RESEARCH OF ADVANCED TECHNIQUES FOR

X-RAY DETECTORS AND TELESCOPES WITH APPLICATIONS TO

ROCKETS AND THE LAMAR FACILITY

NASA Grant NSG-5138

Semiannual Report Nos. 16 and 17

For the Period 1 July 1984 to 30 June 1985

Principal Investigator
Dr. Paul Gorenstein

August 1985

Prepared for

National Aeronautics and Space Administration

Wallops Island, Virginia 23337

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02133

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this grant is Mr. Larry J. Early, Code 1040.0, NASA, Goddard Space Flight Center, Wallops Island Facility, Wallops Island, VA 23337

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1.0 INTRODUCTION

A program for the development of high throughput instrumentation for X-ray astronomy based upon focusing optics is being carried out by the Smithsonian Astrophysical Observatory. The instrumentation is applicable to investigations requiring large area focusing optics for direct imaging or dispersive spectroscopy. The long range goals of this program are the development of telescopes and gratings for future major X-ray astronomy facilities, including additions to the LAMAR OSS-2/SHEAL experiment after the initial flights. Tests of the devices and their more immediate utilization in scientific investigations can be carried out with SPARTAN payloads deployed and retrieved by the Space Shuttle. In fact, in a later section we describe two instruments based upon the work of this program that would be rather unique SPARTAN payloads. However, the present backlog of approved SPARTAN missions is longer than the three-year duration of the program described in this program. Therefore, we concentrate upon laboratory studies and breadboarding of instrumentation. Specific proposals for SPARTAN flights will be made at a later time in response to announcements of opportunity by NASA for new payloads.

The X-ray astronomy communities in the U.S. and Europe have both recommended that a high throughput mission with spectroscopy be given the highest priority as the next major X-ray facility to be developed after AXAF. The high throughput facility should have at least an order of magnitude more effective area than AXAF especially in the higher energy regime around the K lines of highly ionized iron. For reasons of feasibility the high throughput facility will certainly be a modular array of telescopes with moderate angular resolution (like LAMAR). The LAMAR type telescope module that we have developed in this program could possibly be the best technology for the high throughput missions in terms of offering an optimum combination of large effective area and good angular resolution. Indeed, to date, no other technique has succeeded in offering as desirable a combination of good angular resolution, high aperture efficiency and moderate cost. We propose to develop the technology further, to the point where there are breadboard telescopes that are larger and more precise to give credibility to proposals for U.S. and foreign missions. This is applicable to new programs such as a NASA High Throughput Mission or a U.S. contribution to a foreign X-ray astronomy mission such as the ESA XMM or Japan's Astro-D satellites.

Moderate-to-high resolution spectroscopy of cosmic sources at soft X-ray energies (0.3 - 2 keV) is generally considered to be one of the most important frontiers of X-ray astronomy research. Included in this spectral range are the prominent K-shell transitions of all ions of C, N, O, Ne, and Mg, and L-shell transitions of ions of Ni and Fe. The detections of emission and/or absorption features associated with such transitions can provide important diagnostics for physical conditions thought to be appropriate to a wide variety of astronomical objects. As yet, this field is still in its infancy. Although transmission grating spectrometers with modest resolution were flown on both the Einstein and EXOSAT Observatories, the limited effectiveness ($\lesssim$ 1 cm^2) of these instruments restricted their application to only a few of the brightest sources in the sky. In order for soft X-ray spectroscopy to have a truly significant impact on astronomy, vast improvements in sensitivity will be required. To some extent this need will be met by the transmission grating experiments planned for AXAF, however, while AXAF will have excellent resolution, the 100-fold increase in sensitivity they will provide may still not be enough; to obtain adequate statistical quality spectra of "typical" active galaxy sources even larger effective area experiments are necessary.

Indeed, our experience with the *Einstein* and EXOSAT grating spectrometers has shown that statistical quality, even more than resolution, often determines the value of an observation. It is not sufficient to simply detect the strongest spectral features. In order to adequately interpret the data, good measurements of the neighboring continuum and of weaker features are often of critical importance.

In this regard, the high throughput, large effective area is important for soft X-ray spectroscopy. Coupled with a reasonably efficient dispersive system, a LAMAR telescope system would in fact be the instrument best suited for performing moderate-resolution spectroscopic surveys of faint sources. Since spectral resolution degrades essentially linearly with angular resolution for dispersive spectrometers, the limited resolution available with LAMAR is likely to be the principal driving consideration in the design of such an instrument. Clearly, one can maximize the effectiveness by maximizing the dispersion over an appreciable bandpass. As dispersing elements, reflection gratings offer a number of advantages in this respect. In comparison to transmission gratings, they can yield considerably higher dispersion with comparable or higher diffraction efficiency. Unlike crystals, they simultaneously disperse all wavelengths from all parts of the incoming beam. We plan to develop a high throughput dispersive spectrometer based upon a LAMAR type telescope and reflection gratings.

Therefore, the program that we are carrying out extremely relevant to the future needs of the entire X-ray community and is not merely addressing a narrow field of investigations.

2.0 ACCOMPLISHMENTS OF THE PAST ' EAR

2.1 Intrcduction

The activities that took place during the past year was part of a three year program proposed in SAO document P1191-6-82 (June 1982). It has been a laboratory program with the following goals:

(1) improvement of the angular resolution of a Kirkpatrick-Baez telescope;

(2) development of the Imaging Proportional Counter;

(3) studies of a dispersive spectroscopy capability for a LAMAR-type system;

(4) design studies of a mirror/spectrometer rocket payload.

We describe what has been accomplished in each of these areas.

2.2 Moderate Resolution X-ray Mirrors

The accomplishments of the SR&T study were:

1. specification of how to characterize and select glass for flatness by fizeau interferometry and auto-collimator scans,
2. development of a method for pre-curving a flat glass plate into a cylinder whose radius of curvature is approximately that of any given parabola of a Kirkpatrick-Baez mirror assembly,
3. development of a new mechanical design for a tuning system based upon precise linear translators,
4. construction and evaluation of breadboard mirror plates with better angular resolution than before, that demonstrate the effectiveness of the method.

As a result of those improvements, we have arrived at the point where the resolution of the mirror depends mostly upon the flatness of the glass. Hence it is important to have a means of selecting glass. The procedure for characterizing flatness enabled us to select the better glass sheets from a selection of commercial stock fairly rapidly. This is significant because we are now able to purchase large quantities of commercial float glass sheet at relatively low prices and screen the material ourselves. Fizeau interferometry need be applied to only several random samples from a lot of commercial glass to verify that the flatness on a small scale is no worse than 10 wavelengths of visible light per inch. However, it is necessary to make auto-collimator scans of every single plate to select acceptable material. The scanning auto-collimator technique consists of tracing out the path of a pencil light beam from an auto-collimator that is reflected at normal incidence along the entire length of the plate. A perfectly flat plate traces out a horizontal straight line. A uniformly curved plate traces out a line with a finite slope. An acceptable plate will have a root mean square deviation of less than 0.3 arc minute from a straight line and the slope of the line is not greater than 0.1 arcmin/inch. Figure 1 illustrates the interferogram and scanning auto-collimator trace from a good batch of 12" x 20" commercial float glass plate that is 0.07 inches thick. Although the flatness of this material is fairly good, it is desirable to find material that is both flatter and thinner. Flatter material would result in better angular resolution. Thinner material would result in less weight and more useful aperture for the highly nested configurations that are used in grazing incidence telescopes.

One of the important accomplishments of the mirror study was a method for precurving a flat plate into approximately the correct shape without

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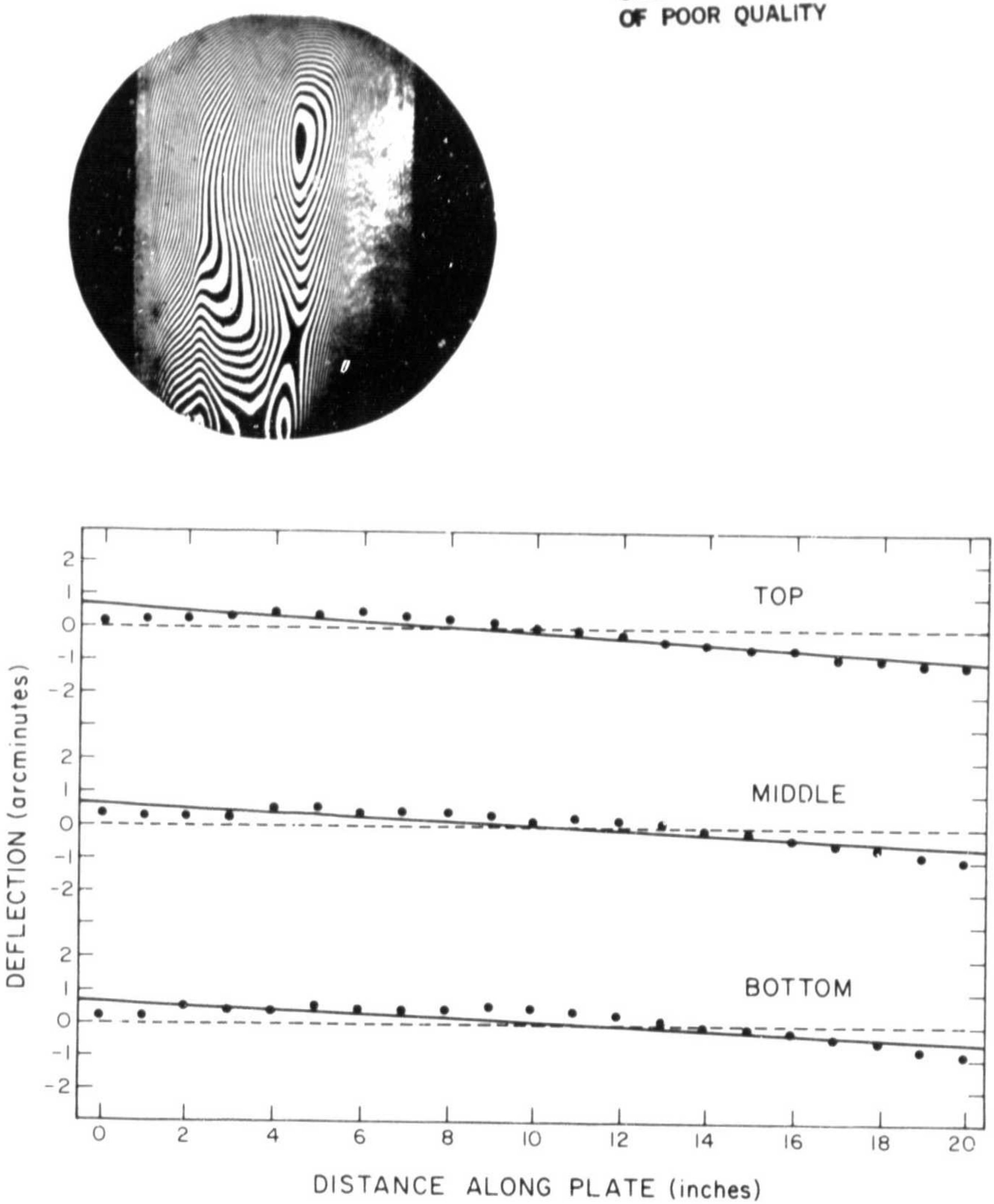

Figure 1. Fizeau interferogram of float glass plate (top). Area shown is 30 cm diameter. Bottom panel shows three autocollimator scans, along the top, middle, and bottom of plate.

concomitant undesirable elastic distortions. Previously, a limitation upon the angular resolution of our mirror system originated from the fact that a mirror plate was given its figure by deforming a flat sheet of glass to a parabola by applying bending moments only along the edges. In that case, there are saddle-like deviations from perfect curvature of the surface because the center of the plate fails to follow the edges perfectly. The project began with experimenting with discrete bar stiffeners that were bonded to the rear of glass plates. These stiffeners succeeded in improving the resolution by about 40% compared to the unstiffened plate. A more significant improvement was achieved by another technique suggested by the Visidyne company. This technique consists of rolling a sheet of .005" titanium whose dimensions match those of the glass plate to a spring with a small radius of curvature, i.e. a few inches or less. When the titanium coil spring is bonded to a .070" thick float glass plate that is initially flat, the compound material assumes a radius of curvature that is about a thousand times larger than the spring. By selecting the initial radius of curvature of the titanium coil appropriately, the final radius of curvature of the compound cylinder is made to be equal to the average radius of the desired parabola. Since the bending force from the titanium coil is applied to the glass over its entire surface, the shape of the compound plate is nearly uniformly cylindrical over its entire width. This is in contrast to the previous system of figure formation where all bending forces are applied to the glass plate only along the edges. Even with this new system it is necessary to tune the plate with small bending forces at the edges (Figure 2) to achieve the desired precision in the final figure. Among other things the tuning process changes the figure from a cylinder to a parabola. However, the bending moments are now very small compared to ones required to deform a flat plate to a parabola and they result in very little lag of the center with respect to the edges. This

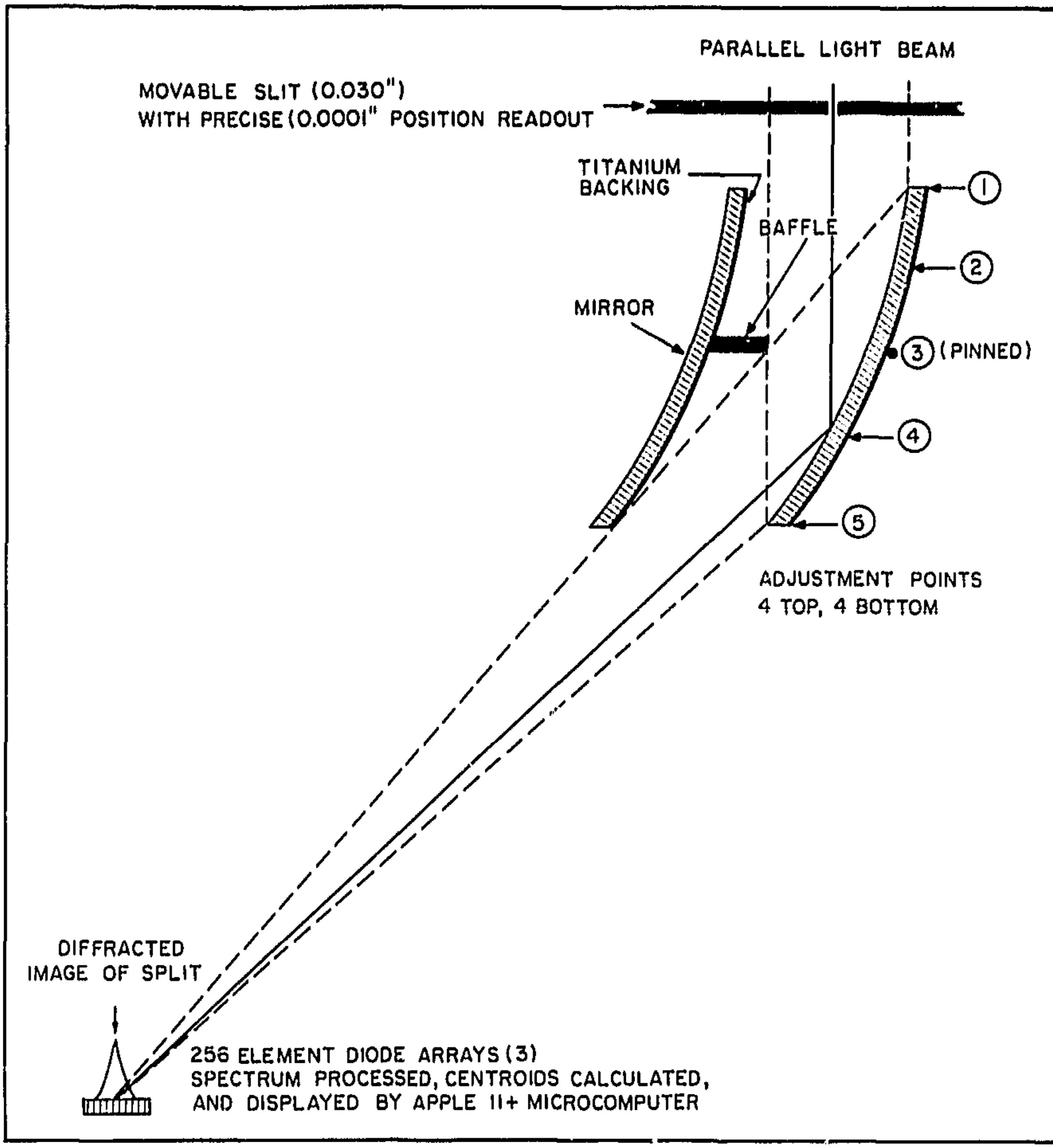

Figure 2. Interactive system for tuning final figure of plate. The points labeled "1", "2", "3", and "4" are driven by precise linear translators. The diode array signals are processed and displayed by a microcomputer.

technique produced better than a factor of two improvement in angular resolution. The limiting factor in the resolution is now believed to be the initial flatness of the glass.

After this technique was successfully tested in a broadboard made under this program, it was applied to the construction of a brassboard mirror that was supported by the LAMAR/OSS-2 program. The brassboard mirror assembly achieved an angular resolution (50% power diameter) averaged over both dimensions of 35 arcseconds. The angular resolution of the LAMAR mirror is shown in Figure 3.

2.3 Imaging Proportional Counter

A major activity of the program has been the development of a state of the art multi-wire position sensitive X-ray proportional counter for the focal plane of an imaging telescope. This aspect of the program culminated in the preparation of a proposal for an instrument for AXAF in response to an AO. A prototype device operating with xenon gas was constructed. With it a series of measurements were carried out in great detail to demonstrate the spatial resolution, spectral resolution, uniformity, and stability of the instrument. The AXAF proposal for "An Imaging Spectrophotometer" contains a comprehensive description of the laboratory measurements. This device is also the prototype for the LAMAR detectors. We were notified in February 1985 that the IPC was not accepted for AXAF. However, there is a possibility that a modified, lower cost version of the instrument would be acceptable.

At this juncture we believe that we have succeeded in attaining our goals with respect to the imaging proportional counter objectives of this program. The device meets the needs of the programs for which it is intended. If these

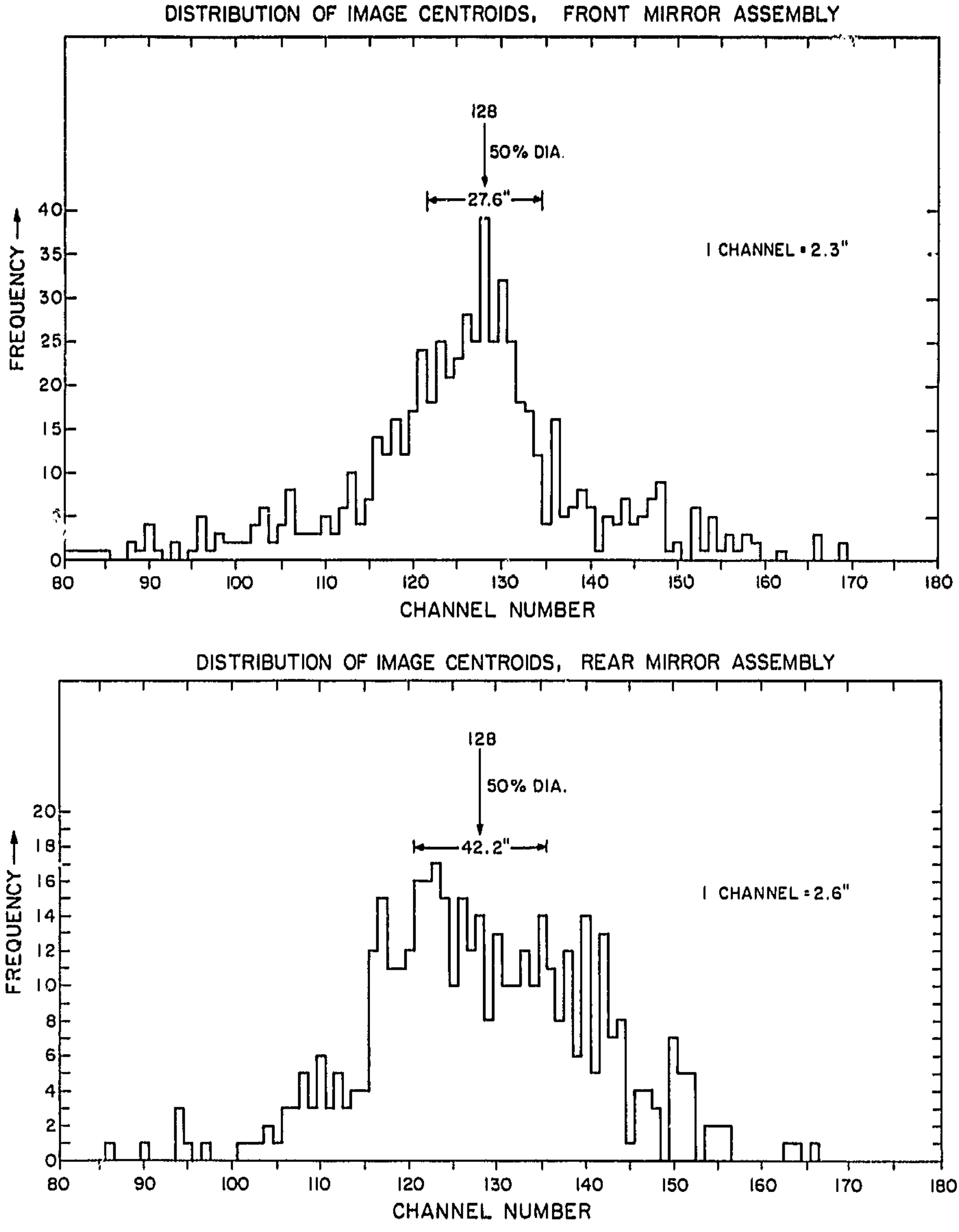

Figure 3. Visible light resolution of the prototype mirror assembly. Each histogram is the distribution of the centroids of pencil light beams reflected through the mirror assembly. The superiority of the front mirror assembly is directly attributable to its being made with flatter plates.

programs choose to utilize this detector, they will support the construction of flight instruments based upon the prototype. No additional detector development work will be proposed for the subsequent three-year program. Some detector work may be needed to support other activities such as telescope and diffraction grating measurements.

2.4 Dispersive Spectroscopy

It is possible to convert an X-ray imaging system to dispersive spectroscopy by the addition of an objective grating. In particular the placement of a reflection grating in front of or behind the mirror appears to be a rather effective method of accomplishing this transition. Reflection gratings offer an important advantage over transmission gratings in connection with moderate angular resolution telescopes. The reflection grating element can provide very much larger dispersion than transmission gratings. This overcomes the limitations of the optics. As part of the current three year program in dispersive spectroscopy, we have carried out a study of the incorporation of reflection gratings into the LAMAR experiment for OSS-2/SHEAL. The design we have chosen to investigate initially is one first suggested by Webster Cash of the University of Colorado (Cash, 1981), in which an array of gratings is placed in front of the telescope as an objective disperser. The gratings are mounted in the conical or off-plane mode, in which the incident light makes a grazing angle, γ, to the grooves, and the diffracted rays lie along a cone of half-width γ centered on the groove direction (see Figure 4). If the grooves are "blazed" to the triangular shape shown in Figure 4, in which each facet is slanted by an angle δ (called the blaze angle), then the grating will exhibit maximum diffraction efficiency for the particular wavelength λ_B (the blazed wavelength) at which the incoming and

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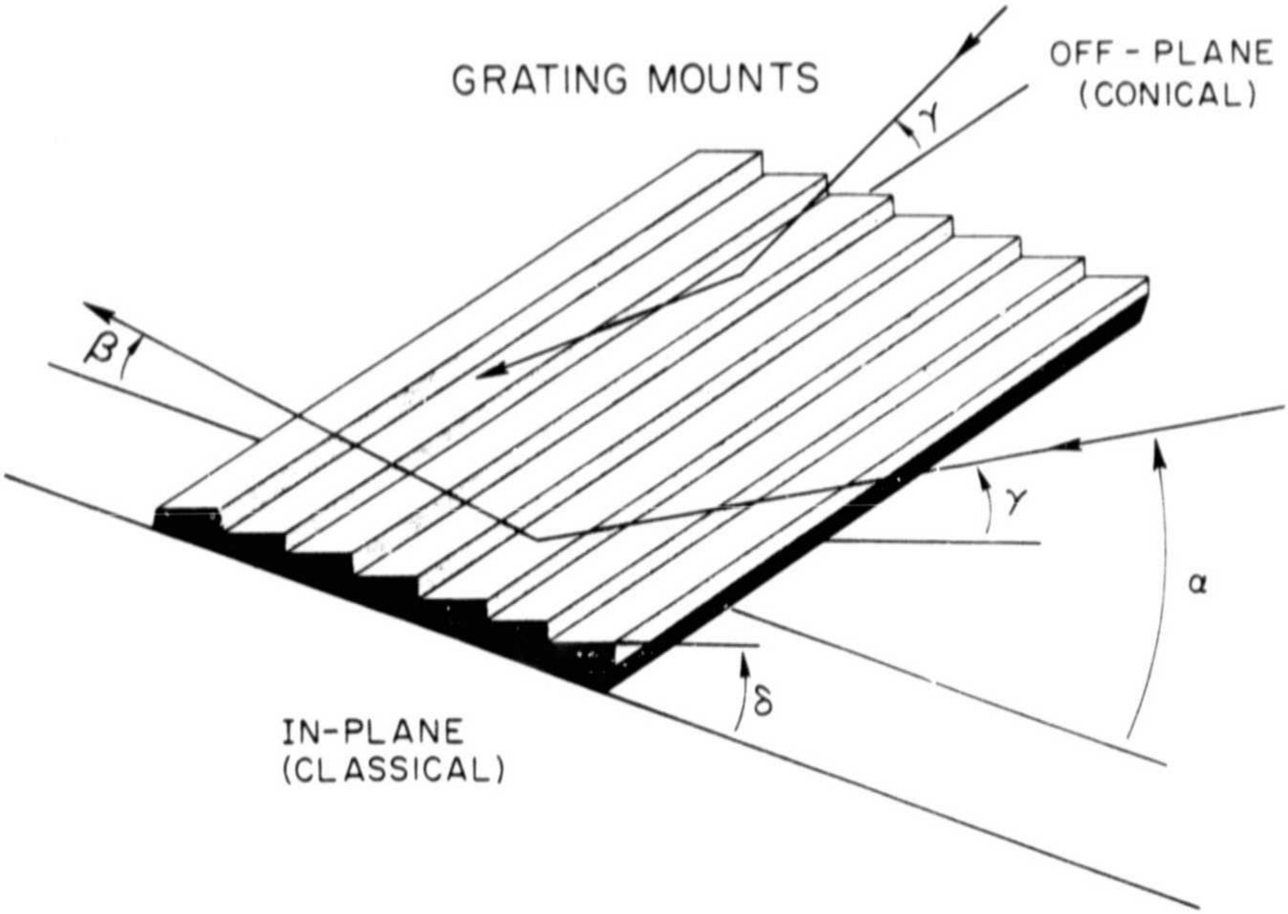


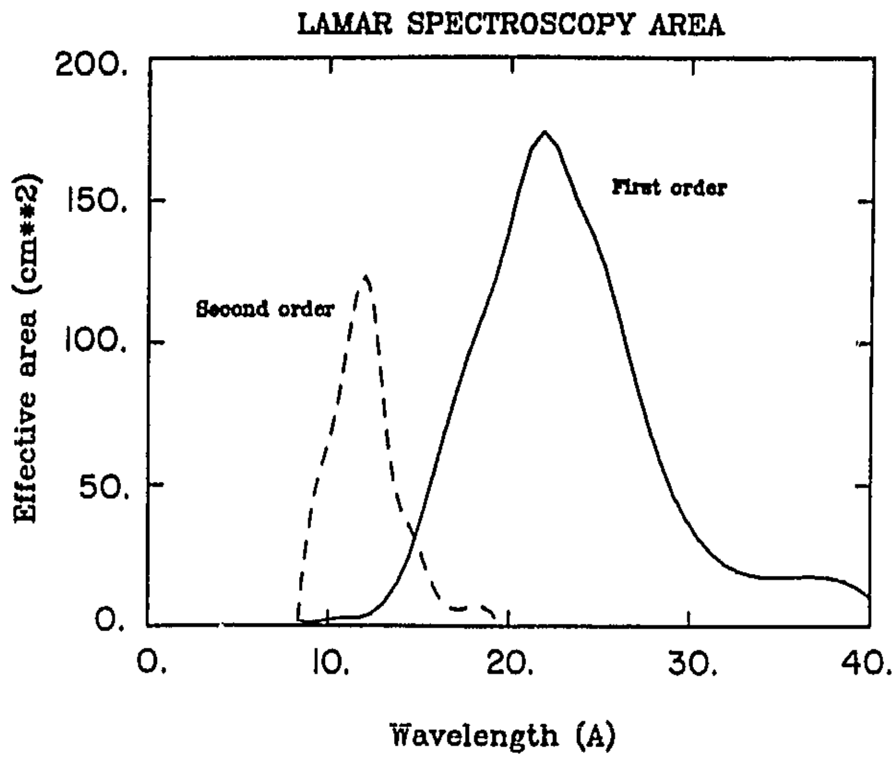
Figure 4. Geometry of a blazed reflection grating for the in-plane or classical mount and off-plane or conical mount.

outgoing angles to the facets are identical. In this configuration, each facet acts essentially like a tiny mirror introducing a pure reflection for the light at λ_B. Because the incoming light is nearly parallel to the grooves, there is little or no shadowing by the groove facets themselves in this configuration.

We have carried out a ray trace analysis of this dispersive system which includes all instrument efficiencies and resolution factors of the gratings, the LAMAR mirror, and the IPC detector. We let the gratings have a line density of 6000 g/mm and a blaze angle of 21°. These are the parameters of an existing grating whose efficiency was measured by Cash and Kohnert (1982). The assumed graze angle was 1°15 which implies a first order blazed wavelength of 24 Å. The results of our analysis are shown in Figure 5, in which we have plotted the effective area and resolution as a function of wavelength for the first and second order spectra. The effective area includes the contribution of all 8 LAMAR modules. We note that the first and second orders overlay each other on the detector. They can be separated using the pulse height information provided by the IPC.

This study demonstrated that it is possible at least in theory to make a dispersive spectroscopy system having rather high throughput and reasonably good wavelength resolution by this technique. These results were used in the updated proposal of the LAMAR experiment for OSS-2/SHEAL missions.

Another accomplishment of the past year was the carrying out of measurements of the performance of a sample grating in the synchrotron X-ray beam at the Brookhaven National Laboratory. The grating, supplied by Webster Cash, had the expected reflectivity but there were some questions about the correctness of the angles at which the maximum reflectivity was observed.



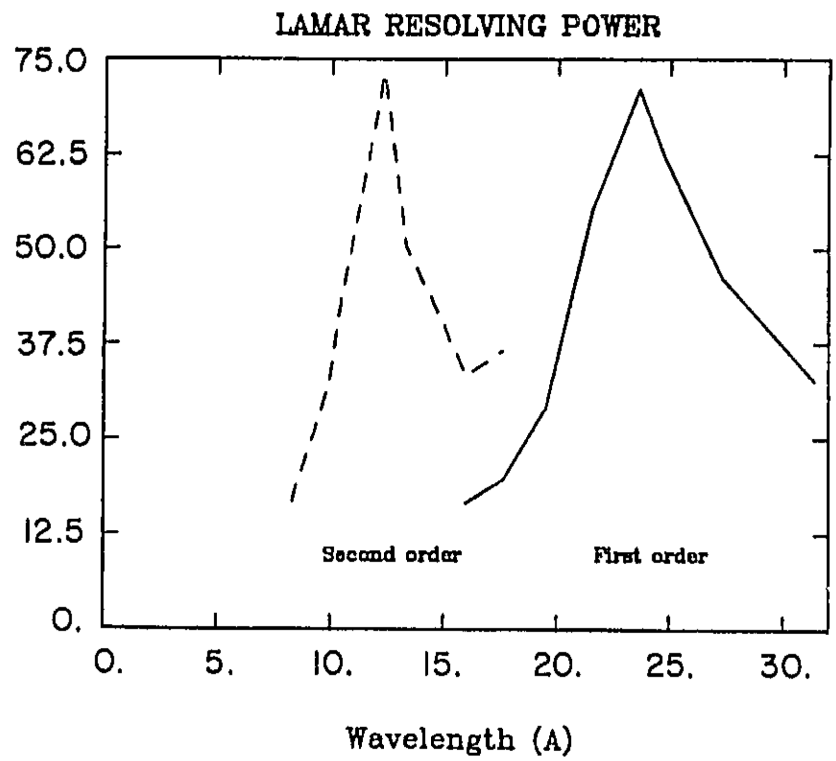


Figure 5. Theoretical performance of a dispersive spectroscopy system consisting of a set of nested conical diffraction gratings in front of a LAMAR mirror as determined from a ray tracing code.

The conclusion is that dispersive spectroscopy with high throughput moderate resolution telescopes in conjunction with reflection gratings is very promising and that further development should be pursued with great vigor.

2.5 Spectrometer Rocket Payload

A rocket payload was described in the previous proposal as an evolving test instrument for imaging and dispersive spectroscopy. However, in order to be able to carry out meaningful measurements, it is essential to have the larger observing times of the SPARTAN flights. A SPARTAN payload was in fact given some consideration during the past year and found to be technically feasible. However, the actual construction of a payload is beyond the scope of this program and would require substantially more funds. A separate proposal would be written for a SPARTAN mission. The present backlog of approved SPARTAN missions makes the possibility of a such flight remote for the near future.