9	7.6	4.1
Cassegrain VI-b	Mo/Si	215 ± 8^P	13^T	10 ± 2^P	211.8	16.8	-
Ritchey Chrétien XII-A	Al/Mg_2F/Os	1216^D	100^P	26^+	-	-	-
Ritchey Chrétien XII-B	Al/Mg_2F/Os	1550^D	200^P	62^+	-	-	-
Ritchey Chrétien XII-C	Mo/Mg_2 Si	304^D	18^T	6 ± 2^P	309.3	22.3	4.1
Ritchey Chrétien XII-D	Mo/Si	152 ± 2^P	8^T	16 ± 2^P	152.5	6.0	19.1
Ritchey Chrétien XII-E	Mo/Si	177 ± 5^P	9^T	17 ± 2^P	175.1	8.6	13.2
Ritchey Chrétien XII-F	Mo/Si	196 ± 5^P	15^T	15 ± 4^P	192.1	10.8	7.3
Ritchey Chrétien XII-G	Mo/Mg_2 Si	335^D	23^T	4 ± 2^P	338.7	18.5	2.0
Herschelian IV-a	Mo/Si	143.3^D	7^T	55	146.8	5.1	28.6
Herschelian IV-h	Mo/Si	132.8^D	5^T	55	133.9	3.9	26.3
Herschelian IV-e	Rh/C	44.1^D	0.6^T	10	-	-	-
Herschelian IV-e'	Rh/C	44.1^D	0.6^T	10	-	-	-
Herschelian LHT	Mo/Si	193^D	21^T	36	200.0	15.4	27.3

*λ_o is central peak wavelength, §FWHM is full width at half maximum of telescope bandpass, •R_o is peak reflectivity
- Not measured this calibration, D Design parameter, P Previous measurement, T Theoretical value,
+ Measured by Acton Research.

Note: Cassegrain and Ritchey-Chrétien telescopes are two mirror systems whereas Herschelians have a single mirror.

Table 2. Filter materials and transmissions.

System	Filter Materials	λ_o (Å)	Calculated Transmission $T(\lambda_o)$ %	Measured Transmission $T(\lambda_o)$ %
Cassegrain VI-a	2856±100 Å Al 382±50 Å C	173	20.9	19.0
Cassegrain VI-b	2834±100Å Al 268±50Å C 873±50Å KBr	211	15.6	15.0
Ritchey Chrétien XII-C	2990±100Å Al 152±50Å C	304	11.9	6.3
Ritchey Chrétien XII-D	6900±100Å Be	150	17.8	7.2
Ritchey Chrétien XII-E	2885±100Å Al 382±50Å C	173	20.9	15.0
Ritchey Chrétien XII-F	2934±100Å Al 268±50Å C 873±50Å KBr	193	17.4	20.1
Ritchey Chrétien XII-G	1746±100Å Al 1288±100Å Te 110±50Å C	335	6.7	0.97
Herschelian IV-a	6900±100Å Be 1046±100Å C	143	9.4	3.4
Herschelian IV-h	6900±100Å Be 1046±100Å C	133	13.1	5.1
Herschelian IV-e	1000±100Å Al 6118±100Å C 4734±100Å Pht	44.1	8.0	-
Herschelian IV-e'	1000±100Å Al 6118±100Å C 4734±100Å Pht	44.1	8.0	-
Herschelian LHT	2954±100Å Al 154±50Å C 1746±100Å KBr	193	17.7	22.4

Notes: Each system utilizes a pair of filters. Material thicknesses shown are the sum of both filters. Each filter includes an 83% transmissive mesh. The 44A filters were not measured.

3. PROCEDURES USED FOR THE 1993 MEASUREMENTS

3.1 Experimental Setup: In our earliest measurements at NIST and SSRL, an XUV photodiode manufactured by UDT was used to detect photon flux. While this instrument proved to be quite stable and uniform in its quantum efficiency, it exhibited a large dark current which led to a low signal to noise ratio. The cause of the large dark current was at that time unknown. Because the higher resolution of SSRL beamline 1-2 allowed us to follow reflectivity curves off the peak it was desirable to measure very small photon fluxes. Specifically, this beamline produced photon fluxes at 60 eV of $\sim 10^{12}$ photons/s when the monochromator slits were set for moderate resolution (.25-1 eV). We would like to be able to measure throughputs down to at least 10^{-3} times this peak value.

Prior to our 1992 runs, discussion of these parameters with P. Pianetta and M. Rowen of SSRL led to the design of the setup shown in figure 1. The detector used was a simple photocathode. The first set of measurements were made using a gold photocathode which was switched in favor of a polished stainless steel photocathode in later measurements for greater surface uniformity. The photoelectrons produced by this material were collected by an anode at high voltage, in most cases the front funnel of a channeltron, and the current was measured using a Keithley 427 current to voltage amplifier. Further details of the instrumentation are discussed by Allen *et al*[5]. For the 1993 runs, we constructed an improved experimental chamber with a large numbers of viewports to ease alignment problems. In addition, we spent some time studying the response of our UDT photodiode. We discovered that the previously observed large dark current was mostly due to stray light, particularly that emitted from the ion vacuum gauge. Extensive light baffling and careful viewport blocking resulted in a diode dark current below the noise of the Keithley 427 amplifier. This permitted us to use the absolutely calibrated UDT photodiode in place of the stainless steel photocathode. Unlike the photocathode, the UDT photodiode exhibited no observable gain change with time. This resulted in a great improvement in the accuracy of the measurements.

A word must be said about one very challenging aspect of this calibration[2], that of alignment. Most users on this beamline require a focused beam as opposed to the collimated beam that we require. As a result there is a toroidal refocusing mirror[12] at the entrance to the user section. The curvature in the horizontal direction could be removed, but the focusing in the vertical direction was fixed. As a result the beam was observed to have a divergence in the vertical direction of approx. 20 arc min. with a spot size at the back of the chamber of approx. 1 cm. Our Ritchey-Chrétien telescopes have an acceptance of ~48 arc-min. while our Cassegrain telescopes have a baffle with a diameter of only ~2 cm. These two factors made for very tight tolerances on the alignment of the telescopes with the calibration beam. If some of the beam is lost on a baffle it introduces a systematic error causing the throughput measurement to be low. Our 1992 alignment system was somewhat crude in that we had our entire chamber on an X-Y stage, but were unable to adjust the telescope within the chamber. This limited range of motion combined with the fact that the chamber viewports afforded limited view of the inside of the chamber, meant that we could not rule out the possibility of flux loss either on a baffle or off the edge of the photocathode. Care was taken to minimize this problem but alignment proved to be particularly difficult for the Cassegrain telescopes. The

1993 chamber improved alignment considerably by increasing the number of viewports and adding an internal three-axis stage to mount optics upon. Unfortunately, the new chamber was too small contain the large optical tubes of the MSSTA Ritchey-Chrétien and Cassegrain telescopes. For these telescopes, the primary and secondary optics had to be removed and tested seperately.

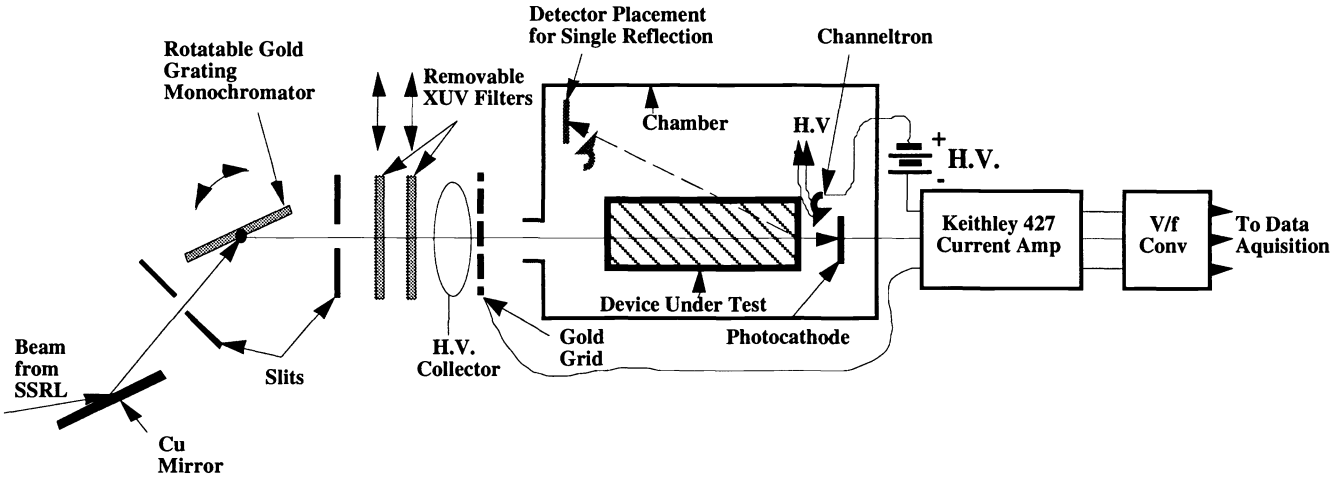

Figure 1. Block diagram of the 1992 experimental set-up at SSRL.

Due to outgassing of the flight components tested at SSRL, it was not possible to maintain an ultrahigh-vacuum in our test chamber. A differential pumping system[13] and a thin prefilter are used to prevent leaks to the SSRL storage ring. Initially we noticed a high partial pressure of carbon compounds in our chamber, likely hydrocarbons from Apiezon-L vacuum grease on our O-rings, evidenced by brownish-gray deposits on surfaces exposed to the zero-order beam from the monochromator. After these deposits were first noticed, on the 193 Å mirror and on the photodiode, it was found that significant deposition occurred only in the relatively high flux of the zero-order beam from the monochromator. Accordingly, a glass shield was added to keep ionizing radiation out of the chamber when using visible light from the monochromator in zero-order for alignment. This scheme succeeded in eliminating the problem of carbon build-up.

Twice during the 1993 run at SSRL, the Si pre-filter was observed to have been punctured at the point where the beam is incident upon the filter. Since the ultrahigh-vacuum of this upstream section of the beamline had not been breached on either occasion, we were faced with the surprising conclusion that the zero-order beam might have destroyed both filters. Since the damage was observed after data taking, it is not known whether the Si filter was in place during measurements. Fortunately, the problem of higher orders is believed to be much less severe at the small wavelengths to which the Si filter pertains (see § 3.2, below).

The SSRL developed differential pumping system (which is not shown in the diagram) that coupled our chamber to the beamline proved to be a crucial element in our measurements. The carbon-epoxy optical benches used in our Ritchey-Chrétien telescopes outgas considerably on pump-down. Our CTI Cryo-8 pump allowed us to reach 5×10^{-6} torr after several hours of pumping. This was not enough to allow us to connect directly to the UHV beamline which was at 10^{-9} torr. P. Pianetta and W. Warburton have developed a differential pump which can support up to four orders of magnitude pressure gradient at these pressures[13]. We are indebted to SSRL for making this pumping system available to us.

3.2 Analysis: Assuming stable photodiode gain , multilayer reflectivities and XUV filter throughputs are given simply by the ratio of the photocurrent obtained with the mirror or filter in the beam to the photocurrent obtained with the mirror or filter removed. This simple strategy is complicated by several factors.

The first complication is that measurements made with the mirror or filter in place are not made concurrently with calibration measurements in which the mirror or filter has been removed from the beam. In the case of the Ritchey-Chrétien telescopes the time separation is limited by the pump down time and thus is a minimum of roughly 6 hrs. This is relevant in that the output flux of the synchrotron is time dependent. This problem is corrected for by the use of a ~90% transmissive gold mesh at the entrance to the calibration chamber. The signal from this detector provides a monitor of incident synchrotron flux. The detector signals can be written

$$I(\lambda,t) = F(\lambda,t)\, M(\lambda)\, Q(\lambda)\, T_O \qquad (2)$$

$$I_O(\lambda,t) = F(\lambda,t)\, Q_O(\lambda)\, (1 - T_O) \qquad (3)$$

where λ is the wavelength setting of the monochromator, $I(\lambda,t)$ is the photodiode current, $I_O(\lambda,t)$ the mesh current, $F(\lambda,t)$ the flux of the monochromator with prefilters, $M(\lambda)$ the mirror reflectivity or filter transmission, $Q(\lambda)$ the photodiode quantum efficiency, $Q_O(\lambda)$ the mesh efficiency, and T_O the mesh throughput (about 90%). If we then look at the ratio $R = I(\lambda,t) / I_O(\lambda,t)$, we get a cancellation of the time dependence. Then, if we measure R first with an empty chamber (*i.e.* $M(\lambda) \equiv 1$) and then with a mirror or filter in the chamber, the ratio of the two R values $M(\lambda)$, is the quantity we wish to measure.

$$R_{device} / R_{empty} = M(\lambda) \qquad (4)$$

Higher Order Contamination: The monochromator on beamine 1-2 at SSRL produces considerable amounts of higher order radiation. The standard method for dealing with such problems is to pre-filter the incident radiation. During our 1992 we used two filters upstream of our gold mesh, an Al/C filter, thickness 2990 Å/152 Å, and a Si filter, thickness 1550 Å, both manufactured by Luxel Corp. These were used selectively for energies from the filter edge to one half that value. (Al edge at ~170 Å, Si edge at ~126 Å) In this way we utilized the sharp drop in throughput of the filter at the edge to ensure that the second order radiation is rejected by at least a factor of 100. With the two filters we had available, this gave us a working energy range of 35 eV to 100 eV. For the 1993 run, we added a tin filter which allowed us to operate in the range from 750 Å to 1500 Å.

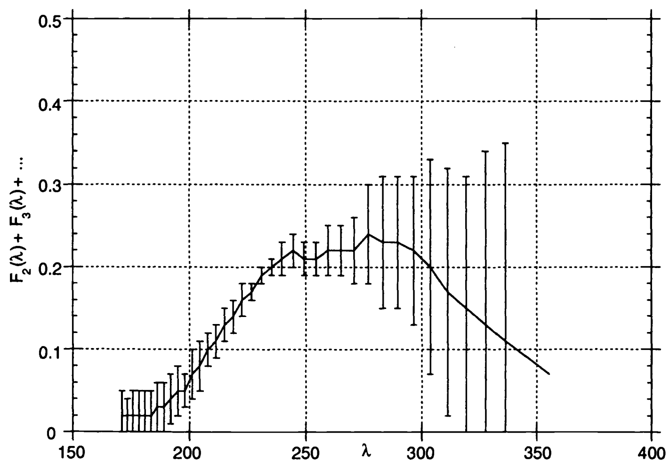

Figure 2. Higher order contamination calculated from three Al/C filters measured during both runs at SSRL beamline 1-2.

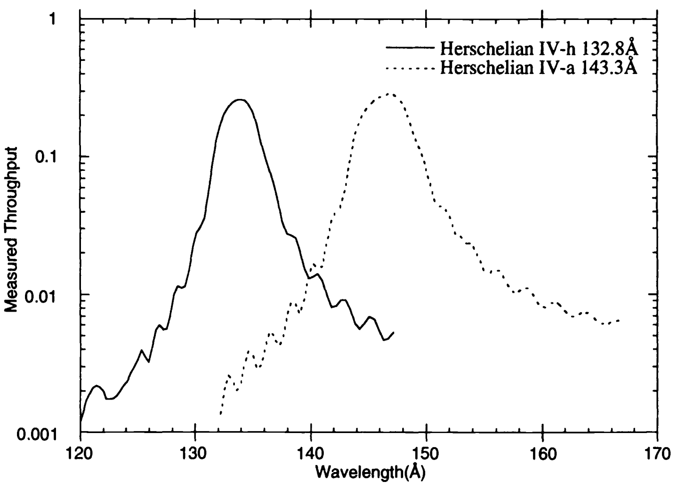

Figure 3. A log plot of Small Herschelian Telescope throughput showing the ability of our apparatus to measure small throughputs with high resolution.

Results from earlier measurements (figure 2) show that while this correction can be as high as 30% at lower energies, by the Al edge at 71 eV it has fallen to <2%. We make the assumption, based on the decreasing reflectivity of gold at higher energies, that this function will not increase at higher energies which implies that our data past the Si edge at ~126 Å are correct to within a few percent.

3.3 Errors: There are several systematic errors in this procedure that have already been touched on. The most serious source of error is that introduced by poor alignment of an optic in the beam. As mentioned above this was a problem with the 1992 Cassegrain calibration and as a result the throughput measurements obtained are almost certainly low. The 1993 setup alleviated this problem to a significant extent.

A second source of error is the fluctuation of the photodiode gain with time. A small decrease was noticed and is believed to be due to carbon buildup on the diode front surface caused by UV light in the zero-order beam. This was observed to be a problem early in the run and the detector was protected by a glass slide during zero-order alignment. As a result, no further loss in gain was observed. In addition to these throughput errors, there is also the possibility of an error in the wavelength calibration of the monochromator. For this reason we recalibrated the wavelength scale using the accepted values for the Si and Al edges. The resultant wavelength calibration is accurate to within ± 0.2 Å.

3.4 Review of the 1992 SSRL Measurements: The 1992 SSRL measurements of the telescope efficiency curves are shown in figures 4 and 6. Combining the telescope efficiencies with the filter throughputs from the 1992 SSRL runs[5], we can obtain the total throughput for each instrument. These total system throughputs are shown in figures 5 and 7. The total throughput for the Ritchey-Chrétien XII-G 335 Å telescope has been scaled by a factor of ten to make it easier to see. With both Cassegrain telescopes we experienced great difficulty with alignment. Thus, although we have great confidence in the reflectivity curve shape measured, we believe that the absolute measured reflectivities are low. We will report on more recent measurements of these telescopes below. Figure 3 shows a log plot of the efficiency curves for the two small Herschelians (132.8 Å and 143.3 Å). This data brings out well the Bragg diffraction pattern near the peak.

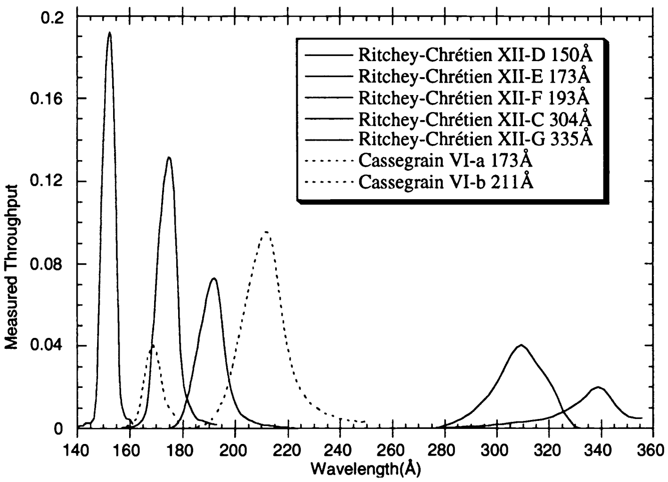

Figure 4. Measured throughputs of the double reflection telescopes.

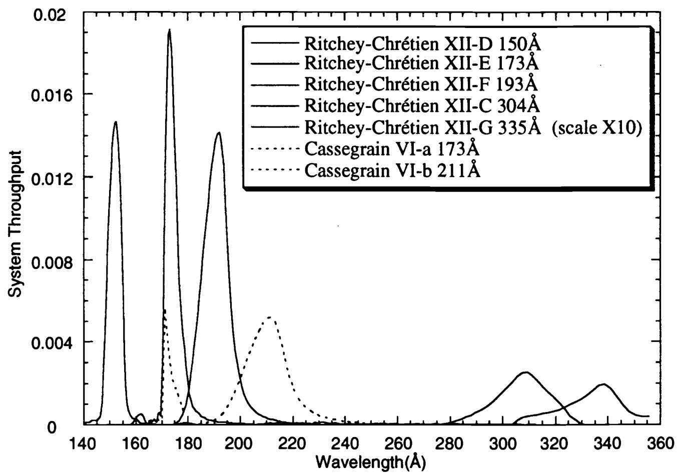

Figure 5. Measured telescope/filter system throughputs for the double reflection telescopes.

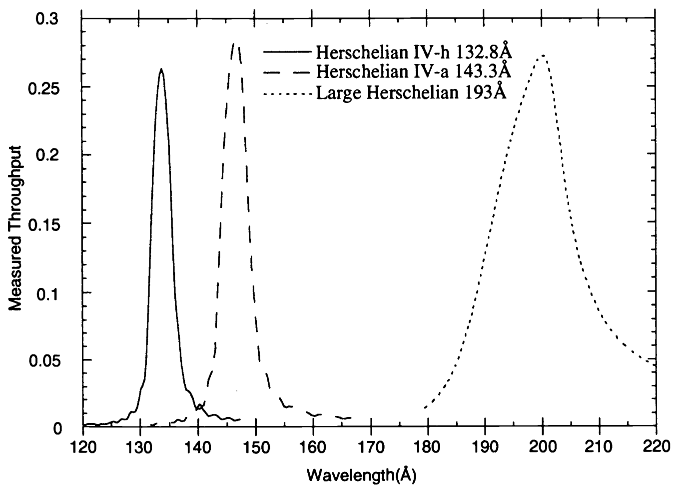

Figure 6. Measured reflectivities of the Herschelian telescopes.

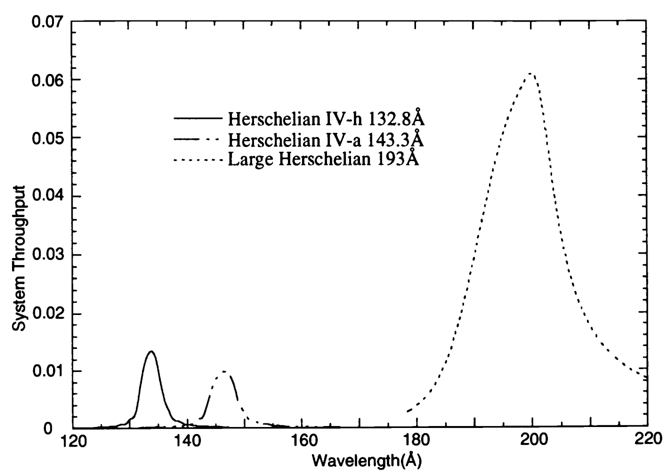

Figure 7. Measured telescope/filter system throughputs for the Herschelian telescopes.

4.0 1993 SSRL RESULTS

100mm Aperture Herschelians: One of the most successful measurements from our 1991 flight was the image obtained from our Large Herschelian Telescope (LHT) which had an aperture of 75mm. The reflectivity of this telescope, as measured in 1992, is shown in Figure 8. We fabricated two new large aperture Herschelians, this time with 100mm apertures. The first was also designed to reflect 193 Å radiation. The reflectivity of this new telescope is shown in Figure 9. The wavelength bandpass of the old 193 Å LHT was actually centered at ~ 200 Å. The new 193 Å LHT appears to be non-uniform in lattice spacing. The central sector is very close to the design wavelength.

Figure 10 shows the reflectivity of the 211 Å LHT. The layer spacing of this mirror is quite uniform. Both of the new LHT's have excellent reflectivity compared to earlier mirrors at the same wavelength.

40mm Aperture Herschelians: Prior to our May 1991 flight, we fabricated a number of Small Herschelian Telescopes with ~ 40 mm apertures. Telescopes were fabricated with bandpasses centered at 44 Å (2 mirrors), 54.7 Å, 132 Å and 143 Å. We flew the two 44 Å mirrors and the 132 Å and 143 Å mirrors. We report here on the measurement of the reflectivities of the 54.7 Å mirror, which is presented in Figure 11. We hope to fabricate a large (100mm aperture) mirror for our next flight at this same wavelength, which corresponds to an Fe XVI line in the solar spectrum.

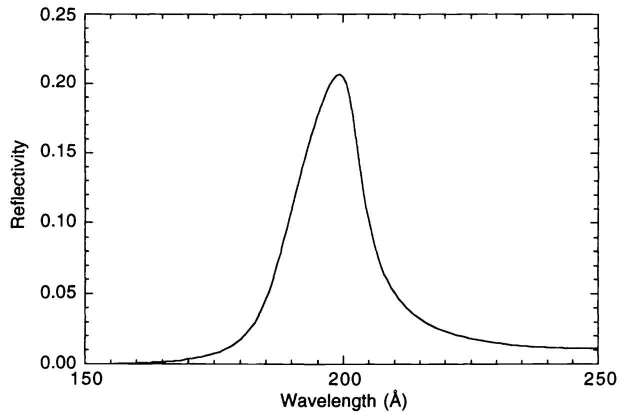

Figure 8. The reflectivity of the old 193 Å Herschelian. The mirror was fabricated with Mo/Si layers by T.W. Barbee, Jr.

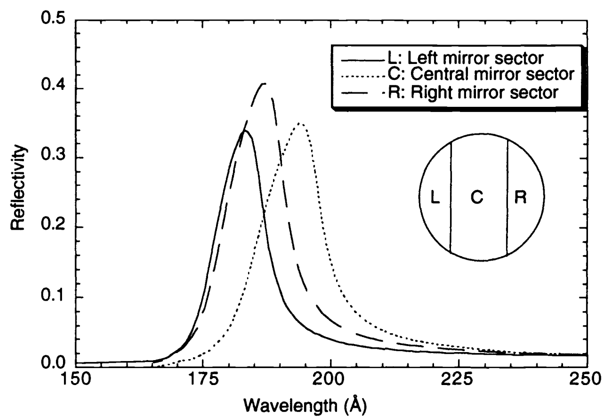

Figure 9. The reflectivity of the new 193 Å Herschelian. The mirror was fabricated with Mo/Si layers by T.W. Barbee, Jr.

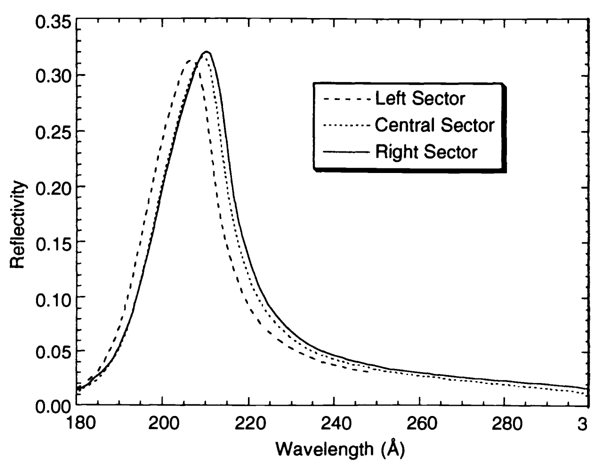

Figure 10. The reflectivity of the 211 Å Large Herschelian. The mirror was fabricated with Mo/Si layers by T.W. Barbee, Jr.

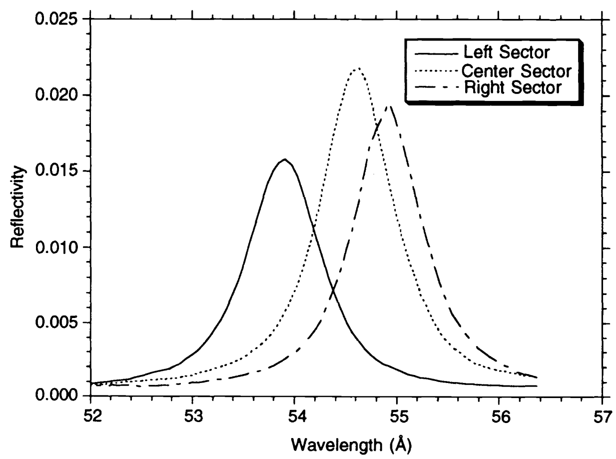

Figure 11. The reflectivity of the 54.7 Å Small Herschelian. The mirror was fabricated with W/C layers by Ovonics.

The 173 Å Cassegrain Telescope: The first multilayer optics high resolution image of the sun was obtained with a Cassegrain telescope with a bandpass centered at 173 Å. Allen *et al*[5] reported on the degradation of the throughput of this telescope due to the shift of the central wavelength of the primary bandpass. In early 1993, we asked Dr. Phil Baker to repolish a set of spare optics for this telescope, which were subsequently recoated by Troy Barbee. The measured reflectivity of the new 173 Å Cassegrain optics is shown in Figures 12 and 13. The throughput of these new mirrors is twice that of the original 173 Å Cassegrain.

The 211 Å Cassegrain Telescope: Allen *et al*[5] reported a number of problems in a previous measurement of the reflectivities of the 211 Å Cassegrain telescope mirrors in 1992. We re-measured the reflectivities of this telescope in 1993, Figures 14 and 15 present the results. Note that the primary mirror reflectivity is quite uniform, and precisely at the design wavelength.

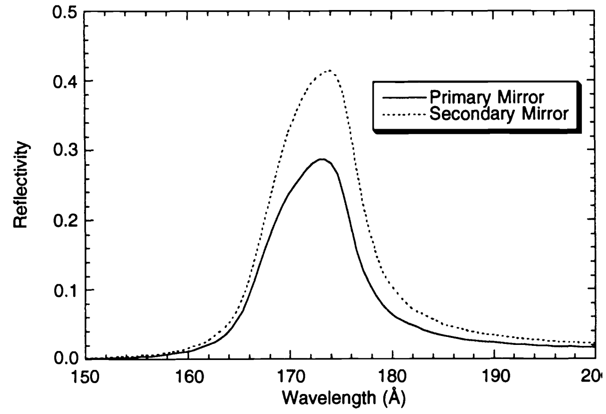

Figure 12. The reflectivity of the primary and secondary mirrors for the 173 Å Cassegrain. The mirrors were fabricated with Mo and Si layers by T.W. Barbee, Jr.

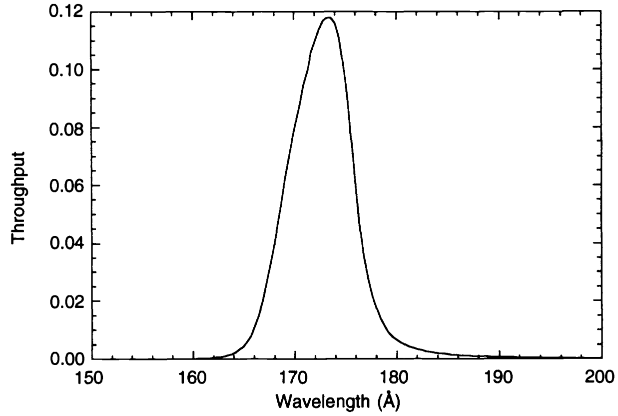

Figure 13. Total system throughput of the new 173 Å Cassegrain Telescope.

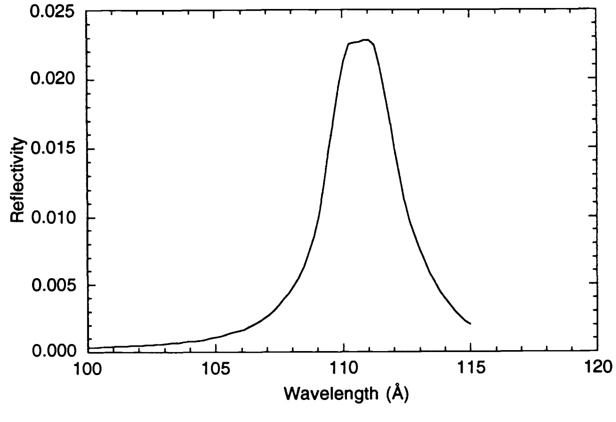

Figure 14. The reflectivity of the 211Å Cassegrain primary mirror in second order. This mirror was fabricated with Mo and Si layers by T.W. Barbee, Jr.

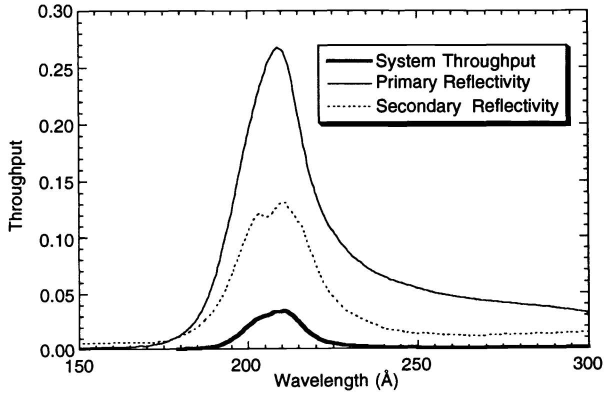

Figure 15. The reflectivity of the 211Å Cassegrain primary and secondary mirrors, and the telescope throughput.

4. DISCUSSION

Because of filter thickness and the limited data taking time of the sounding rocket (< 5 min.), the images obtained by MSSTA during the 1991 flight were underexposed, and required aggressive developing to obtain a reasonable density range so that the images could be used for quantitative work. It is probable that the developing process significantly degraded the spatial resolution of the film. The new multilayers which we have measured show much higher efficiency than those coated for the 1991 flight. Combined with the increased collection area of the new LHTs and improved filter transmission, these will be much faster systems than those flown in 1991.

The new multilayer coatings also show somewhat better spectral resolution than those flown in 1991 ($\lambda/\Delta\lambda$ ~15 and ~12, respectively), if we consider only one of the three new LHT sectors. For the 193 Å new LHT, it may be advantageous to mask the left and right sectors since they have low response at the target wavelength. The resulting system would still be faster than the original 193 Å LHT.

One surprising result from our measurements is the strong specular reflectivities of all the multilayer mirrors at wavelengths greater than the central bandpass. This effect is insignificant in our two mirror systems since the rejection is so much better. However, for our Herschelian telescopes, contamination from lines well outside the bandpass of the instrument cannot be ignored. In particular, most of the MSSTA Herschelian systems will respond to the very strong He II 304 Å line, produced by material at ~10^5 K. The central sector of the new LHT 193 Å mirror, for example, is about 5% reflective at 304 Å. The resulting modification of the temperature response of the system is not huge, but it must be corrected either by filter design or by software (for example, synthetic filtering by use of the image from the 304 Å telescope) or both.

5. ACKNOWLEDGMENTS

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