NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOR

DEVELOPMENT OF HIGH THROUGHPUT X-RAY TELESCOPES FOR X-RAY IMAGING AND DISPERSIVE SPECTROMETERS

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1.0 Introduction

A new phase of the program supported by NSG-5138 began this year following the submission of a proposal. It extends the program for a period of three years that lasts until November 30, 1988. During this past year we have concentrated upon certain technical approaches that were described in the proposal submitted in August 1985 and have discarded others. In addition, a significant fraction of the year's effort was devoted to the development of two concepts for Explorer type X-ray astronomy missions.

The following topics are discussed in this progress report:

(1) Mirror Development,
(2) Spectroscopy,
(3) All Sky Telescope,
(4) Explorer Concept Studies.

2.0 Mirror Development

2.1 Introduction

During the past year our technical approach to the realization of a high throughput Kirkpatrick-Baez X-ray mirror became better defined in terms of construction methodology and factors which affect maximum size. More progress was made than anticipated in the area of automatic figure formation (see below). However, efforts to improve the resolution of float glass by simple techniques were not successful. Several topics are discussed individually below.

2.2 Automated Figure Formation

We completed all our goals in the area of automated figure formation, or more precisely, computer controlled tuning of a flat plate to a parabola of the desired curvature. With hardware supplied by the LAMAR program, which has an immediate need for the methodology, we developed the software and practical techniques for optimizing the figure of a plate. The figure is adjusted at eight points, four along the top of the plate and 4 along the bottom. From the time that tuning control points are attached until the figure is optimized some 40 minutes pass without human intervention. The precision of the system is believed to be better than 10". A paper describing the system was presented at the Orlando, FL (1986) meeting of the SPIE and is attached as Appendix A.

2.3 Improved Angular Resolution

We are investigating methods for improving the angular resolution of a Kirkpatrick-Baez mirror. The principal limitation is the flatness of the present material, selected commercial float glass. We attempted two procedures for improving the flatness of the glass. Unfortunately, neither was successful. One, float glass was set upon a flat steel base and heated in an oven to temperatures below melting in the hope that the increased flow would smooth the irregularities. Although not entirely unexpected, results were opposite to what was hoped for. Surface irregularities grew in the elevated temperature environment, probably due to relief of internal stress. It is possible that higher temperatures and longer curing times would yield better results but that would have required more elaborate equipment and a greater effort and cost than we were able to expend.

The other procedure consisted of starting with a thicker piece of float glass than the final product and reducing it with a grinder-polisher. Thicker samples are generally flatter and there was reason to believe that the flatness would be preserved as it was made thinner. A small purchase order was issued to an optics company to attempt to grind a 125 mil sample to 70 mil on their unique polishing apparatus. This was also not successful as the sample was more distorted after grinding than before.

Another procedure was investigated conceptually and preliminary plans were made to implement it. However, it was not attempted because of cost and difficulty. This procedure consists of melting the float glass completely and allowing it to "refloat" upon stationary liquid tin. The idea is that the liquid would be stress free and solidify to a perfect flat. Telephone discussions with float glass industry technical personnel indicated that the refloated product would assume a thickness of 250 mils which is much too thick for our purposes. Because of this and the fact that we lack the facilities to carry out this process, we were discouraged from pursuing it at SAO. However, we did make a plan to carry it out in collaboration with the Optical Sciences Laboratory at University of Arizona. We have not implemented it.

2.4 Larger Mirrors

Analytic studies were carried out of possible problems arising from attempting to make Kirkpatrick-Baez mirror plates larger than the present 12" x 20" size. The conclusion is that we should not attempt to make a float glass plate any wider (i.e. distance between top and bottom edges) than 12". The length of the plate may be increased arbitrarily along the optic axis. However, practical experience suggests that it will be increasingly difficult to select acceptable float glass flats as we increase the length requirement.

2.5 Titanium Backing

In previous reports and publications, we had described a process for precurving a plate to nearly the correct radius of curvature by applying a rolled titanium backing. However, over the past year, we found that by and large the process has more negative than positive features. Results are too unpredictable and the backing more than doubles the cost of fabricating a mirror. Having gained a better understanding of how to select and assign glass plates to optimum positions in the mirror module according to their overall curvature we found that we were able to obtain satisfactory angular resolution without a pre-curving titanium backing on the plates. We also gained a much better understanding of the benefits and drawbacks of the pre-curved backing. They would still be required for attaining the highest angular resolution. However, the backing would be better as a smaller strip confined to the central region of the plate rather than encompassing the entire plate.

3.0 Dispersive Spectroscopy

The progress of the past year was mostly in the conceptual and analytic aspects of the problem of developing an optimum configuration of dispersive spectroscopy. Laboratory measurements were carried out successfully at the University of California, Berkeley but mostly at the lower energy end of our range of interest.

The baseline approach to dispersive spectroscopy has been refined. Four configurations were considered conceptually. All involve the use of blazed reflection gratings. They are: (1) uniform ruled gratings in the conical mode in front of the telescope, (2) uniform ruled gratings in the normal mode in front of the telescope, (3) variable spaced ruling in the conical diffraction mode behind the telescope, and (4) variable spaced ruling in the normal mode behind the telescope. Number (1) was the approach that was emphasized in last year's progress report. With the passage of a year we now favor number (4) as the baseline approach. This is the "alternative design" described in the proposal submitted last year. It has the advantage of not being subject to degradation of resolution off the principal wavelength as do (1) and (2). It should have higher resolution than (3) because of apparent spacing of the lines is small due to the projection effect at small angles of incidence.

We realized during this past year that configuration (4) has another feature that could turn out to be of great practical importance. The reflection gratings intercept only 50% of the radiation passing through the mirror and displace the focus several degrees. The remainder of the flux is imaged as if the gratings were not present. That is, there are two images that are well separated, one is dispersed and the other is normal. By using two detectors the system can do both imaging and spectroscopy simultaneously without requiring changes in configuration or moving parts. This is a great simplification given that the gratings will be massive and difficult to move out of the way when the "objective of the observation" changes from spectroscopy to imaging. This is illustrated in figure 1.

4.0 All Sky Telescope

During the past year, a detailed ray tracing code was developed to investigate the performance of the all sky camera in the focussing direction. The all sky camera is described briefly in the proposal and in the progress report of 1984. All possible paths for the X-ray were considered and the reflection efficiency of gold as a function of energy and angle was included.

Every azimuthal direction is equal a priori to every other which requires that both faces of the reflectors function. Rays experiencing one (or three) reflections in the case of very soft X-rays are focussed to a common azimuthal angle on the detector surface. Some rays near the center of the incident beam arrive at the detector without being reflected. The very center of these straight throughs add to the focussed image; the rest become side lobes of the image. Rays experiencing two reflections are deviated only slightly from their incident direction and are an additional side lobe component. They are not significant at the higher energies. A mirror system of the following dimensions was studied with the ray tracing code:

R:	Main radius (distance to center of reflector)	120 cm
L:	Length of reflectors	20 cm
T:	Thickness of reflectors	0.0127 cm
	Reflector surface material	gold
A:	Angular separation of reflectors	6 arcmin

H: Length of the mirror and detector along axis 200 cm

The effective area of this mirror system is shown in figure 2. With a 50% open coded aperture and assuming the source directing is perpendicular to the axis of the cylinder the effective area of the image prior to the detector is 350 cm^2 at 0.25 KeV, 200 cm^2 at 2 KeV, 150 cm^2 at 5 KeV, and about 70 cm^2 at 10 KeV. The point response of the mirror system at 7 KeV and 2 KeV is shown in figure 3-3. The two are not identical because the relative contribution of the side lobes resulting from the straight through rays, with respect to their focussed intensity are different.

The angular resolution, defined as the full width at half maximum of the image, is 7 arcminutes. The total power in all side lobes, off-center straight throughs plus doubly reflected rays, is 50% of the power in the focussed image in the 2-6 KeV band and about 75% at 0.2 and 10 KeV. However, the average power in any one side lobe is only about 3% of the image. The principal effect of the side lobes is to increase the diffuse X-ray background by 50% and reduce sensitivity in the vicinity of strong sources. The effective area falls to about 50% of the zenith value at 45 degrees to the cylinder axis and to 25% at 30 degrees. The net effective area, including the detector efficiency (determined by the window transmission) is shown in Figure 2. The point response in the focussing dimension is shown in Figure 3.

5.0 Explorer Concepts

5.1 Introduction

A considerable amount of effort was devoted to the development of two concepts for Explorer Missions. That were eventually submitted in response to a NASA "Dear Colleague" letter inviting proposals for Explorer concept studies. The titles of the two concepts are:

(1) "A High Throughput X-ray Spectroscopy and Wide Field Imaging Explorer",

and

(2) "All Sky Supernova and Transient Explorer (ASTRE)."

Both concepts include complete payloads for Explorer type missions. They are innovative and have unique capabilities for performing X-ray astronomy measurements. Each is compatible with the Explorer programs in terms of size and cost.

5.2 The High Throughput Spectroscopy Explorer

This payload is based on the method of spectroscopy and imaging described in section 3. It is illustrated in Figure 1. Its properties are summarized in table I and the effective area as a function of energy is plotted in Figure 4.

The high throughput X-ray spectroscopy and imaging Explorer could be built using existing technology at a cost well within the typical Explorer budget. This Explorer would be capable of unlocking the enormous scientific potential of

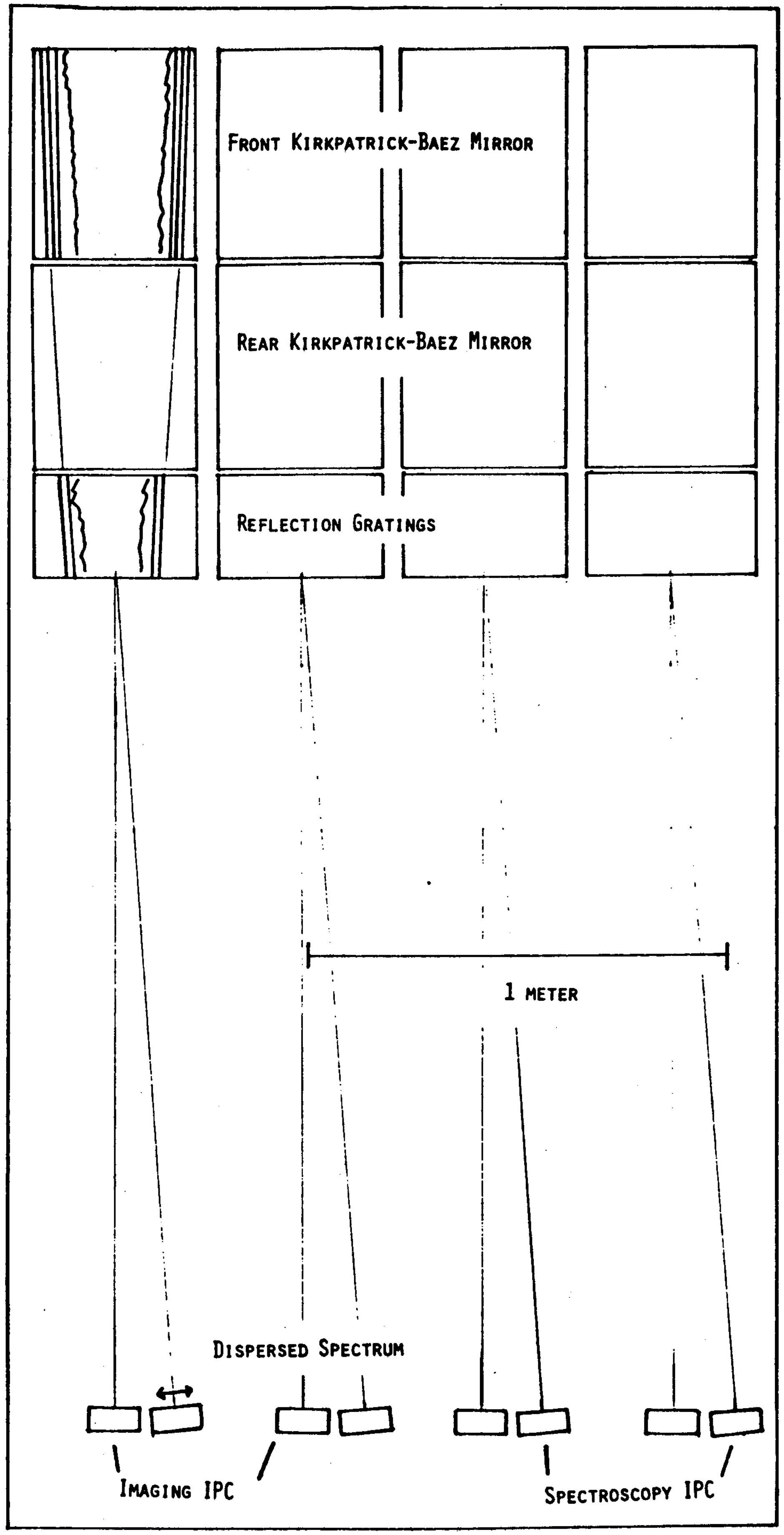

Fig. 1 Side view of configuration providing Spectroscopy and imaging. Four modules are shown.

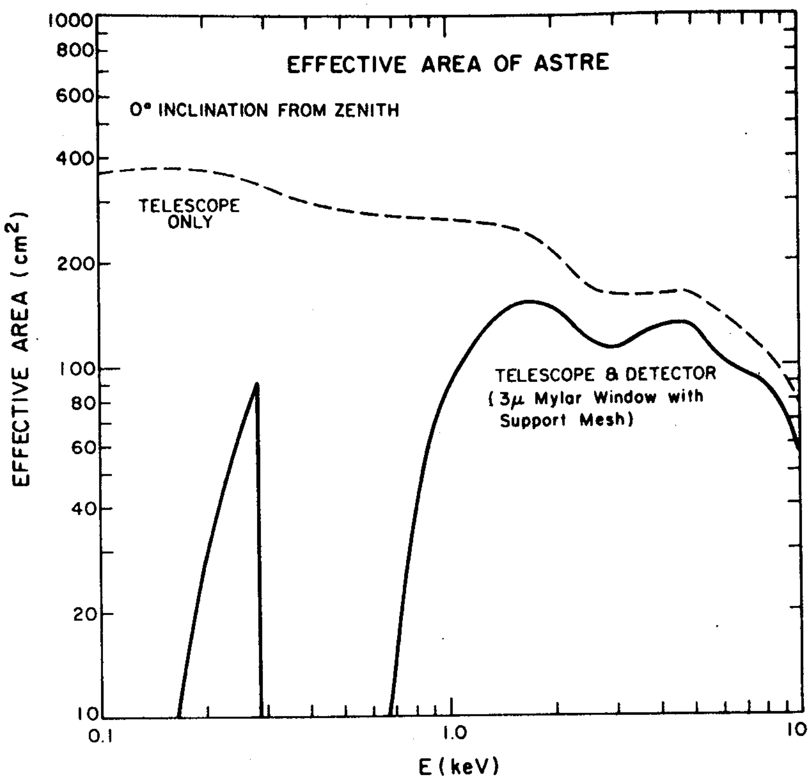

Fig. 2 Effective area of ASTRE's all sky camera as determined by ray tracing program. The reflectors are gold.

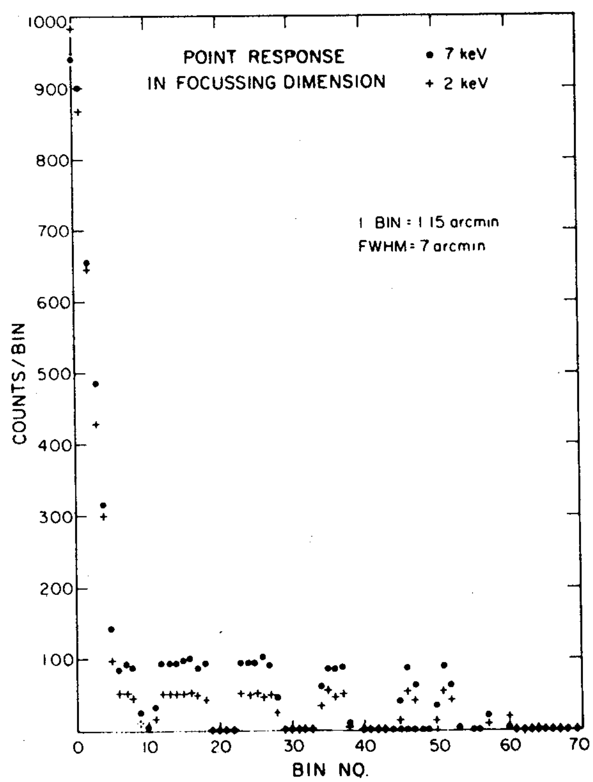

Fig. 3 Point response of the all sky camera in the focussing dimension at 7 an(2 KeV. There are sidelobes outside of the focussed image due to straight througl rays.

TABLE 1

CHARACTERISTICS OF THE SPECTROSCOPY-IMAGING EXPLORER

Energy range (imaging)	0.1 - 10 keV		
Energy range (spectroscopy)	0.4 - 2 keV		
Effective area (imaging)	$1400\ cm^2$ at 1.5 keV		
	$140\ cm^2$ at 6.0 keV		
Effective area (spectroscopy)	keV	Å	cm^2
	0.38	32	100
	0.62	20	315
	1.03	12	585
	1.55	8	540
	2.07	6	85
On-axis angular resolution (mirror plus detector)	35″ at 1.5 keV		
Dispersive Spectroscopy resolution	$E/\Delta E$ = 100 to 200		
IPC detector energy resolution	3.0 at 1 keV		
	5.3 at 6 keV		
Imaging sensitivity in 10^4 seconds (AGN spectrum)	2×10^{-14} ergs $cm^{-2}\ s^{-1}$ (0.2 to 8 keV)		

high resolution soft X-ray spectroscopy (6 to 20 Å) with an effective area of ~500 cm^2 and a resolution E/ΔE of ~150. simultaneous high throughput imaging observations (~1400 cm^2 at 1.5 keV) could be carried out over a 1° field of view and a 0.1 to 10 keV bandwidth. Although this instrument has a very substantial capability and is large, the cost of developing it will be much less than previous large instruments, such as HEAO, and quite compatible with an Explorer budget. It is a single instrument that is constructed from modular, low-cost, simple subunits. It has its own spacecraft frame for accommodating MMS components. Most of the technology has already been demonstrated during the development of a Space Shuttle experiment, LAMAR, for the SHEAL III mission.

5.3 All Sky Supernova and Transient Explorer (ASTRE)

The principal instrument of this payload for an Explorer satellite is the all sky camera described in section 4. It also contains two other detectors to record the hard X-ray and gamma-ray spectrum of transients. One of these detectors is the position sensitive fluorescence gated hard X-ray spectrometer that was described in a previous progress report.

The Explorer Payload concept is known as ASTRE. ASTRE combines high sensitivity, good angular resolution, and very broad field of view to a much higher degree than ever before. The night sky (77%) is imaged semi-continuously in the 0.2 to 10 keV band. Other detectors without directionality extend the spectral band to 10 MeV for spectro-photometric studies of bursts and transients. ASTRE can detect many Type II supernova explosions per year if prompt soft X-ray flares are near predicted levels. ASTRE will carry out a large number of other important scientific investigations in parallel by simultaneously observing the temporal behavior of many objects ranging from quasars to stars across the entire night sky. The scientific investigations include active galactic nuclei, comprehensive studies of gamma-ray and X-ray bursters including the determination of precise positions, as well as studies of binary X-ray sources and stars on all time scales ranging from sub-millisecond to the duration of the mission. Furthermore, ASTRE's unique combination of properties makes it more likely than any other X-ray instrument to make discoveries of new temporal behavior. ASTRE's mechanical configuration is fixed and the instruments are always oriented in the anti-solar direction.

The payload concept is illustrated in Figure 5. The experiment properties are summarized in Table 2.

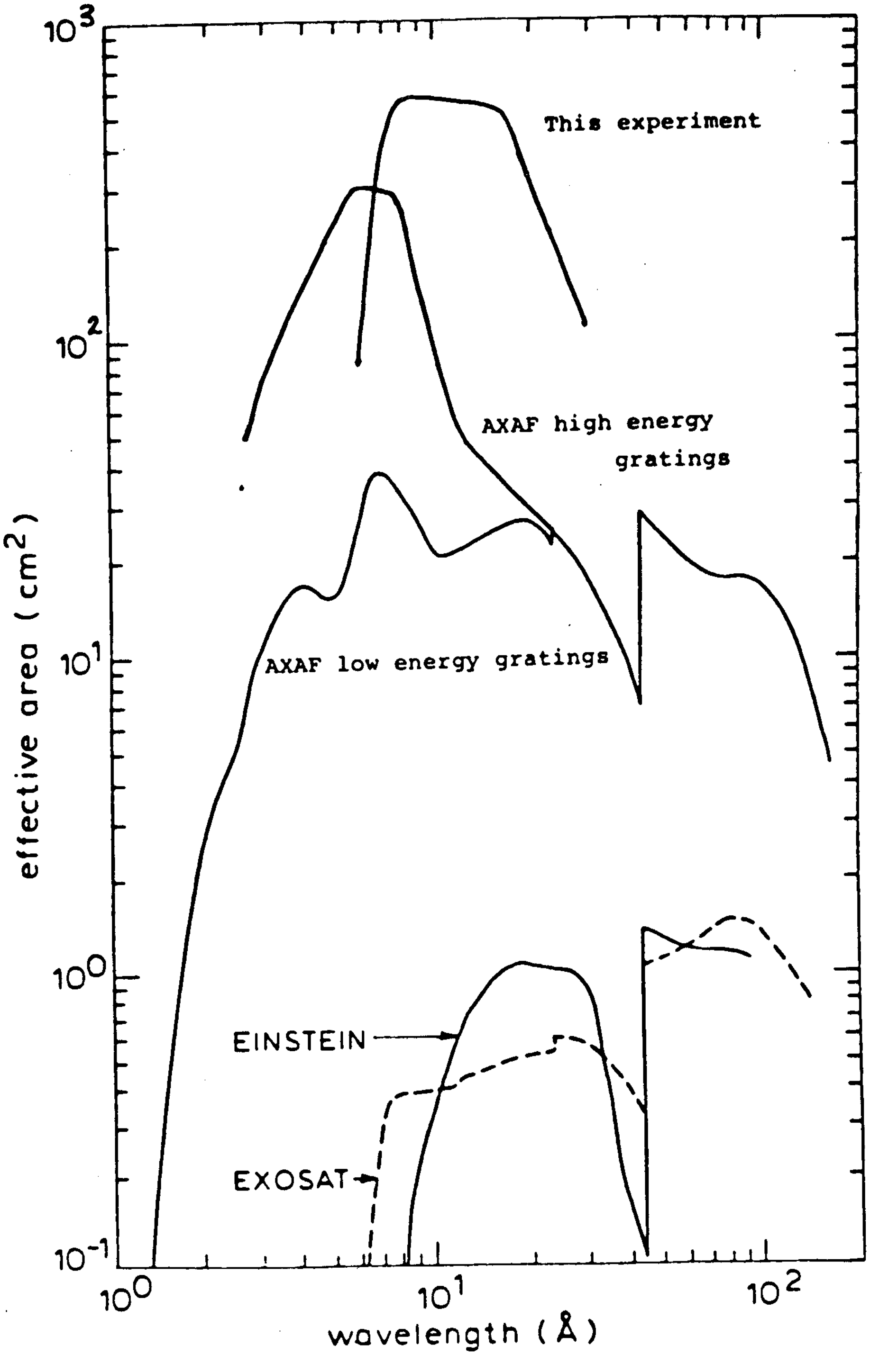

Fig. 4 Effective area for dispersive spectroscopy (including detector efficiency) offered by this Explorer and other instruments.

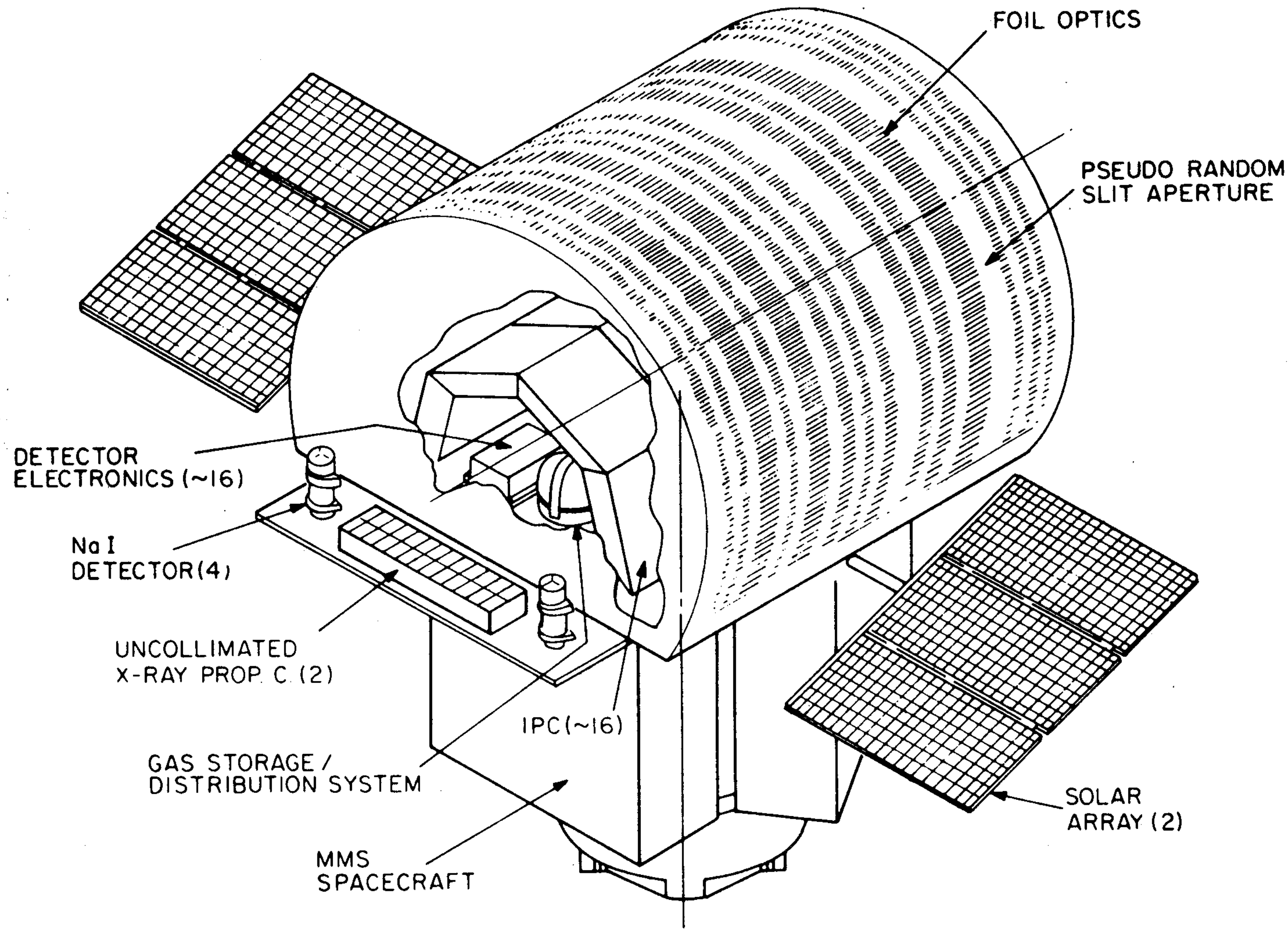

Fig. 5 ALL SKY SUPERNOVA AND TRANSIENT EXPLORER (ASTRE)

Table 2

CHARACTERISTICS OF THE ALL SKY SUPERNOVA AND TRANSIENT EXPLORER (ASTRE)

EXPLORER MISSION CONCEPT

Technical Summary

Major Instruments:	All Sky X-ray Camera Hard X-ray Spectrometer Gamma-ray Spectrometer
Spacecraft Option:	Explorer Bus (MMS)
Mechanical Configuration:	Dimensions of Instrument Package 3M x 2.4M x 1.5M: On platform
Weight:	2000 Kg
Power Requirements:	1200 watts (average)
Pointing Requirements:	Anti-solar orientation of instruments
Data Rate:	50 Kb/sec minimum up to 1.2 Mb/sec desirable

Automated Figure Formation for a Kirkpatrick-Baez X-ray Mirror

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Abstract

An automated figure formation system for Kirkpatrick-Baez geometry grazing incidence X-ray mirrors is described. The system is based on an IBM PC/XT microcomputer and utilizes primarily commercially available equipment. The mirror assemblies currently being manufactured for the LAMAR experiment attain an angular resolution of ~30″ (50% power diameter) on axis. The angular resolution is limited by the float glass used for the mirror plates, not the figure formation process.

Introduction

The first of eight identical X-ray mirror assemblies for the LAMAR experiment is nearing completion. The LAMAR experiment is designed to fly aboard the Space Shuttle, mounted in a two axis stabilized pointing system. The LAMAR experiment is designed to obtain X-ray images in the 0.15 to 8.0 keV energy range, with an angular resolution of 30″. Modifications to add a dispersive spectroscopy capability are anticipated. The effective area per assembly is 150 cm^2 at 0.28 keV, 100 cm^2 at 2 keV, and 23 cm^2 at 6 keV.

The mirror assemblies are constructed from nested sheets of float glass bent to a parabolic shape and arranged at grazing incidence in two orthogonal modules, in what is commonly known as the Kirkpatrick-Baez (or K-B) geometry. Each mirror assembly for the LAMAR experiment will have an aperture of ~20 cm by 30 cm, with an overall length of slightly more than 1 m. The distance from the front of the assembly to the focal plane is 3.4 m. There are 32 individual float glass plates measuring 20 by 50 cm in the front module, and 22 plates measuring 30 by 50 cm in the rear module. The plates are each 1.8 mm thick and are coated with 500 Å of gold upon a 500 Å undercoat of chromium. The theoretical on-axis resolution of the mirror assembly is ~10″, although imperfections in the best available float glass limit the actual performance to a 50% power diameter of ~30″.

The K-B design is attractive because it allows the construction of large area, moderate resolution X-ray mirrors from inexpensive materials at moderate cost. Because float glass has a surface finish of ~5 Å as manufactured, no polishing is required, and mirror construction reduces to the problem of bending the individual mirror plates to the correct shape and then bonding them in position. The radii of curvature of the plates range between 250 and 2500 m, and the plates have one dimensional projected apertures between 1.5 mm and 11 mm.

Introduction to Figure Formation

The forces and physical displacements required to form the figure of the mirrors are quite modest, less than 1 Newton and 0.1 mm respectively. The bending force is applied to the plates at four positions along the top and bottom of the plates, at both ends and 12.5 cm in from the ends. Small clips (2.5 cm long) are bonded to the mirrors at these points, and rods extend from the clips through 6 mm diameter holes in the side of the mirror boxes. An additional two clips are bonded at the midpoints along the top and bottom of the plate, and rods extending from these clips are bonded into the mirror box. The plate is free to rotate about these pins, but is prevented from translating. The bending force is applied to the eight moveable pins by linear translation stages driven by precision linear DC motors. A 1 μ displacement of a pin results in ~3″ deflection of reflected light; however the linear motors exceed this performance by well over an order of magnitude. A diagram of the mirror bending apparatus is shown in Figure 1.

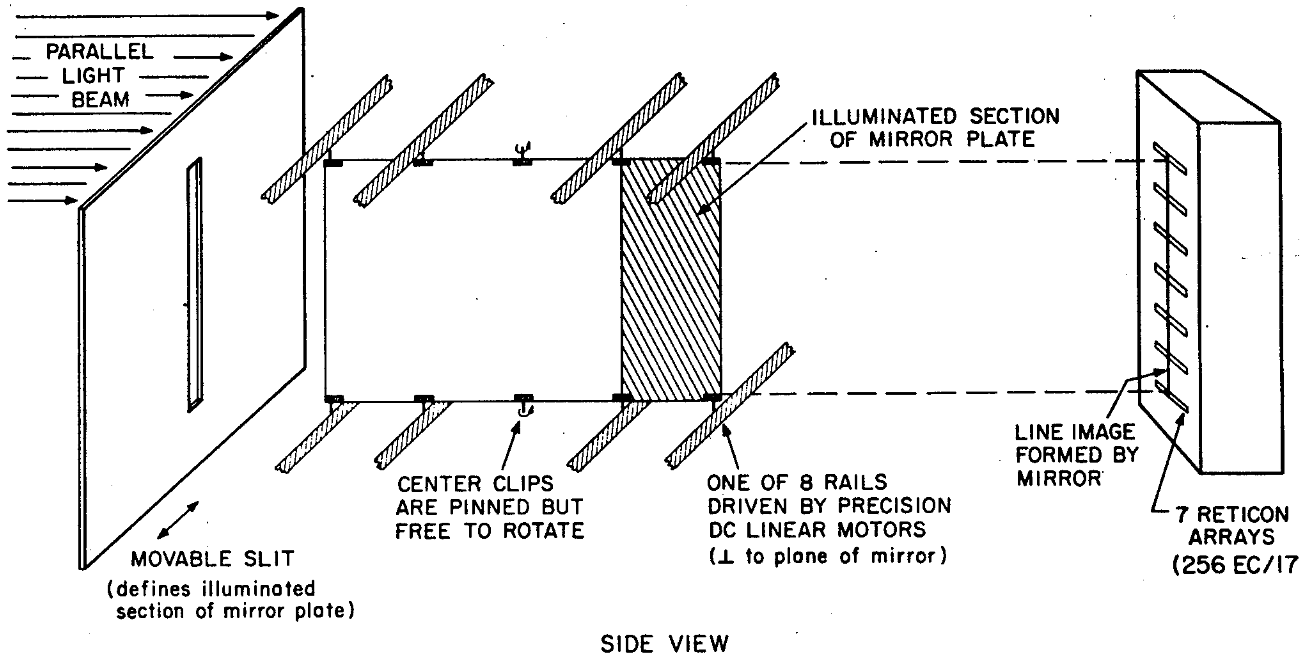

Figure 1. Diagram of Tuning Apparatus.

The figure of a single plate is adjusted at a given time by observing the image of a parallel light beam (6328 Å) reflected from that plate. The front and rear modules are adjusted separately with the plates held vertically to avoid gravitational deformations. Because the plates have projected areas as small as 1.5 mm, diffraction of the visible light beam typically dominates the image width. We therefore adjust the figure by observing the position of the centroid of the line image formed by reflection from a quarter of the plate at a time. The line image is sampled at seven points along its length with photodiode arrays (EG&G Reticon type 256EC/17). The Reticons have 256 25 μ wide channels, spaced by 50 μ, giving a total coverage of 1.3 cm at the focal plane. Integration times of 0.1 sec are typically required. Figure formation is accomplished iteratively, by illuminating the front quarter of the plate and adjusting the pins at the front of the plate, followed by illuminating the rear quarter of the plate and adjusting the pins at the rear of the plate. The inner quarters of the plate are adjusted next with the inner pins. The adjustment consists of driving the motor until the average of the 7 image centroids falls as close as possible to the center Reticon channels. The upper and lower edges of the plate are adjusted individually but in sequence. Since the adjustments interact, this process is repeated until the overall figure of the plate stops improving, typically 7-8 passes. This sequence is shown in Figure 2. The tuning pins are bonded into position after the process is complete by injecting epoxy into the holes in the mirror box. An epoxy curing time of 6 hours is typically required before removal of the tuning motors.

Automated Figure Formation

There are thus three major components required to form the figure of K-B mirrors by this technique: the Reticons, the linear motors used to bend the plates, and a stepper motor driven moveable slit of variable width used to select the illuminated region. These items are commercially available and the additional hardware required to adapt them to this use is relatively simple. In addition, it is a straightforward matter to interface these components to microcomputers. Since the figure formation process is easily specified and repetitive it seemed natural to attempt to automate the process. This has been accomplished, and human intervention is now only required to attach the tuning pins on the appropriate plate to the tuning motors, and to inject the epoxy after the figure formation is complete.

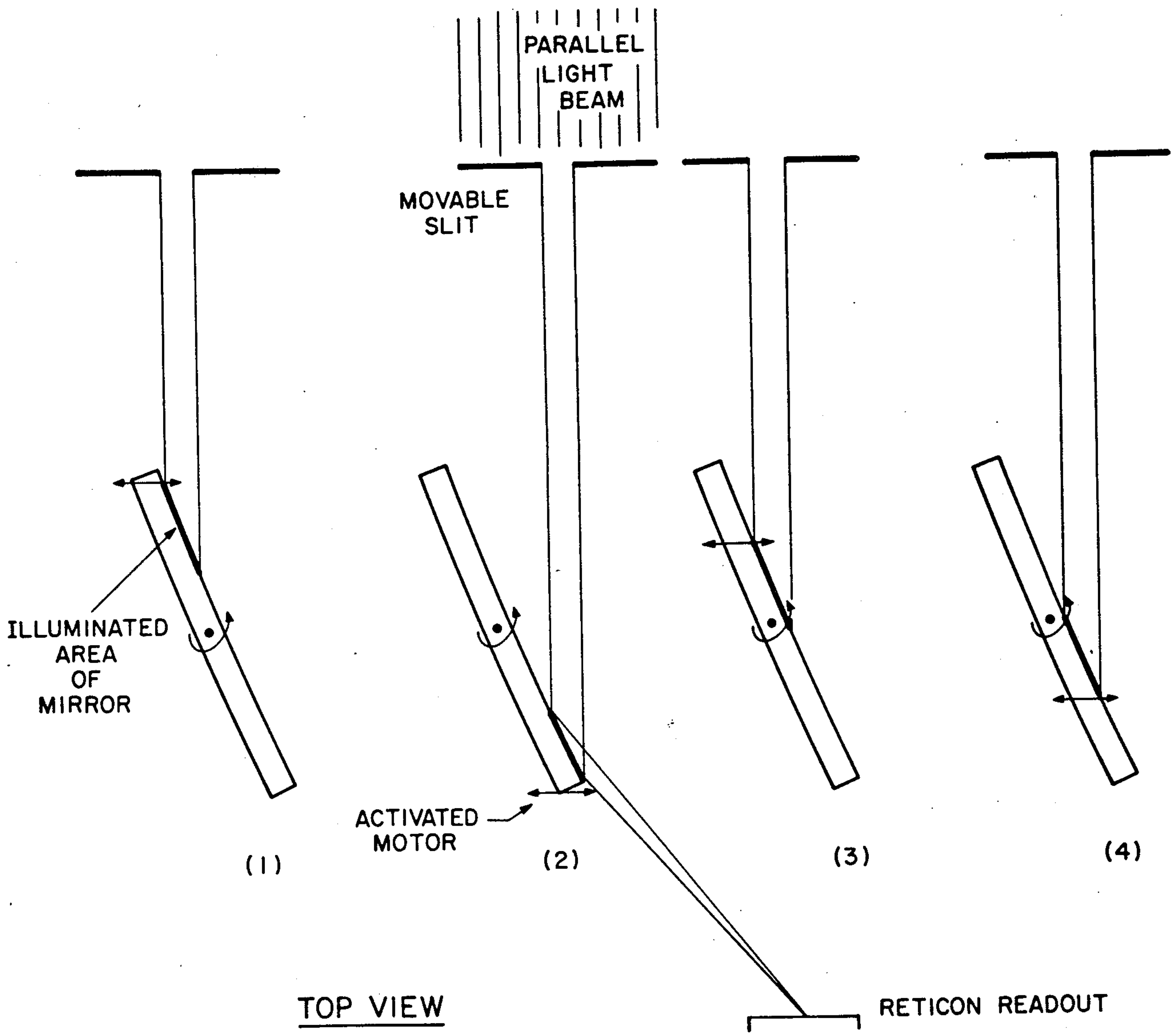

Figure 2. Tuning Sequence.

An IBM PC/XT has been chosen to be the controlling computer, principally due to the availability of accessories for interfacing and software. All communications between the computer and the equipment used for the figure formation is carried out over an IEEE488 bus, with the exception that the Sony Magnescale used to read out the position of the moveable illumination slit uses an RS232 bus. A block diagram of the system is shown in Figure 3. The interfaces for the DC tuning motors and the stepper accept simple mnemonic ASCII codes. The interface to the 7 reticons was partially custom built, but makes use of a commercially available adapter to format parallel data for IEEE488 communications.

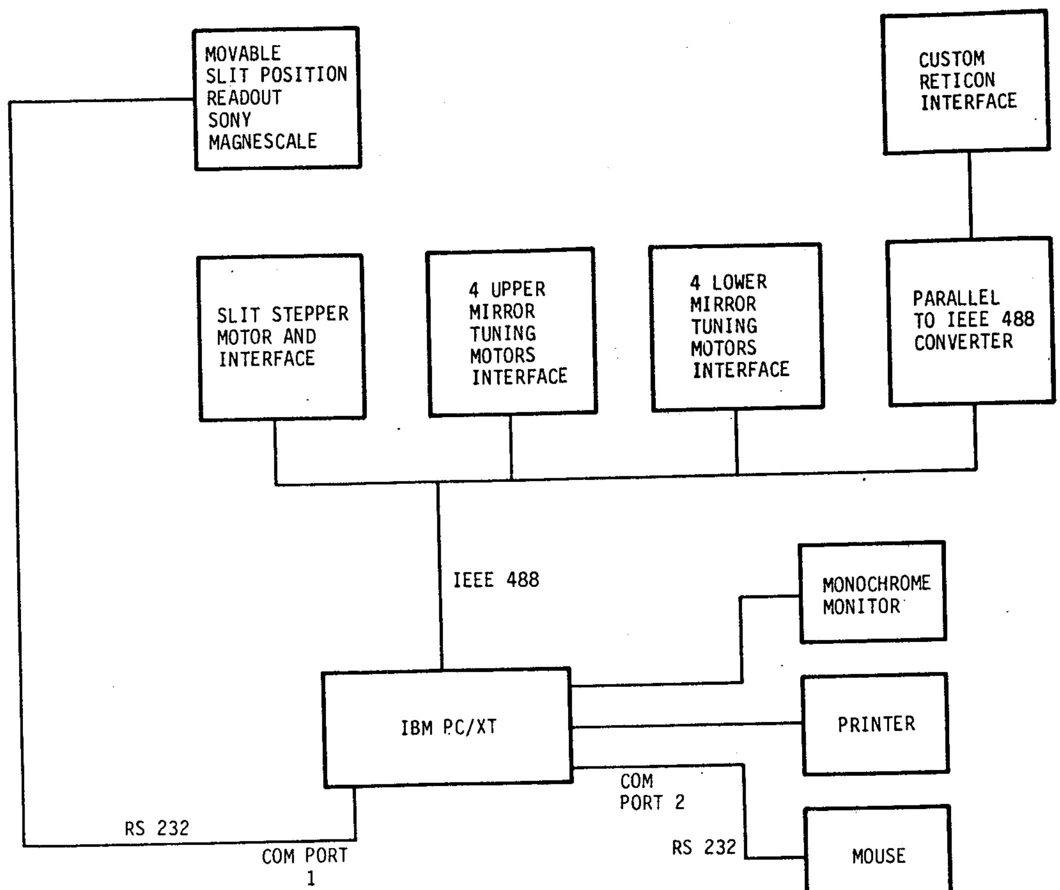

Figure 3. Block Diagram of Tuning System.

The tuning sequence for a given plate goes as following. Before the automatic figure formation begins, the tuning pins from that plate must be attached to the tuning motors, and the position of the plate crudely adjusted so that the light from each of the quarters of the plate falls on the Reticons. The histograms from all 7 Reticons are displayed on the computer's monitor together with centroid data throughout the automatic tuning to allow an observer to follow the tuning process if desired. The computer then moves the illumination slit to the first tuning position and records the mean deviation of the line image centroids in the top 3 Reticons from the central channels. The computer then records the results obtained moving the upper DC motor forward and backward by $\sim$20 μ. If either of the new positions results in a lower average deviation, the motor is driven in 20 μ steps in that direction until the deviation of the image centroids begins to increase. The motor is then returned to the best position. The lower DC motor is then driven in the same fashion, observing the line image centroids in the lower 3 Reticons. The slit is then moved to illuminate the next tuning position. The computer then cycles through the tuning postions for a total of 4 coarse tuning passes, then begins 3 fine tuning passes. Fine tuning is done in much the same way except that the step size is $\sim$5 μ, and the movement of the image centroids in all 7 Reticons is observed.

The entire figure formation process takes $\sim$45 minutes, although this could be speeded up by a factor of 2 by modification of the Reticon interface. More sophisticated tuning algorithms might be conceived, but the technique just described has proven to quite resistant to imperfections in the motor movements, interactions between the tuning positions, and ripples on the float glass surface. The automatic tuning system just described would be capable of forming the figure to a far higher accuracy than the ~30″ level dictated by the float glass. Thus, if a flatter material for the mirror plates were identified, mirrors approaching the theoretical limits of the K-B geometry could be produced simply and rapidly.

Test of Mirror Figure

After a given mirror plate is tuned by the previous technique, it may be scanned in optical light using the same illumination slit used in the figure formation. Depending on the projected area of the plate, up to 20 scans, corresponding to linear slices of as small 2.5 cm along the plate, may be made to measure the figure of the plate. However, the minimum sampling size increases to 12.5 cm for the innermost plates due to their small projected area. Diffraction becomes too severe to attempt finer scans. Thus, a partial assessment of the mirror performance is possible in visible light. A histogram of such optical light scans is shown in Figure 4. An X-ray test at several energies is planned for May 1986.

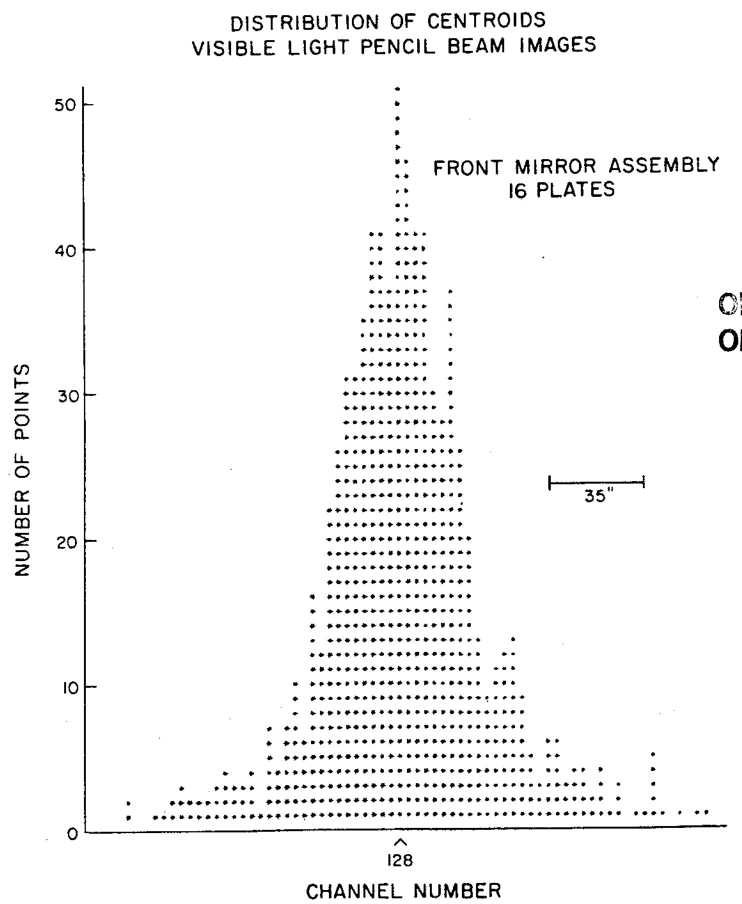

Figure 4.

Conclusions and Future Prospects

The system developed to produce the LAMAR mirrors is quite suitable for the construction of larger mirror modules or many additional modules without added complexity. The cost per mirror assembly of LAMAR dimensions could be expected to drop to ~ \$25,000 in large quantities. Highly skilled labor is not required since the computerized system is capable of providing a detailed mirror production history as well as quality control. A short training period should be sufficient to acquaint a new worker with the system. Thus, a technology to construct effective areas of 50,000 cm^2 with angular resolutions of 30″ at low cost is available and should be given serious consideration for future high throughput X-ray facilities. Effective areas of this size with the high angular resolution (0.5″) Wolter optics of the type proposed for AXAF appear to be unmanageably expensive and would be considerably larger and heavier. If a method of producing large quantities of flatter reflectors is identified to replace the float glass, the resolution of K-B mirrors may be improved to the 10″ level. Angular resolutions in the 10 to 30″ range are sufficient for dispersive spectroscopy with $E/\Delta E$ exceeding 100 with high dispersion reflection gratings now under development.[1,2]

References

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2. Kahn, S, and Hettrick, M, ESA SP-239, p. 237, 1985