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ABSTRACT

Photos obtained during 5 min. of observation time from the flight of our 10 inch normal incidence soft x-ray ($\lambda = 63.5\text{\AA}$) telescope on September 11, 1989 are analyzed and the data are compared to the results expected from tests of the mirror surfaces. These tests cover a range of spatial periods from 25 cm to $1\text{\AA}$. The photos demonstrate a reduction in the scattering of the multilayer mirror compared to a single surface for scattering angles above 1 arcmin, corresponding to surface irregularities with spatial periods below $10\text{ }\mu\text{m}$. Our results are used to predict the possible performance of future flights. Sounding rocket observations might be able to reach a resolution around 0.1 arcsec. Higher resolutions will require flights of longer durations and improvements in mirror testing for the largest spatial periods.

1. INTRODUCTION

Diffraction defines the resolution limit of optical instruments for visible light and the capabilities of fabricating diffraction limited visible light optics has existed for about a century. Multilayer coated mirrors for soft x-rays have permitted the fabrication of optical elements (telescopes and microscopes) for wavelengths that are 100 times shorter with a corresponding improvement in the theoretically possible resolution. Even a modest size telescope with 10 cm aperture has the potential for 0.01 arcsec resolution. The fabrication, assembly, testing and use of such an instrument, however, poses some challenges that are beyond our present technology.

Multilayer mirror telescopes have been flown on sounding rockets [1, 2] and have produced x-ray images of the sun with a resolution better than 1 arcsec. We discuss in this paper the present limits on the performance of such telescopes, using our 10 inch telescope for $\lambda = 63\text{ }\text{\AA}$ and its Sept. 11, 1989,

flight as a specific example. Areas where progress is needed are defined, and estimates are given on the improvements that we expect in future missions.

2. MIRROR OPTICS

The height deviations $z(x,y)$ of the actual surface of a mirror from its perfect shape have to be drastically smaller for soft x-rays than for visible light. The same is true for all the boundaries within the multilayer coating. The Fourier transform of the deviation $z(\vec{r})$, $\vec{r} = (x,y)$ defines the two-dimensional power spectrum of the surface errors [3-6]

$$S_2(\vec{f}) = \frac{1}{A} \left| \int_A z(\vec{r}) e^{2\pi i \vec{f} \cdot \vec{r}} d\vec{r} \right|^2, \quad (1)$$

From one-dimensional scans $z(x)$ of the surface one obtains the one-dimensional power spectral density

$$S_1(f_x) = \frac{2}{L} \left| \int_0^L z(x) e^{2\pi i f_x x} dx \right|^2, \quad (2)$$

where A , L are the area or length of the scans, $\vec{f} = (f_x, f_y)$ is the 2-D vector of spatial frequencies, and $f_x = 1/\Lambda_x$, Λ_x = spatial period in the surface. See Ref. [4] for the formulas that connect S_1 and S_2 .

All statistical properties of a surface can be obtained from the power spectral density. The rms surface roughness is given by

$$\sigma^2 = \int_0^\infty S_1(f_x) df_x, \quad (3)$$

or

$$\sigma^2 = 2\pi \int_0^\infty S_2(f) f df. \quad (4)$$

Figure 1 contains a list of methods that are used to characterize optical surfaces. Each method characterizes a surface over a limited band of spatial frequencies or periods and the bands for different methods are indicated in the figure together with their sensitivity. For a high quality, near diffraction limited x-ray mirror, the entire range of spatial frequencies from periods in the 1 Å-range up to the size of the optics is important. The fine features in the surface roughness reduce the reflectivity of a mirror, and the roughness should be smaller than about 1/10 of the multilayer period for good reflectivity. The reduction of the reflectivity is described by the well known Debye-Waller factor [7-9]. The roughness value σ obtained from an x-ray reflectivity measurement contains all spatial frequencies from a lower limit (determined by the detector aperture in a reflectometer) to infinity (or in practice the value defined by atomic structure).

Total Integrated Scattering (TIS) with visible light also yields a value of σ integrated over a large frequency band with a resolution in the 1 Å range. However, the band of frequencies included in this measurement, is of lesser importance for x-ray optics. The methods below the dotted line in Fig. 1 permit measurement of the power spectral density for each spatial frequency separately. Electron

microscopy [10, 11] and tunnel microscopy [12] cover the high spatial frequencies and can even show each individual boundary in a sliced multilayer coating. X-ray scattering represents a direct Fourier analysis of a surface, and the intensity of the scattered light is completely determined by the structure as obtained by the microscopes. However, additional work is still required to connect the results between the two methods.

Fig. 1. Methods to characterize mirror surface for different ranges of spatial frequencies. Total integrated scattering (TIS) and x-ray reflectivity measurements give only the integral over all spatial frequencies within their range, while the other methods can measure the power spectrum of the surface errors at each spatial frequency within their range.

The topography of a surface at the highest spatial frequencies is mostly determined by the growth processes in the coating structure and by the size of the atoms. The metrology for these highest spatial frequencies has drastically advanced in recent years. Figure 2 shows the surface topography of Co-C multilayer coatings as obtained with a scanning tunnel microscope. At the left is the surface of the coating used in the 10 inch telescope flown in 1989, while the right picture represents the top surface of a coating, where the boundaries have been ion polished [13]. Ion polishing has reduced the roughness mainly for the spatial periods in the 100-500Å range. The roughness values obtained from reflectivity measurements and those derived from the tunnel microscope are in quantitative agreement. We also hope to obtain results from x-ray scattering and from microscopy of sliced coatings. While it still may be a problem to fabricate a surface with the required quality, the characterization is not a serious problem for the highest spatial frequencies.

There have also been advances in the characterization of surfaces at the low spatial frequencies. Optical interferometry with phase modulation can have a height resolution in the 1Å-range and commercial instruments, which are easy to use, have been developed. Figure 1 shows that instruments which cover the entire range are now available and we have used the instruments to characterize our telescope optics. The results of these tests are summarized in Fig. 3, where the 1-D power spectrum S_1 is plotted over 10 decades of spatial frequencies. The curves labeled "TUNNEL" are obtained from about 30 pictures such as those in Fig. 2; WYKO represents measurements with a commercial optical profilometer [14], BNL is the LONG RANGE PROFILOMETER at the Brookhaven National Laboratory [15] and ZYGO is a commercial Fizeau interferometer [16] (Fig. 4). The top scale in Fig. 3

Fig. 2. Tunnel micrographs of the 140 layer Co-C coating as used for the 10 inch telescope (left) and of a similar Co-C coating, where the layers have been smoothed by ion polishing. The size of the pictures in each row is indicated.

Fig. 3. Power spectral density $S_1(f)$ of the 10 inch telescope mirror obtained by various methods. Tunnel: Data derived from tunnel micrograph like those shown in Fig. 2. WYKO: data obtained from an optical profilometer. BNL: data from the long range profilometer at the Brookhaven National Laboratory. ZYGO: data from a commercial Fizeau interferometer. The dotted line is a smooth curve through the data. The black square arc derived from an analysis of the x-ray photo of the sun (see Fig. 5) and show the reduction in scattering in a multilayer structure compared to a single surface. The scattering angle on the top scale are for normal incidence.

Table 1 Contribution to roughness and figure errors σ from different spatial frequencies ranges in the power spectral density of the telescope mirror obtained from the dotted curve in Fig. 3. The second column give the range of scattering angles $\Delta\theta$ and the fourth column is the fraction of the reflected light that would be scattered by a single surface into this angular range.

f range(μm^{-1})	$\Delta\theta$	$\sigma(\text{\AA})$	$1 - \exp - \left(\frac{4\pi\sigma}{\lambda} \right)^2$
10^{-4} - 10^{-3}	$0.1''$ - $1''$	1.3	0.06
10^{-3} - 10^{-2}	$1''$ - $10''$	2.5	0.21
10^{-2} - 10^{-1}	$10''$ - $100''$	3.8	0.43
0.1 - 1	$1.7'$ - $17'$	4.5	0.55
1 - 10	$17'$ - 3°	4.1	0.48
10 - 100	3° - 30°	2.9	0.28

gives the scattering angles θ_s for normal incidence and $\lambda = 63.5\text{\AA}$, $\sin\theta_s = \lambda/\Lambda$. The black squares have been obtained by analyzing the pictures (Fig. 5) obtained during the flight in 1989, and the dotted line is a smooth interpolation of most of the data. The most difficult region is at the lowest spatial frequencies where measurements over large distance along the mirror surface are required. We believe that the two curves (ZYGO and BNL) in Fig. 3 do not represent the quality of the mirror but the noise level of the instruments. For the tests with the ZYGO interferometer (Fig. 4) most of this noise is due to vibrations and fluctuations in the air path. We think that this noise can be reduced by averaging over a large number of interferograms. Testing of the optics in a vacuum tank will probably be required, if one wants to predict the performance below the 0.1 arcsec range. The performance of the BNL profilometer with a much shorter air path is presently limited by amplifier noise, which we expect to reduce in the near future.

Fig. 4. Setup for the test of a prime focus and a Ritchie Chretien telescope in a Fizeau interferometer.

Fig. 5. X-ray picture of the sun obtained from the 10 inch telescope on Sept. 11, 1989. The contrast in the picture (exposure intensity in dark areas compared to close-by bright areas) has been used to obtain the points in Fig. 3.

Fig. 6. Density versus exposure for our modified Technical Pan Film, measured for $\lambda = 44.8\text{\AA}$. We used the same curve also for the analysis of our photos obtained at $\lambda = 63.5\text{\AA}$.

Fig. 7. Exposure as a function of resolution on the film (bottom scale) or angular resolution of a telescope with $f = 2\text{m}$ focal length (top scale) for 1000 photons/pixel. The exposure ranges in active regions obtained for 1 min exposure on Technical Pan and 10 sec on $T_{\max} 400$ on the Sept. 11, 1989, flight are indicated by vertical lines. The point SO-253 represents the expected exposure for a high resolution holographic film. The dotted horizontal lines represent exposure intensities for 1 min obtained for various efficiencies of the telescope η .

We can for a single surface mirror estimate the size and intensity of the halo of scattered light around each image point, by integrating Eq. (4) over a finite frequency band to obtain an effective value for σ and by estimating the fraction SC of the incident light scattered into a small ring around the image point from

$$SC = 1 - \exp \left[- \left(\frac{4\pi\sigma}{\lambda} \right)^2 \right]. \quad (5)$$

The result of this estimate derived from the dotted curve in Fig. 3 is given in Table 1. The data predict a large amount of scattering for the larger scattering angles above 10 arcsec which is not con-

sistent with the quality of the pictures obtained (Fig. 5). The discrepancy can be explained, if one assumes that the roughnesses of the different boundaries in the multilayer become un-correlated for high spatial frequencies above $1/\mu\text{m}$. In this case the contributions to scattering from different boundaries are added with random phases, and the effective roughness of a multilayer is reduced by nearly a factor $1/\sqrt{N}$ (N = number of layers) over that of the single boundary [5, 6, 9], resulting in a drastically reduced amount of scattering. Our Fig. 5 is the first experimental verification of this effect for soft x-rays.

We want to note that the points in Fig. 3, derived from the x-ray photo of Fig. 5, represent upper limits. Using the measured density versus exposure curve of the film (Fig. 6), we select dark areas close to very bright areas in the photo. Measuring the exposure intensity in the bright and the dark areas and assuming that all the intensity in the darker section is produced by scattering from the surroundings, we obtain a σ value and an estimate for the power spectral density. The actual values might be lower, because some x-ray flux might also emanate from the darker regions in the corona.

3. PHOTON FLUX AND DETECTOR

About 1000 photons per pixel have to be collected to obtain a picture with about 100 gray levels. Photos with increased resolution have more pixels and therefore require a higher exposure. For sounding rockets the size of the optics and the observation time are limited and define an effective limit on the ultimate resolution. We used modified Kodak Technical Pan and $T_{\text{max}}400$ film for our flight and have plotted in Fig. 7 the range of exposure intensities in a 1 min. and a 10 sec. exposure in the image of active regions of the sun at the spatial resolution of those films. We have also plotted an estimate for film of drastically higher resolution, holographic film SO253.

The exposure level required for 1000 photons/pixel is plotted as a function of spatial resolution in the film plane (bottom) or angular resolution of a telescope with 2m focal length (top). The horizontal dotted line at 4×10^9 photons/cm² min represents the exposure level obtained for the brighter parts of the active region during our 1989 flight within 1 minute. We cannot expect a drastic increase in resolution in future flights unless we increase the number of photons collected. The collection efficiency η of a telescope is defined as

$$\eta = \left(\frac{AP}{IM} \right) \cdot T \cdot R, \quad (6)$$

where AP is the area of the entrance aperture, IM is the area of the sun's image on the film, T is the x-ray transmission of all filters in the telescope and R the mirror reflectivity; we had $\eta = 0.25$ in 1989. By using improved filters [17] and a mirror with higher reflectivity produced with ion polishing [13] we expect a value $\eta = 1$ for the next flight with a resolution potential of 0.3 arcsec. A collection efficiency of 5 would be required for a resolution of 0.1 arcsec for 1 min observation time, and this would require multilayer mirrors with boundaries of $\sigma < 2.5\text{\AA}$, or larger mirrors.

An improvement in the resolution of a telescope requires a detector that matches the required resolution and sensitivity. There is at the present time a gap in the commercially available films in the

range from 400-1000 lines/mm resolution. Matching the instrument to existing photographic films requires a telescope with larger focal lengths. However, $f = 2\text{m}$ is close to the limit of the payload lengths of a sounding rocket, and a folded system like a Ritchie-Chretien as we used in our first flight suffers from the reflection loss in the second mirror.

We conclude that the available photon flux will permit us to reach a resolution around 0.3 arcsec in the next flight and that 0.1 arcsec represents the optimistic limit that one could hope to achieve with a sounding rocket at $\lambda = 63.5\text{\AA}$. Some emission lines at longer wavelengths are more than a factor 10 stronger than the FeXVI line at $\lambda = 63.5\text{\AA}$ and should easily provide the photon flux required for 0.1 arcsec resolution. However, the photos [1] obtained at these wavelengths up to now have a lower resolution than those obtained at $\lambda = 63.5\text{\AA}$.

4. MECHANICAL STABILITY AND ALIGNMENT

For observations from sounding rockets the telescope has to be assembled, aligned and focussed on the ground in such a way that the changes in environment and the severe vibrations during launch do not change any critical parameter. For the Ritchie-Chretien telescope the position of the secondary mirror is the most critical parameter; the error in this position has to be within $\pm 4\text{ }\mu\text{m}$ for a resolution of 0.1 arcsec for our design. For the prime focus telescope as used in 1989 ($f = 2\text{cm}$, diameter 25cm) the film has to be within $\pm 8\text{ }\mu\text{m}$ of the correct focus for the same resolution.

The mechanical design of our payload has been described previously [18]. The secondary mirror, or the camera in the prime focus geometry, are held in position by a carbon fiber/epoxy tube with a thermal expansion coefficient of $0.9 \times 10^{-6}/\text{C}^\circ$. The tube is shielded with Al foils against the influence of humidity changes. A heat shield between this tube and the rocket skin isolates the rocket skin from the telescope. The temperature of the heat shield rose by 1°C during our last flight, while the temperature changes of the epoxy tube were smaller than 0.1°C . We conclude that the thermal stability of our telescope is well within the requirements, even for a resolution below 0.1 arcsec.

Focussing of the telescope is a major effort. The depth of focus is considerably larger for visible light than for soft x-rays. We used the arrangement in Fig. 8. The coordinates of the test pattern in the film plane and its return image were measured using an indicator on the microscope. After a measurement series the thickness of a shim plate in the camera mount was adjusted to move the return image into focus at the film plane. With about 100 focus readings we were able to focus the instrument to within $\pm 5\text{ }\mu\text{m}$; this error is sufficiently small for a resolution of 0.1 arcsec.

Fig. 8. Focussing of the telescope. A test pattern in the film plane is incoherently illuminated and the microscope is focussed on the test pattern and the image of the test pattern returned from the flat mirror.

5. ROCKET POINTING STABILITY

The "Solar Pointing Attitude Rocket Control System" (SPARCS) has been developed for solar observations from sounding rockets over the last three decades [19, 20]. The fine sun sensor contains two masks, one behind the other: the front mask has a square opening in the center and the back mask has with 4 openings in the penumbra of the front mask, and a detector behind each opening. Perfect pointing is defined by equal intensity for each detector. A magnetometer and a Rate Integrating Gyro (RIG) measure the roll of the spacecraft and jets of Freon gas are used for control. The specification for the system was ± 1 arcsec/min until 1989 and it appears from our photos that the actual performance was better. Recent tests have shown a jitter well within 0.5 arcsec peak to peak and efforts to reach 0.1 arcsec are under way. It appears probable that the pointing stability will match the progress in the performance of telescopes for the next few years.

Free-flying spacecraft, such as the Hubble Space Telescope, use gyro assemblies for stabilization with the capability of better than 0.01 arcsec fine-pointing stability [21]. Photon flux limitations will require the use of longer observation times and larger telescopes than are possible with sounding rockets for resolutions in the 0.01 arcsec range. We conclude therefore that the performance of future soft x-ray telescopes will not severely be limited by the available pointing stability.

6. SUMMARY

Normal incidence soft x-ray telescopes with multilayer coatings have achieved sub-arcsecond resolution in photos of the corona of the sun from sounding rockets flights. Improvements in future flights can be expected. Resolutions better than 0.1 arcsec will require the use of satellites, where larger telescopes and longer observation times can provide the required number of photons. For the characterization of mirrors for diffraction limited performance it is necessary to measure deviations from the ideal surface with precision in the $1\text{\AA}$ -range for spatial periods covering the range from 10cm to $1\text{\AA}$, and we are presenting measurements over this range. The highest spatial frequencies affect mainly the reflectivity of the mirrors and several methods give results that are consistent with each other. It is much more difficult to measure the long spatial period ($\Lambda = 1\text{cm}$ to 10cm) figure errors with the same precision, and all our measurements in this range represent mainly the noise of the instruments and are upper limits on the figure errors of the optics. The performance of interferometers will have to be improved to reach the required precision.

Flights on sounding rockets will be limited to a resolution of 0.1 arcsec and it appears to be possible to maintain the mechanical tolerances on a telescope assembly throughout the launch and flight. Resolutions in the 0.01 arcsec range will require satellites with in-flight alignment (focussing) of the instrument. A comparison of the contrast of our photos with the measurements of the surface topography of the mirror surface demonstrates the reduction in the relative scattering from a multilayer mirror compared to that of a single surface.

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