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A.B.C. Walker Jr.
J.F. Lindblom
J.G. Timothy
R.B. Hoover
T.W. Barbee Jr.
P.C. Baker
F.R. Powell

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High Resolution Imaging with Multilayer Soft X-Ray , EUV and FUV Telescopes of Modest Aperture and Cost

Arthur B.C. Walker Jr., Joakim F. Lindblom and J. Gethyn Timothy

Center for Space Science and Astrophysics, Stanford University
Stanford, CA 94305 USA

Richard B. Hoover

NASA Marshall Space Flight Center
Huntsville, AL 38512 USA

Troy W. Barbee Jr.

Lawrence Livermore National Laboratory
Livermore, CA 94550 USA

Phillip C. Baker

Baker Consulting
Walnut Creek, CA 94596 USA

Forbes R. Powell

Luxél Inc.
Friday Harbor, WA 98250 USA

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ABSTRACT

The development of multilayer reflective coatings now permits soft x-ray, EUV and FUV radiation (λλ ~ 40Å-2000 Å) to be efficiently imaged by conventional normal incidence optical configurations. Telescopes with quite modest apertures (~ 0.1 - 0.5 meters) can, in principle, achieve images with resolutions (~ 0.1 arc-second or better) which would require apertures of 1.25 meters or more at visible wavelengths. We review the progress which has been made in developing compact telescopes for ultra-high resolution imaging of the sun at soft x-ray, EUV and FUV wavelengths, including laboratory test results and astronomical images obtained with rocket-borne multilayer telescopes. We discuss the factors which limit the resolution which has been achieved so far, and the problems which must be addressed to attain, and surpass the 0.1 arc-second level. We also describe the application of these technologies to the development of solar telescopes for future space missions.

1. INTRODUCTION

The Rayleigh criterion for the angular resolution ($\delta\theta$) of a telescope of aperture D, at wavelength λ

$$\delta\theta \sim 1.22\lambda/D \qquad (1)$$

dictates the critical technologies which must be addressed in order to achieve astronomical images with high angular resolution at a particular wavelength. At radio wavelengths, five centimeters for example, resolution of one arc-second requires an aperture of ~ 12 kilometers, while sub arc-second resolution (~ 0.1 arc-second) requires apertures of hundreds

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of kilometers. The techniques of aperture synthesis[1] permit arrays of antennae to effectively behave as would a single antenna with an aperture of tens of kilometers[2] to thousands of kilometers[3]. At optical wavelengths, 5000 Å for example, an aperture of 1.25 meters is required to achieve a resolution of 0.1 arc-second. Deploying a meter class telescope in space is a formidable undertaking, requiring extensive measures to maintain a benign and stable mechanical and thermal environment. Space observatories of this class such as Hubble,[4] and the planned Orbiting Solar Laboratory (OSL)[5] are regarded as moderate to major missions by NASA, with anticipated costs of $750 million to $2 billion!

Because of the low reflectivity of conventional optical surfaces at soft x-ray (~ 1 Å - 300 Å), EUV (~ 300 Å - 1000 Å) and FUV (~ 1000 Å - 2000 Å) wavelengths, the development of space-borne optical systems able to achieve sub arc-second resolution at these wavelengths has only recently become a realistic goal. At soft x-ray wavelengths, imaging has been carried out at grazing incidence with the deep conic mirror configurations proposed by Wolter[6], or the orthogonal mirror systems of Kirkpatrick and Baez[7]. Both configurations[8] suffer from severe optical aberrations at field angles only a few arc minutes off axis, as a result of inherent violations of the Abbé Sine condition.[9] The difficulty of mounting and aligning nested grazing incidence mirrors further limits the resolving power which can be achieved. Sub arc-second resolution, at the level of ~0.5 arc seconds, appears to be a reasonable goal, and is actively being pursued in the development of the Advanced X-Ray Astronomy Facility (AXAF)[10], but resolution at the 0.1 arc second level does not appear to be a goal which is attainable with grazing incidence optical systems in the next decade.

In the past, single reflection normal incidence (Herschelian) optical configurations have been used for space borne observations at EUV wavelengths[11]; since optical coatings capable of reflecting radiation with sufficient efficiency to permit the use of conventional double reflection cassegrain optical systems[12] were unavailable.

The invention by Barbee[13] and Spiller[14] of multilayer coatings that permit the efficient reflection of soft x-ray and EUV radiation (~40 Å < λ < 1000 Å) at normal incidence has permitted the development of soft x-ray/EUV optical systems which utilize conventional optical configurations such as the Ritchey-Chrétien. Such systems have very small aberrations, so that optical performance approaching the diffraction limit can be contemplated.

At soft x-ray, EUV and FUV wavelengths, very high resolution, as defined by the Rayleigh criterion, can be achieved with quite modest apertures. For example, to achieve a solar image with a diffraction limit of 0.1 arc-second in the light of the Fe XVIII line at 93.9 Å (which is excited at $T \sim 6 \times 10^6$ K) requires an aperture of only 2.5 centimeters! Clearly, at these wavelengths, aperture will be determined not by the Rayleigh criterion, but rather by source brightness. For the strong hydrogen Lyman α line at 1215.6 Å, the modest aperture of 30 centimeters is sufficient to achieve a diffraction limit of 0.1 arc second. Conventional optical systems, operating between 100 Å and 2000 Å, with apertures between 10 and 50 centimeters, when coated with appropriate reflective coatings, can achieve an extraordinary level of resolution (~0.1 arc-second or better); achieving this level of resolution requires heroic measures at longer wavelengths. The cost of telescopes of such modest aperture in space are sufficiently low, that we can deploy arrays of such telescopes[15,16,17,18] to allow simultaneous observations over a broad range of wavelengths, permitting study of the evolution of structures in the solar atmosphere over temperatures ranging from 10,000 K to 30,000,000 K.

2. TECHNOLOGICAL BASIS AND STATUS OF HIGH RESOLUTION XUV/FUV IMAGING

Fundamental advancements in six areas of technology underlie the results that have been achieved and that are anticipated in the near future in imaging XUV [we refer to the soft x-ray and EUV spectral regions (~1A to 1000Å) as the XUV] and FUV radiation; (i) optical coatings for the XUV and FUV, (ii) ultra smooth mirror substrates, (iii) XUV and FUV filters, (iv) active servo control of mirror aspect to achieve image stability, (v) high resolution XUV/FUV sensitive photographic emulsions, and (vi) photoelectric array detectors. Barbee has described the development of multilayer optical coating technology[19], and Baker[20] has described the techniques used to manufacture ultrasmooth mirror substrates, Walker *et al*[21] have described the development and application of multilayer mirrors for astronomical imaging and Powell and Powell *et al*[22] and Spiller *et al*[23] *have* described XUV filter technology. Timothy and Timothy *et al*[24] have discussed the status of photoelectric detector arrays, and Hoover *et al*[25] discuss XUV and FUV sensitive high resolution photographic emulsions. Raab *et al*[26] have shown that multilayer coated optics can form diffraction limited images at soft x-ray and EUV wavelengths.

We obtained the first high resolution XUV image of an astronomical source with multilayer optics [Walker *et al*[27]; Lindblom *et al*[28]] in 1987 with a 60 mm aperture sphere-sphere pseudo-Cassegrain telescope (Figure 1). The resolution of Figure 1, ~ 1.2 arc-seconds, is representative of the "second generation" of astronomical multilayer telescopes [see also the recent results of Golub *et al*[29]]. The "first generation" is represented by the Herschelian telescope flown by Underwood *et al*[30] in 1985, which obtained a solar image with ~ 10" resolution. A "third generation" astronomical multilayer instrument, the rocket borne *Multispectral Solar Telescope Array (MSSTA)* [Walker *et al*[15]] recently developed by the authors, has been tested and has been shown to be capable of obtaining solar images with resolutions of 0.1 - 0.3 arc-seconds [Hoover *et al*[31,32], Lindblom *et al*[33]]. A "fourth generation" of multilayer astronomical instruments, which will be capable of resolutions exceeding 0.1 arc second are currently being planned[16,17,18]. Zmek *et al*[34], Harvey *et al*[35]; and Spiller *et al*[36] have previously discussed the technological issues which must be addressed in order to achieve 0.1 arc-second images at soft X-ray/EUV wavelengths.

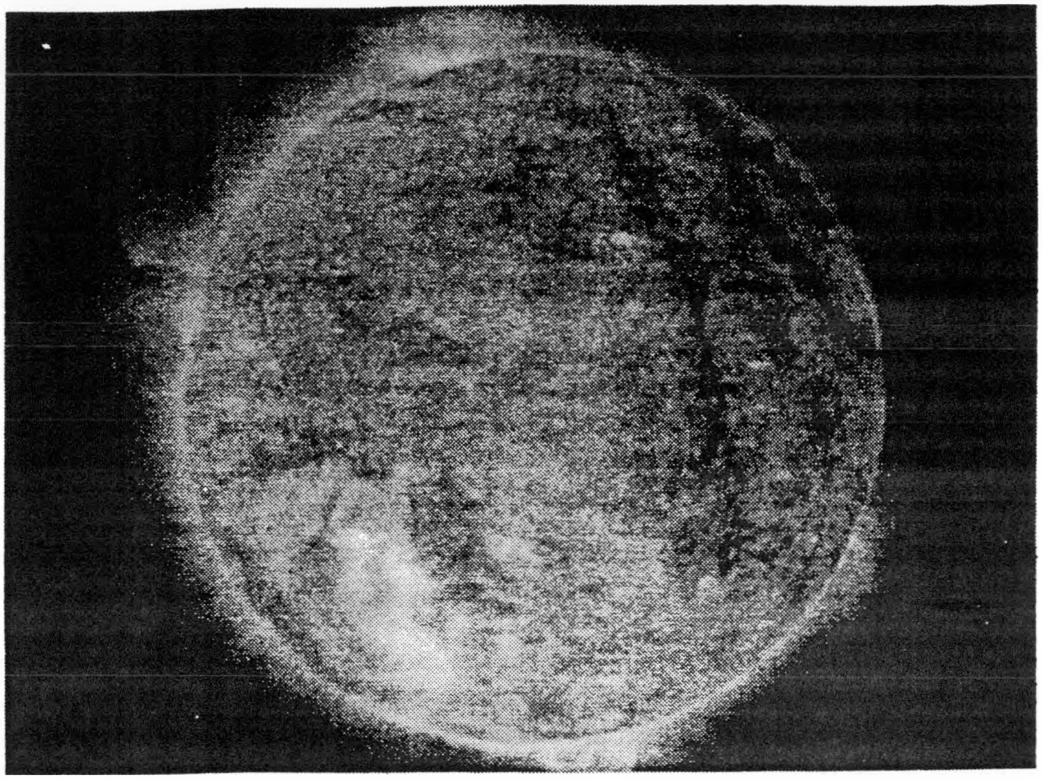

Figure 1. Image of the sun in the wavelength band λ λ 171 Å - 175 Å obtained with a rocket-borne multilayer x-ray telescope by the authors. [27] The image is dominated by structures at ~ 1,000,000 K.

3. OPTICAL COATINGS AND MIRROR SUBSTRATES

The technology required to fabricate efficient optical coatings for the XUV and FUV has advanced rapidly in the past decade. Equally fundamental to the development of efficient XUV and FUV mirrors is the surface quality of the substrates on which the coatings are applied. We have described the status of these technologies previously[15,21], we review their status briefly below.

Ultrasmooth Mirror Substrates: The surface quality of mirror substrates for XUV and FUV mirrors is of critical importance for two reasons: (i) the efficiency of multilayer coatings is dependant on substrate surface quality [this dependance becomes critical for wavelengths below ~ 80 Å, since reflectivity ε decreases as $\varepsilon = \varepsilon_t \exp[-(2\pi\sigma/d)^2]$, where σ is the RMS roughness of the substrate, d is the multilayer lattice constant, and ε_t is the theoretical efficiency for an ideal multilayer] and (ii) scattering from surface inhomogeneities decreases image contrast and degrades image quality. Baker Consulting Inc. has polished 7 Ritchey-Chrétien mirror pairs and 5 Herschelian mirrors for the *Multi-Spectral Solar Telescope Array (MSSTA)* rocket borne Observatory, using the flow polishing technology developed by Baker.[20] The *MSSTA* mirror substrates are Zerodur blanks. The measured RMS smoothness of the *MSSTA* mirrors is ~1 - 2 Å RMS.[31] Baker Consulting Inc. has also polished sapphire substrates for a Schwartzschild microscope under development by the authors.[37] The measured RMS smoothness of the microscope mirrors is better than 0.5 Å. These surface finishes are, we believe, adequate to achieve 0.1 arc-second resolution in an assembled telescope.

Multilayer Coatings for the XUV/EUV: The development of multilayer coating technology [19,38,39] for the XUV has now progressed to the point that the reflection efficiency of optical coatings for the wavelength region ~ 100 Å < λ < 350 Å are approaching the levels predicted for "perfect" multilayer structures. We have recently completed the measurement of reflectivity for the *MSSTA* Ritchey Chrétien and Cassegrain Telescopes.[40] The reflectivities [typically ~ 50% (at ~ 150 Å) to ~ 25% (at ~ 300 Å)] measured are ~ 70% - 80% of the reflectivity for ideal multilayer structures. A measure of the progress that has been achieved is demonstrated by the comparison of the reflectivity of the mirrors of the Cassegrain Telescope which obtained the image of figure 1 (~ 25%), with the reflectivity of our recently completed 171 Å - 175 Å Ritchey Chrétien Telescope mirrors (~ 43%). For two reflections, this results in an almost 250% increase in throughput! The reflectivity of contemporary multilayers at wavelengths below ~ 70 Å, typically ~ 10%, is too low to permit the use of double reflection telescopes for the weak solar lines in this spectral range. The single reflection Herschelian configuration is used for the *MSSTA* telescopes[15] in this wavelength interval. The fractional bandpass ($\delta\lambda/\lambda$) of a multilayer mirror can range between ~ 1% and 10%, allowing, within limits, a mirror to be specifically designed for a particular application (*i.e.* narrow band imaging, providing an image for a grating spectrometer, etc.).

Coatings for the Long Wavelength EUV: For the long wavelength EUV (~ 400 Å < λ < 1100 Å) Hass and Hunter [41] and Windt *et al* [42] have shown that heavy metals such as iridium and osmium are reasonably efficient (~ 30%) reflectors. Figure 2 shows the reflectivity of several heavy metals in this wavelength interval. Silicon carbide[44,45] becomes an efficient reflector at wavelengths between 600 Å and 2000 Å.

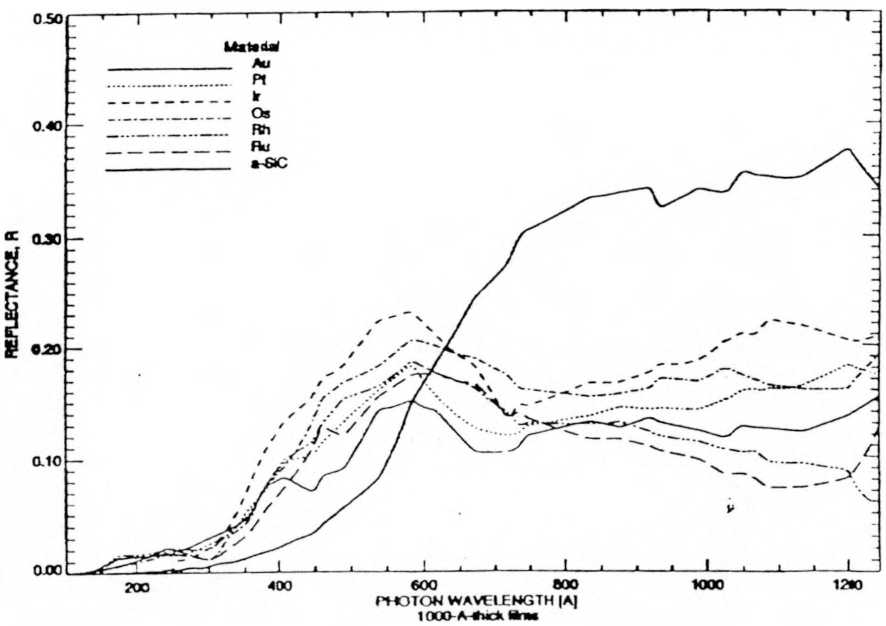

Figure 2. Normal Incidence Reflectance of heavy metals and SiC after D. Windt.[43]

Interference films for the FUV: Aluminum surfaces overcoated with MgF_2 are efficient reflectors in the FUV[41]. Spiller [46] and Zukic *et al* [47] describe the properties of interference films which can result in enhanced efficiency in the reflection of radiation in the FUV (1000 Å < λ < 2000 Å). These films are commercially available, and can be fabricated with bandpasses between ~100 Å and 500 Å wide. For example, we have obtained coated Ritchey-Chrétien Optics from Acton Research Inc. with efficiencies for two reflections of 25% at 1216 Å, and 60% at 1550 Å[31].

4. IDENTIFICATION OF FACTORS AFFECTING RESOLUTION

Image Quality: The quality of the image formed by a XUV or FUV telescope is determined by the following factors, where δ_i represents the full width at half maximum of the point spread function due to factor, i.

i. Geometrical aberrations (for a perfect optical system) and diffraction (δ_a)
ii. Aberrations due to mirror distortion, mirror decentration and tilt, (δ_t), and to slope errors, system misalignment and other imperfections in manufacture and assembly (δ_e).
iii. The widening of the point spread function due to scattering by surface imperfections (δ_r).
iv. Defocussing due to errors in primary/secondary separation (δ_s)
v. Image blurring due to spacecraft and pointer jitter and tracking errors (δ_j)
vi. Image blurring due to target motion (δ_m)
vii. Image blurring due to finite film or detector resolution (δ_d)
viii. Scattering and diffraction due to the various filters (and supporting meshes) used (δ_f)

The net resolution, δ, is given by

$$\delta(r,\lambda) = [\delta^2_f(r,\lambda) + \delta^2_a(r,\lambda) + \delta^2_t(r,\lambda) + \delta_r^2(r,\lambda) + \delta^2_e(r,\lambda) + \delta^2_s(r,\lambda) + \delta^2_j(r,\lambda) + \delta^2_m(r,\lambda) + \delta^2_d(r,\lambda)]^{1/2}$$

where r is the field position relative to the optical axis. For large field angles, and in the FUV, $\delta_a(r,\lambda)$ will dominate the net resolution, δ. At small field angles and at XUV wavelengths, δ_a can be held to 0.02-0.06" (*i.e.* we can achieve diffraction limited performance). We list a preliminary allocation of the error budget for a 12.7 centimeter aperture λ 304 Å telescope, which we have recently completed for the *MSSTA* payload, below. The net on-axis resolution at 304 Å projected by Table 1 is 0.09 arc-seconds.

Table 1. On Axis Image Point Spread Allocation at λ 304 Å

Term	Allocation	δ^2	Term	Allocation	δ^2
$\delta_f(0)$	0.02"	0.0004	$\delta_s(0)$	0.03	0.0009
$\delta_a(0)$	0.06	0.0036	$\delta_j(0)$	0.03	0.0009
$[\delta_t{}^2(0) + \delta_e{}^2(0)]^{1/2}$	0.03	0.0009	$\delta_m(0)$	0.02	0.0004
$\delta_r(0)$	0.03	0.0009	$\delta_d(0)$	0.02	0.0004

We discuss the factors which determine image quality more fully below.

5. ANALYSIS OF TELESCOPE ABERRATIONS AND DEFOCUSING

Hadaway *et al* [48] and Hoover *et al* [32] describe the ray trace analysis and testing of the optical properties of the Ritchey-Chrétien telescopes developed for the *MSSTA* rocket payload, which is shown in Figure 3. The Ritchey-Chretien configuration, which is the aplanatic form of the Cassegrain, has been described in detail by Wetherall and

Rimmer[49]. Figures 4a and 4b which summarize the results of the raytrace analysis, demonstrate that for a flat focal plane, the Ritchey-Chrétien configuration permits resolution better than 0.05 arc-seconds at 173 Å over a 5 arc-minute field.

In figure 4b, the resolution for flat fields at different positions along the optical axis is shown. We note that in order to achieve the highest possible resolution on-axis with the Ritchey-Chrétien optical design, we must place the film plane at the optimum focal position (*i.e.* paraxial focus). Since the surface of optimal focus (*i.e.* Petzval surface) is curved toward the optics, the resolution degrades off-axis when a flat detector is situated at the paraxial focus. For example, when the film plane is situated at the paraxial focus of the λ 173 Å *MSSTA* Ritchey-Chrétien telescope; the resolution degrades from 0.03" on-axis to 0.05 at 3' off-axis, 0.33 arc sec 16' off-axis, and 0.75 arc sec at 24' off-axis.

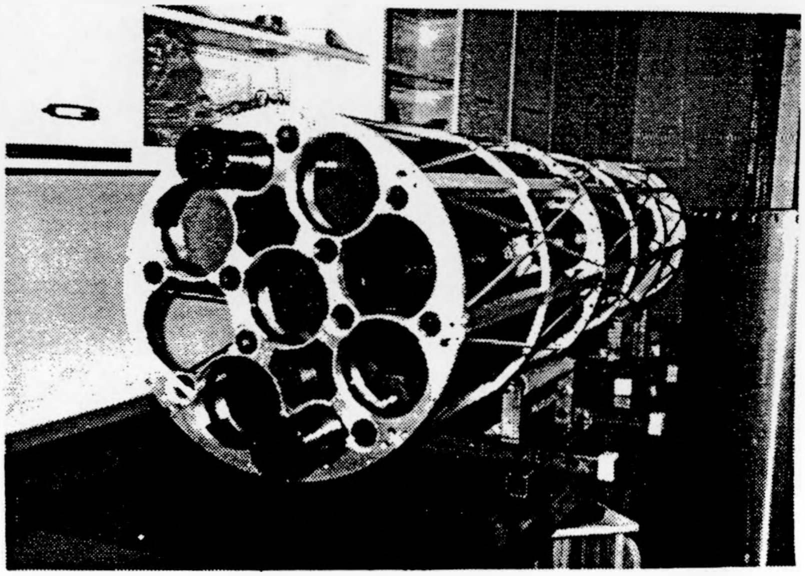

Figure 3. The *MSSTA* payload is shown during assembly.

Since it is difficult to contour the film plane to the curvature of the Petzval surface, we compromise for some telescopes by placing the flat film plane slightly forward of the paraxial focus to achieve the best overall system resolution balance. If we were able to curve the focal plane to match the Petzval surface, we could achieve a much larger field at the highest angular resolution, as figure 4b illustrates. A curved focal surface can be achieved with the MAMA detector, as we point out below.

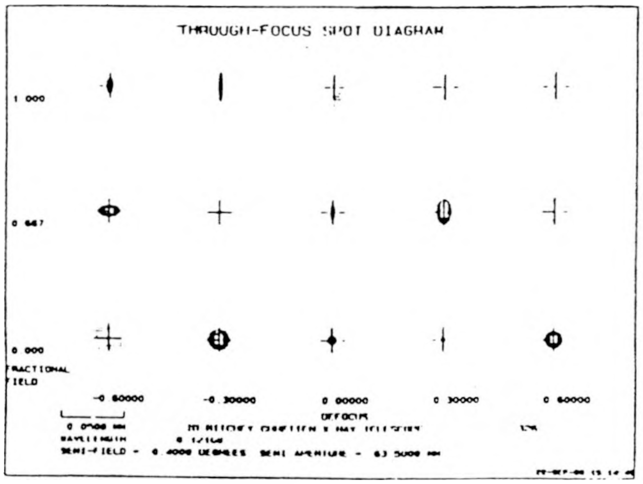

Figure 4a. Spot diagrams for the *MSSTA* Ritchey Chrétien design at 173 Å[48]. For the focal length of 3500 mm, the scale of 50 microns shown above corresponds to 3 arc-seconds.

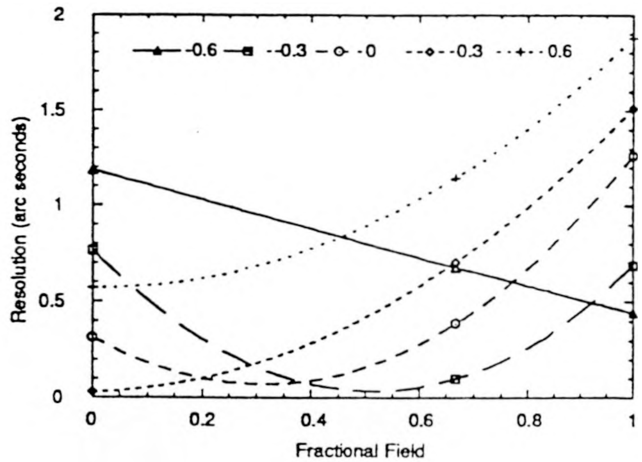

Figure 4b. Dependence of the *MSSTA* Ritchey-Chrétien resolution on field angle at 173 Å[48]. The full field is 48 arc-minutes.

6. THE EFFECT OF MIRROR TILT AND DISTORTION, SLOPE ERRORS, MISALIGNMENT, AND DEFOCUSING

We have assembled and tested the seven 12.7 centimeter aperture Ritchey-Chrétien telescopes which will be flown in the *MSSTA* rocket payload payload in April of this year. These tests have allowed us to access the impact of mirror imperfections (*i.e.* slope errors, mirror distortion), tilt, decentration and other misalignments, and defocusing on the quality of the image. For optical telescopes of large aperture, such imperfections often prove to be the factors which limit performance, requiring the use of active optics[50]. The mounting and assembly of the *MSSTA* telescopes are described by Hoover *et al*[31,32]. The tests were carried out using a He/Ne Laser (λ 6328 Å) interferometer, and analyzed using the code Micro-Fringe 3.1, allowing the *geometrical* performance of the telescopes to be determined. Figures 5a and 5b illustrate the results achieved for the λ 335 Å telescope, which are typical. The optical quality of the systems was found to be ~λ/100 for 6328Å light. Figure 5a indicates that, neglecting defraction and scattering, 90% of the energy of a point source on axis would be placed in a circle of radius 0.06 Airy Radii, or 0.004". These results demonstrate that the careful, but cost effective approach that we have developed for the fabrication of compact XUV and FUV telescopes is able to achieve telescopes of sufficient mechanical perfection to achieve resolutions exceeding 0.1 arc-seconds.

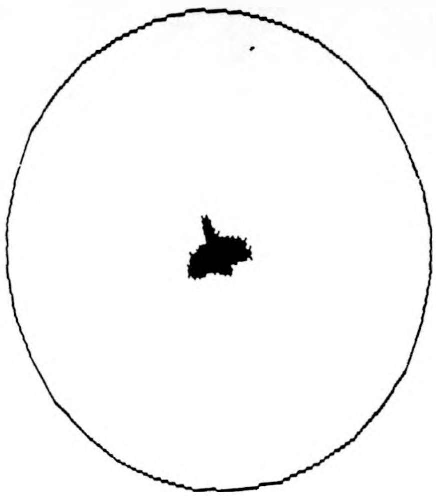

Figure 5a. Calculated Geometrical Zonal Spot Diagram for the λ_0 335 Å telescope based on interferometric measurements. The circle represents the Airy Disk radius (0.066").

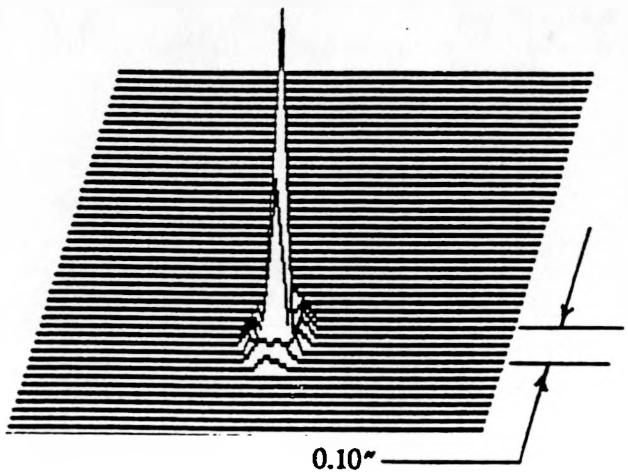

Figure 5b. Calculated point spread function (PSF) of the λ_0 335 Å telescope based on interferometric measurements. The PFS is dominated by diffraction effects.

Based on the analysis of these measurements (figure 5b), and on the raytrace analysis described above, we have achieved diffraction limited performance, *i.e.* geometrical aberrations and diffraction, (δ_a), ~ 0.06" for the *MSSTA* λ 304 Å telescope in Table 1; aberrations due to imperfections in manufacture and assembly, $[\delta_t^2 + \delta_e^2]^{1/2}$, have been conservatively estimated at ~0.03". For the small aperture *MSSTA* telescopes, the use of active optics[50] to achieve diffraction limited performance does not appear to be necessary.

From figure 4, we can see that in order to maintain image quality, at the level of 0.1 arc-seconds the position of the focal plane must be maintained to a precision of 0.06 mm (60 microns). Since the magnification of the secondary is ~ 4, this corresponds to ~15 microns precision in the separation of the primary and secondary mirrors. In our *MSSTA* telescopes, which are developed for a modestly funded rocket program, we have used a graphite epoxy optical bench to minimize the sensitivity of primary/secondary separation to temperature. Our measurements indicate that we are able to meet this requirement[31]; we have estimated blurring due to defocusing to be δ_s~ 0.03" for the *MSSTA* telescopes. We note, however, that fiber epoxy optical benches are known to be sensitive to moisture which can cause dimensional changes, consequently for a satellite borne telescope, an active focusing capability must be developed.

7. EFFECT OF SURFACE IMPERFECTIONS

Zmek *et al*[34] and Harvey *et al*[35] have modeled the impact of minor surface imperfections on image quality for multilayer mirrors operating at soft x-ray and EUV wavelengths. The power of the surface density (PSD) of minor imperfections, $\sigma^2(f_x f_y)$, may be expanded as[36]

$$\sigma^2(f_x, f_y) = (1/A) \left| \iint_A z(x,y) \exp\left[\, 2\pi i\, (f_x x + f_y y)\, \right] dxdy \right|^2$$

where z(x,y) represents the deviation of the real mirror from the surface of an ideal mirror at point x, y; (f_x, f_y) represents the spatial frequency; and the integral is taken over the area, A, of the mirror. The quantity σ^2 may be measured over specific frequency ranges using various techniques, as described by Spiller *et al*[36], to provide an average surface roughness over some range of surface frequencies, f'

$$\sigma_{f'}^2 = \int_{f'} \sigma^2(f)\, df\, .$$

Harvey *et al* divide the surface roughness into three spacial frequency domains, low frequency (σ_L, on the scale on millimeters or larger), microroughness, (σ_H, on the scale of 0.01 microns or less), and "mid-frequency" roughness (σ_M). Microroughness degrades multilayer efficiency. However, because scattering at the various multilayer interfaces is uncorrelated, scattering by imperfection on this scale is attenuated by $\sqrt{N}$, where N is the number of reflecting layers. The very high reflectivity at their respective working wavelengths indicates that this effect is small for our mirrors. Our interferometric tests demonstrate that figure errors are also small for our mirrors[31,32]. Control of mid-frequency surface roughness, then, becomes critical for the performance of normal incidence multilayer mirrors. Both Harvey *et al*[35] and Spiller *et al*[36] evaluate its effects. It is difficult to measure mid-frequency surface roughness density; it is generally assumed that surface roughness scales as, $bf^{-\alpha}$, where b is determined from surface microroughness measurements, and $2 \le \alpha \le 3$. The microroughness of our mirrors, $\sigma_H \sim 1 - 2$ Å RMS, is ~ 3 times lower than the values selected by Harvey *et al* [35] in their analysis; based on their analysis ~ 85% of the energy from a point source will be within a circle of diameter 0.06 arc seconds at λ 304 Å for a mirror with $\sigma_H \sim 5$ Å RMS. The analysis of Spiller *et al* predicts that for their Herschelian mirror, which operates at ~ 63 Å, the measured spectral density of defects should produce observable effects in their images. Since such effects are not observed, they conclude that their measurements represent an upper limit to the actual roughness at mid-frequencies. Because the scattering of energy (I) from the central point spread function varies as

$$I_{scattered} \sim 1 - \exp\left[\, - (4\pi\sigma/\lambda)^2\, \right] ,$$

the predicted scattering is only ~ 3% for a mirror such as theirs, operating at ~ 300 Å. The measured roughness of our mirrors is approximately half of that reported by Spiller *et al.* Based on these analyses, we conclude for our telescope, that scattering due to surface imperfections should not significantly reduce the fraction of incident energy in the central diffraction peak, and should have a negligible effect on the point spread function. We have assumed that $\delta_r(0) \sim 0.03$ arc seconds for our λ 304 Å telescope in Table 1 (Section 4).

8. FILTERS

For most stellar sources of soft x-ray, EUV and FUV radiation, the intensity of ultraviolet, visible, and infrared radiation exceeds the intensity of the short wavelength radiations by factors between 100 and 1,000,000. For the sun, the ratios are $L_{Soft\ X\text{-}ray}/L_{Total} \sim 10^{-6}$, $L_{EUV}/L_{Total} \sim 10^{-4}$, and $L_{FUV}/L_{Total} \sim 10^{-2}$. For multilayer optical systems, the two multilayer reflections are able to discriminate against nearby offband radiation by factors of ~ 100 - 300, consequently if the objective is to obtain an image of structures as seen in a strong solar line such as He II λ 304 Å, Fe IX λ 173.1 Å, etc., then we only need to be concerned with "leakage" from distant XUV lines, and from UV and visible radiation. Unfortunately, multilayer coatings are reasonably efficient (~ 50%) reflectors for visible light. If a polychromatic detector such as film is used, it is necessary to attenuate off-band radiation by the use of filters. Rejection of visible light by a factor of ~ 10^{10} must be achieved[33]. If a MAMA detector with a "solar blind" photocathode is used, the demands on the filter are reduced, but not eliminated.

Powell *et al*[22] discuss the design and fabrication of XUV filters; Lindblom *et al*[33] describe the *MSSTA* filters in detail. At XUV wavelengths, a filter consists of one or more (usually two, to prevent pinholes from illuminating the focal plane) thin (typically 1000 Å - 2000 Å thick) metallic films, supported by a nickel mesh; the films are made of materials such as aluminum or beryllium for the suppression of UV, visible and infrared radiation. Normally, the filter is placed in front of the focal plane, and intercepts the beam after reflection from the secondary[15]; some investigators also place a thin unsupported Aluminum filter in front of the primary aperture[23] which has the advantage of reducing the thermal load seen by the telescope. Although the primary function of the filter is to reject visible light, it also can reject off band XUV radiation (materials such as carbon, tellurium, etc are added to the filter for this purpose),[33] and narrow the telescope wavelength bandpass. Filters can also cause shadowing effects (due to the mesh) on the image, if placed too close to the focal plane; and although the photoelectric effect is the primary interaction of X-rays with the filter material, Compton scattering and Raleigh scattering can occur, and can cause a lowering of contrast in the image. For low energies, the elastic scattering is nearly isotropic, so that it does not affect the point spread function, rather it merely lowers the fraction of the energy in the central peak. Examination of the two high resolution multilayer images that have been obtained[27,29] suggest that scattering in the filters is not a serious problem, since it's effects would be as apparent for 1 arc-second images as for 0.1 arc-second images. We have estimated that these effects will cause only minor degradation of the *MSSTA* images ($\delta_f \sim 0.02"$).

At FUV wavelengths, filters are generally multilayer interface films[51] that are placed on MgF_2 flats, and should have no adverse impact on image quality.

9. DETECTORS

The resolving power of the detector used is critical for a compact XUV or FUV telescope, because it determines the plate scale, and hence the focal length of the telescope. For the *MSSTA* rocket payload, we have used special XUV sensitive films prepared by Kodak.[52] Hoover et al [25] have carried out detailed measurements on the 2 films which we have used, XUV100, which has a resolving power of 200 *lines/mm* (*ie* 2.5 micron "pixels") and the XUV649 emulsion, which has a resolution of 2000 *lines/mm* (*i.e.* 0.25 micron "pixels"). With the XUV100 film, the resolution of the *MSSTA* telescopes (3500 mm focal length) is limited to 0.3 arc-seconds, with the XUV649 emulsion, resolution exceeding 0.1 arc-second is possible. While less sensitive than the XUV100 film[25], the XUV649 emulsion is sufficiently sensitive to allow images to be obtained with the *MSSTA* telescopes for the strongest lines (*i.e.* He II λ 304 Å, H I λ 1215.6 Å), and for a wide range of solar emission lines in the wavelength interval 40 Å < λ < 300 Å with the larger (20 centimeter apertures) telescopes planned for the *Ultra High Resolution XUV Spectroheliograph (UHRXS)*, a comprehensive solar observatory proposed by the authors, and selected by NASA for development as an attached payload on the space station *Freedom.*[53] [We note that attached payloads may not be compatible with the revised Space Station[54], however we have developed a revised configuration of the *UHRXS*[55] suitable for deployment on a free flyer.]

For missions on free flying satellites,[55] or in deep space locations such as on the moon,[18] the use of a photoelectric array detector is essential. The MAMA detector developed by Timothy[24] has a number of advantages for use with high resolution XUV and FUV telescopes. The MAMA detectors currently under development utilize a microchannel plate (MCP) with 10 micron channels on 12 micron centers, read by a 2048 x 2048 pixel anode array capable of resolving a single pixel. In the next few years, we believe that it will be possible to develop a MAMA configuration which utilizes a MCP with 5 micron channels on 6 micron centers, coupled to a 2048 x 2048 pixel anode array read out in double precision[56,57] allowing the resolution of a single 6 micron pixel with a 4096 x 4096 pixel format. The MAMA detector has the following additional advantages: (i) it has submicrosecond response time; (ii) it does not suffer from bias levels that vary across the array (i.e., non "flat field") as does the CCD; (iii) its nature (event detection by coincidence with orthogonal anode arrays) allows compensation for image motion to be achieved, at the microsecond level, within the detector with virtually no compromise to the quality of the image[58]; (iv) it can be made with a photocathode that is blind to the visible, greatly simplifying the problem of suppression of scattered light in UV, EUV, and XUV instruments; (v) the detector format is flexible since the array size which is read out can be electronically controlled; and (vi) the face of the MCP can be curved[59] to match the Petzval focal surfaces of the telescopes. We have developed a design for a modified version of the UHRXS solar observatory[55] which incorporates a long focal length (24,750 mm) Gregorian telescope which has a plate scale of 120 μ/arc-second, permitting a pixel of 0.05 arc-seconds with a detector having a six micron pixel.

We anticipate that the image blurring due to finite film resolution will be quite small for the XUV649 emulsion; we have estimated $\delta_d \sim 0.02''$ for the *MSSTA* λ 304 Å and λ 1215.6 Å telescopes.

10. SPACECRAFT JITTER AND TARGET MOTION

The capability to stabilize a spacecraft to a level of a few hundredths of an arc-second or better has been demonstrated by the OAO and Hubble[60] spacecraft. However, such stabilization systems are complex and expensive, and require the use of star trackers. Furthermore, even if a satellite carrying an array of high resolution solar telescopes could be stabilized relative to an "inertial" reference frame to this level of accuracy, the rotation of the sun around its axis, and the apparent rotation of the solar disk in the spacecraft frame of reference would introduce additional components of image or target motion which must be compensated. The solar rotation causes a motion of ~ 5×10^{-3} arc-seconds per second, or 1/10 pixel/second for a 0.1 arc-second resolution image. Finally, the advantages of the low cost approach to high resolution imaging represented by compact XUV and FUV telescopes is lost, if a costly satellite stabilization system is required. Therefore we propose the following approach to image stabilization to compensate for spacecraft jitter, and photon address correction to compensate for target motion and target rotation.

Image Stabilization and Active Mirror Servos: The pointing accuracy and stability required to attain the resolution envisioned for the compact soft x-ray, EUV and FUV telescopes we have described can be achieved by an internal stabilization capability, the Active Mirror Servo (Figure 5), which can control the tilt of the secondary mirrors. The Active Mirror Servo (AMS)[61], a compact mirror articulation system developed by Ball Aerospace Systems Division, has already demonstrated stabilization of a 6-inch (16 centimeter) aperture mirror to a level of 0.08 arc-seconds with a 600 Hz band width. The primary pointing error signal can be derived from a SPARCS rocket sensor,[62] which has been shown to be capable of 0.05" arc second precision. Pointing errors and jitter can also be corrected electronically by the MAMA detector, based on the SPARCS error signal, as described below. This technology will provide a backup image stabilization capability.

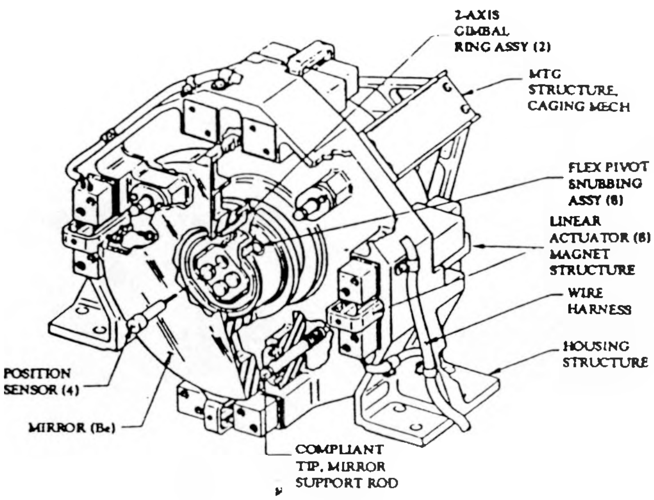

Figure 5. The Ball Aerospace active mirror servo.

Photon Address Connection: The MAMA detector is a rectangular array of pixels, in which the x,y position of each photon is recorded as a function of time. Consequently, if a real time-pointing error signal is available, then a logic circuit can be utilized between the MAMA address electronics and the MAMA memory so that the address of each photon event can be corrected for pointing errors before being placed in memory. This real time image stabilization capability has been demonstrated by Illing, Zaun and Bybee[58] of Ball Aerospace. A supplementary pointing error signal can be generated by a correlation tracking error signal derived from a solar image in a line, e.g. H Lyman-α, which shows phenomena such as the solar granulation. Morgan *et al* [63] have shown that the centroid of an image recorded by the MAMA detector can be located to within 0.04 pixel. Note that image "derotation" (which is caused by the orbital motion of the telescope) can also be provided electronically by the MAMA.

The approaches described above are not as yet incorporated into our *MSSTA* rocket observations; we must for the present rely on the SPARCS rocket aspect system[64]. We discuss the performance of this system in section 11.

11. CONCLUSIONS

We conclude that there are no insurmountable obstacles to achieving 0.1 arc-second images at soft x-ray, EUV and FUV wavelengths, using low cost compact multilayer coated optics. Spiller *et al*[36] have addressed the question of photon flux and conclude that it will be possible to achieve 0.3 arc-second resolution for the weak solar lines below 100Å, and to achieve 0.1 arc-second resolution for the strong lines between 171Å and 350Å. We concur, and have calculated the expected fluxes for our *MSSTA* telescopes[15], and for our larger *UHRXS* telescopes.[53] Spiller *et al* suggest that 1000 photons per pixel is a reasonable goal; for high resolution moderate sensitivity films such as XUV649 we think 10,000 photons is a more comfortable level. We have calculated that for our *MSSTA* H Lyman α telescope, the flux in a 0.1 arc-second pixel is ~ 2.4 x 10^6 photons/sec, for the He II λ 304 Å telescope the flux in a 0.1 arc-second pixel is 4 x 10^4 photons/sec. The next strongest line is the Fe IX/X (λ 173 Å) complex for which the flux is 10^4 photons/sec. Therefore, we anticipate that it may be possible to achieve resolution approaching 0.1 arc-seconds with the *MSSTA* He II and Fe IX/X telescopes (the 12.7 cm aperture of the *MSSTA* telescopes limits the resolution attainable at 1216 Å to 0.25 arc-seconds) in the near future. We have set a goal of 0.1 arc-seconds for the He II λ 304 Å images, and a goal of 0.25 - 0.3 arc-seconds for the other *MSSTA* telescopes for our April, 1991, flight. We anticipate that the resolution limit will be set by jitter associated with the rocket aspect system, the SPARCS (Solar Pointing Altitude Rocket Control System). Efforts are underway to improve the performance of the SPARCS system, and we hope to determine the present level of performance during our April 1991 flight. If it is not possible to reach the level of 0.1 arc-second with the SPARCS system, we plan to incorporate an Active Mirror Servo (Section 10) into our He II λ 304 Å telescope to reach the stability required to achieve 0.1 arc-second images.

With photographic recording, our *Ultra High Resolution XUV Spectroheliographic* experiment,[16,53] which was selected for deployment on the Space Station *Freedom*, can achieve 0.1 arc-second resolution in a wide range of solar lines, from ~ 50 Å to 1216 Å, using techniques described here and elsewhere[21,53], permiting the study of structures in the solar atmosphere over the temperature range 7,000 K to 100,000,000 K with 0.1 arc-second resolution. Achieving resolution of 0.1 arc-second over this broad temperature interval using photoelectric detector arrays will require a somewhat larger instrument,[53] since telescopes of longer focal length (but with the same aperture) will be required.

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