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A Wolter Type I LAMAR

R.C. Catura, W.A. Brown and E.G. Joki

Lockheed Palo Alto Research Laboratory
Dept. 52-12, Bldg. 255
3251 Hanover Street
Palo Alto, California 94304

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Abstract

Observational objectives for the LAMAR and their influence on the instrument design are discussed. It is concluded that the most important design parameter is the angular resolution of the LAMAR modules since it so strongly influences sensitivity, optical identifications, source confusion, spectral resolution for objective gratings and the ability to resolve small extended sources. A high resolution Wolter Type I LAMAR module is described, its hardware status discussed and the performance of a LAMAR observatory presented. A promising technique for enhancing the reflectivity of Wolter Type I X-ray optics in a selected bandpass at high energy has been investigated and the performance of the LAMAR module, utilizing this method, has been calculated.

I. Introduction

There are a number of important objectives in X-ray astronomy which require large collecting area to achieve high sensitivity in timing measurements, spectroscopy and the study of faint sources. Because of detector background noise and source confusion problems, the only practical way of achieving such large area instruments is to utilize X-ray imaging with good angular resolution. Due to the properties of X-ray reflection, however, large effective areas cannot be achieved at X-ray wavelengths with a single telescope and thus the concept of an array of co-aligned telescopes, in modular units, has arisen. This concept has become commonly known as the Large Area Modular Array of Reflectors and is identified by the acronym, LAMAR. The purpose of this paper is to discuss, in general terms, the objectives of LAMAR observations and to show how achieving these objectives very strongly influences design of the instrumentation. Also, the current status of a hardware program to develop Wolter-I X-ray optics for the LAMAR will be described and the design of a LAMAR module utilizing these optics will be discussed. Capabilities and performance of a 24 module LAMAR have been calculated and compared with those of the Einstein Observatory and AXAF. Finally, a promising technique for improving the high energy response of Wolter I optics by deposition of multilayered diffraction coatings on their reflecting surfaces will be discussed.

II. Important LAMAR Characteristics

Many specific objectives in X-ray astronomy which can be addressed by LAMAR observations were presented during the first day of this workshop. Several general observational objectives for the LAMAR and how their achievement very strongly influences the LAMAR design are discussed below.

1. Surface Brightness Measurements of Faint Diffuse Emission.

This objective includes study of emission from intracluster gas in galaxy clusters, galactic halo emission, shadowing of the diffuse component of the extragalactic X-ray background by absorption in nearby galaxies and investigation of soft diffuse emission within the Galaxy.

Since higher angular resolution will not concentrate the diffuse X-rays onto a smaller detector area, sensitivity to extended emission depends primarily on maximizing the LAMAR effective area and minimizing detector background rates. However, good angular resolution is also very important in providing increased sensitivity for detecting and subtracting the contribution from discrete sources. Since the temperature of cluster sources is 5 keV it is important that the LAMAR sensitivity extend to as high an energy as possible. Also, since the detector in each module adds noise, it is important to achieve the large effective area with the fewest number of modules.

2. <u>High Sensitivity Timing Measurements</u>

Studying the size of the emitting volume and the efficiency of energy conversion in active galactic nuclei are important objectives of these measurements. Also, such measurements allow the investigation of evolution in binary, pulsating and burst sources during periods of low mass transfer, the study of stellar flares, cyclic variability in stars and the identification of time variable sources in nearby galaxies.

For brighter sources, where background is negligible, statistical uncertainties in timing measurements depend only on LAMAR effective area. However, for faint point sources, where sensitivity to time variability is statistically limited by background, it is critical to minimize the counting rates from detector background. Also, the importance of assigning observed variability to a particular source requires minimizing source confusion by achieving good angular resolution. Since sensitivity to the largest possible region of the sky maximizes observational efficiency by allowing concurrent study of many sources, it is important for the LAMAR modules to have as large a telescope field as possible.

3) <u>Survey Observations</u>

Such observations may take the form of limited surveys of particularly interesting regions of the sky or an all-sky survey. These surveys will provide the resource for extending luminosity functions of various classes of objects to much lower luminosities and for various statistical studies in correlating X-ray characteristics with properties measured at other wavelengths. An all sky survey would provide a source of reference data for many studies, identifications, archival data for tests of models and theories without requiring further observations. Perhaps most important, a deep survey would discover interesting new objects of low population which answer or raise important questions in astronomy or provide an immediate test of theory.

The sensitivity of a survey, of course, depends on maximizing signal from the sources, minimizing detector noise and being able to survey as large a field as possible in a single observation. Thus, survey observations require not only large effective area but also good angular resolution to minimize noise, reduce source confusion and improve chances for optical identifications. In addition, the LAMAR telescopes must provide uniform response over their fields to allow a survey of uniform sensitivity.

4) Spectroscopic Measurements

The importance of spectroscopy at optical wavelengths is well known and it will provide the same advantages to X-ray astronomy. Study of temperatures, electron densities, chemical abundances, emission mechanisms and red shifts all become possible with the capability for highly sensitive medium resolution ($E/\Delta E \sim 150$) spectroscopy.

Broad band spectroscopy with non dispersive detectors again requires maximizing effective area and minimizing background noise. However, the resolving power of objective grating spectroscopy depends linearly on the telescope resolution and its uniformity over the telescope field. In addition, the spectral range covered by the instrument is dependent on the size of telescope field.

Obviously all of the above discussion can be summarized by saying we need a LAMAR with largest effective area over the widest energy range, lowest background noise, best angular resolution with uniform response over the broadest possible field. However, assuming comparable effective area, angular resolution of the telescopes has the most important impact on LAMAR performance.

The image sensors in a LAMAR will experience an appreciable counting rate from both the diffuse X-ray flux, B_d, and charged particle background, B_p, that will degrade the instrument's sensitivity to point sources. These background counting rates, summed for all modules of the LAMAR, are given by:

$$B_d = FR^2A \text{ counts sec}^{-1} \tag{1}$$

$$B_p = K(Rf)^2 N \text{ counts sec}^{-1} \tag{2}$$

where F is the intensity of diffuse X-rays, A, R and f are the LAMAR effective area, angular resolution and focal length respectively, K is the charged particle counting rate per unit detector area, and N is the total number of detectors (modules) in the LAMAR. The product Rf is the pixel size on the detector. The total background counting rate, B_t, is then:

$$B_t = B_d + B_p = R^2(FA+Kf^2N) \tag{3}$$

The extragalactic component of the diffuse X-ray background, with no interstellar absorption ($\sim 1\ E^{-1.4}$ ph cm^{-2} s^{-1} keV^{-1} sr^{-1}), is a reasonable lower limit to the flux from most places in the sky at energies above 0.5 keV. In the range 0.5 - 6 keV this provides an intensity, $F = 2 \times 10^{-6}$ photons cm^{-2} sec^{-1} (arc min)$^{-2}$. For imaging proportional counters in the range .5 - 6 keV, K is approximately $5 \times 10^{[illegible]}$ counts sec^{-1} per mm^2 of detector area. For a LAMAR with 10^4 cm^2 effective area, and a focal length of 2m the total background counting rate, B_t, is:

$$B_t = R^2\ (.02 + 1.5 \times 10^{-4}\ N) \text{ counts sec}^{-1} \tag{4}$$

where R is measured in arc minutes. It is evident that the diffuse X-ray background is the principal source of noise in a LAMAR. However, if the number of modules grows to of order 100 the particle background is no longer negligible.

Also, if an appreciable fraction of the diffuse X-ray background may be resolved into discrete sources, as it now appears from Einstein observations, particle background rates will become dominant for a LAMAR with many modules.

When background is negligible, the faintest detectable source strength varies as $(AT)^{-1}$, where T is the observing time. When the X-ray source must be detected above random fluctuations in the background counting rate the faintest detectable source intensity, I, varies as:

$$I \propto \frac{(B_t\ T)^{1/2}}{AT} \simeq \frac{(R^2 FAT)^{1/2}}{AT} = R\left(\frac{F}{AT}\right)^{1/2} \qquad (5)$$

where the particle background in eq. 3 has been neglected. A telescope's sensitivity, therefore, varies linearly with its resolution, but only as the square root of other parameters. This effect is shown in Figure 1 where the faintest detectable source (5 counts detected with zero background or sufficient detected counts to be 5 standard deviations above the background) is plotted as a function of observing time, for three values of angular resolution in a LAMAR with 10^4 cm^2 effective area. These calculations utilize the background rate in equation (4), neglecting B_p. The limiting sensitivity of a telescope with perfect resolution varies as T^{-1} and is indicated by the solid line. Telescopes with finite angular resolution depart from this line as they begin to acquire background counts and thereafter their sensitivity varies as $T^{-1/2}$, indicated by the dashed lines. A LAMAR having an angular resolution of 1 arc min or larger becomes background limited in less than 100 sec of observing time. Figure 1 indicates that if X-ray optics of 20" resolution instead of 3' resolution are utilized it is possible to improve the LAMAR sensitivity by a factor of 10. Thus, sources down to 10^{35} ergs sec^{-1} (.01 Her X-1) can be detected in M31 in 10^4 sec observing time and with a spatial resolution of ~ 70 pc, if 20 arc sec optics are employed for LAMAR.

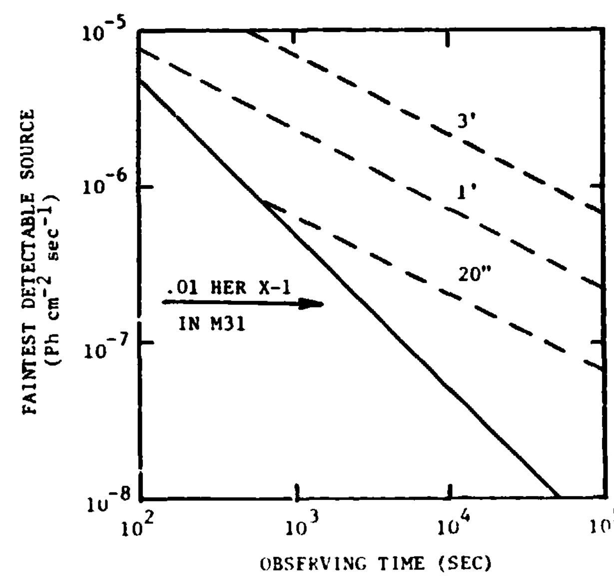

Figure 1. Sensitivity of a 10^4 cm^2 LAMAR as a function of observing time for various values of its angular resolution.

Figure 2 shows the effect of LAMAR angular resolution on the ability to detect time variability of faint sources. A step function change of intensity, δI_A is assumed to occur in the intensity, I, of a source at the center of the 10^4s observation (eg. a partial X-ray eclipse). Detection of this change with a significance of 5 standard deviations above background noise is assumed for these calculations. Figure 2 indicates nearly a factor of 10 improvement in

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ability to detect faint eclipsing binaries ($\delta I/I=1$) if the LAMAR angular resolution is improved from 3' to 20".

Other advantages of the higher angular resolution, not related to sensitivity are:

1. Improved ability to optically identify newly discovered sources.

2. Higher spectral resolution in using objective gratings. For a telescope with 20" resolution and a 6000 l/mm grating one can obtain $\lambda/\Delta\lambda \sim 200$ while 3' resolution allows $\lambda/\Delta\lambda$ of only 20.

3. Ability to distinguish extended sources from point sources on a much finer scale. This is important in distinguishing emission of distant extended clusters from that of compact galactic nuclei and in separating discrete low luminosity galactic sources from diffuse emission. Studies of the angular diameter-redshift relation in distant cluster X-ray sources provide an even more important application for a telescope of improved angular resolution, since the distant clusters are expected to be smaller than a few arc minutes in angular diameter.

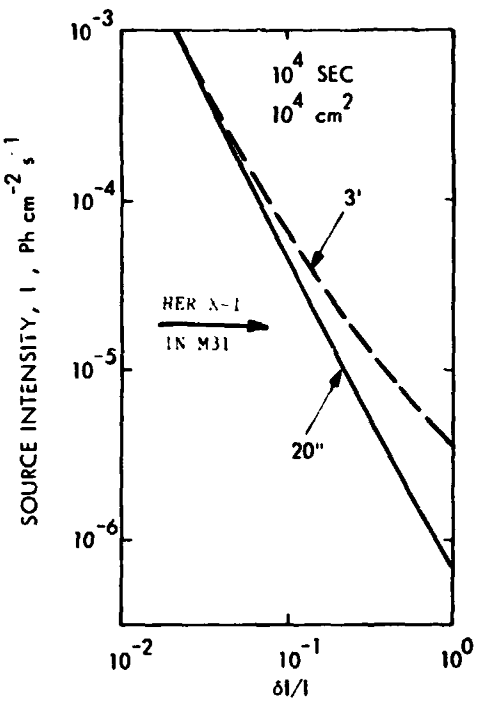

Figure 2. Ability to detect time variability in faint sources as a function of LAMAR telescope angular resolution.

4. Less source confusion. The limit that there should be no more than one source per 40 pixels becomes an important factor in studies of faint sources. This will be discussed in more detail later.

III. Hardware Status

A large Wolter-I X-ray telescope has recently been fabricated in a joint program involving the Mullard Space Science Laboratory and the National Physical Laboratory in the U.K. and our own laboratory here in the U.S. The Wolter-I telescope is the same optical design that was used on the Einstein Observatory and involves

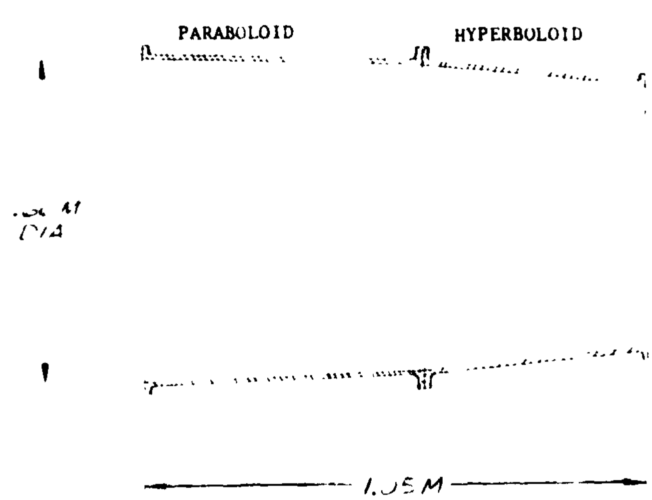

Figure 3. The Aries rocket telescope shown in cross section.

successive X-ray reflections from paraboloidal and hyperboloidal mirror elements. The telescope, which was flown on a NASA-Aries sounding rocket, has a focal length of 2.3 m, a grazing angle of 1.9°, an entrance aperture 66 cm in diameter and a geometrical collecting area of 380 cm^2. The telescope mirrors, shown schematically in Figure 3, were made from rolled ring forgings of 5083 aluminum alloy. These mirror blanks were figured by the process of diamond turning, which utilizes a precision air-bearing lathe and a diamond cutting tool to machine the required curves to within 1 micron. These figured surfaces were then plated with a thin coating of electroless nickel and polished to obtain the final X-ray reflecting surfaces.

Prior to flight, the telescope performance was measured in the 1000 ft. X-ray calibration facility at the Marshall Space Flight Center. Measurements were made at X-ray energies of .277, .572, .705, .933, 1.5 and 2.05 keV. Preliminary results of the measured effective area which the mirrors present to a distant point source are shown in Figure 4. The solid disks indicate the effective area calculated from the X-ray optical constants (Ershov, Brytov and Lukirskii, 1964) of the nickel surface, while the crosses show the measured values. The statistical uncertainty in the measurements is negligible, however, there are systematic uncertainties in these data due to imprecise knowledge of the imaging proportional counter efficiency, which is now being determined. The data points at .277 keV disagree appreciably because some X-ray events at this energy fall below the lower level pulse amplitude discriminator on the imaging proportional counter (IPC) output and therefore fail to be counted. Corrections for this effect are also being determined. The measured effective area at .933 keV falls well above the calculated value because this is in the vicinity of the L-shell X-ray absorption edges in the nickel reflecting surfaces where the optical constants are very poorly known. At .572 and .705 keV, where the systematic uncertainties are smallest, the measured values are approximately 60% of those calculated. Since there are two reflections in the telescope, these data indicate the polishing process has achieved ~ 75% of the theoretical reflection efficiency.

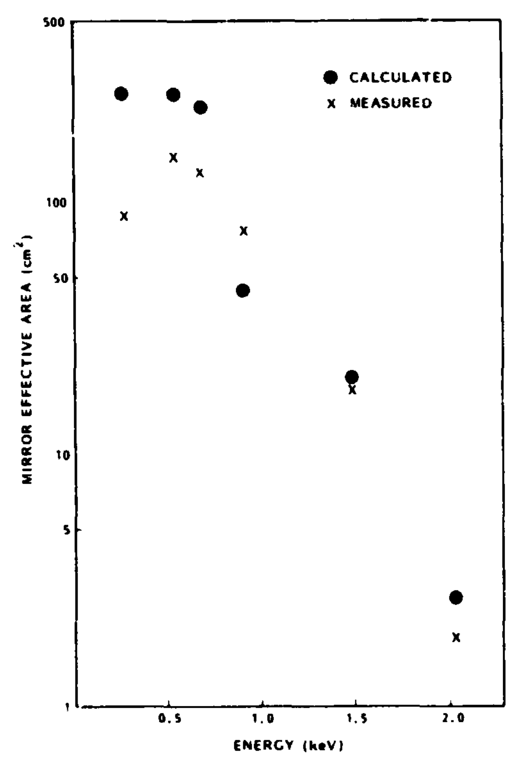

Figure 4. Comparison of measured and calculated effective area for mirrors in the Aries rocket telescope.

The Point Spread Function (PSF) of the telescope (mirrors plus IPC) measured at 1.5 keV is shown in Figure 5. The PSF is obtained by determining the centroid of the X-ray source image and summing the counts in IPC pixels which lie within successive annuli of increasing radius. The total counts within each annulus is then divided by the number of pixels contributing to the sum to obtain the normalized PSF. The PSF is shown on a semi-log plot where the horizontal coordinate, which is given in IPC pixels, corresponds to off-axis angle in the telescope field. Since each pixel is 15 arc sec in size, the entire plot covers the central .4° radius of the field. This point spread function shows the typical response of an X-ray telescope in having a very intense central core followed by a low intensity tail (down by a factor of 10^4). When the image broadening due to the IPC is removed from the telescope PSF we obtain a value of 30 arc sec FWHM for the PSF from the mirrors alone. This is very encouraging since the design goal for figuring the mirrors was a blur circle diameter of 40 arc sec. This result, along with having achieved 75% of theoretical X-ray reflectivity from the mirror surfaces, on our first attempt at fabricating a telescope, is very encouraging and gives us confidence in using this technique of mirror fabrication for LAMAR applications. Figure 6 shows an image of Cyg X-1 obtained during the Aries rocket flight. This object was observed as a point source calibration late in the flight and for spectral observation by a companion experiment.

Our laboratory, in collaboration with our U.K. colleagues, is currently in the process of fabricating two additional mirror pairs utilizing refinements in production technique gained from experience with the present telescope. Diamond turning of the mirrors will be carried out in the U.K. on their newly commissioned diamond turning facility. These mirrors will be nested within the existing set to form a three-element telescope which will be used with objective reflection gratings for spectroscopic observations. This spectroscopic application is undertaken in collaboration with Webster Cash at the University of Colorado, who will discuss objective reflection

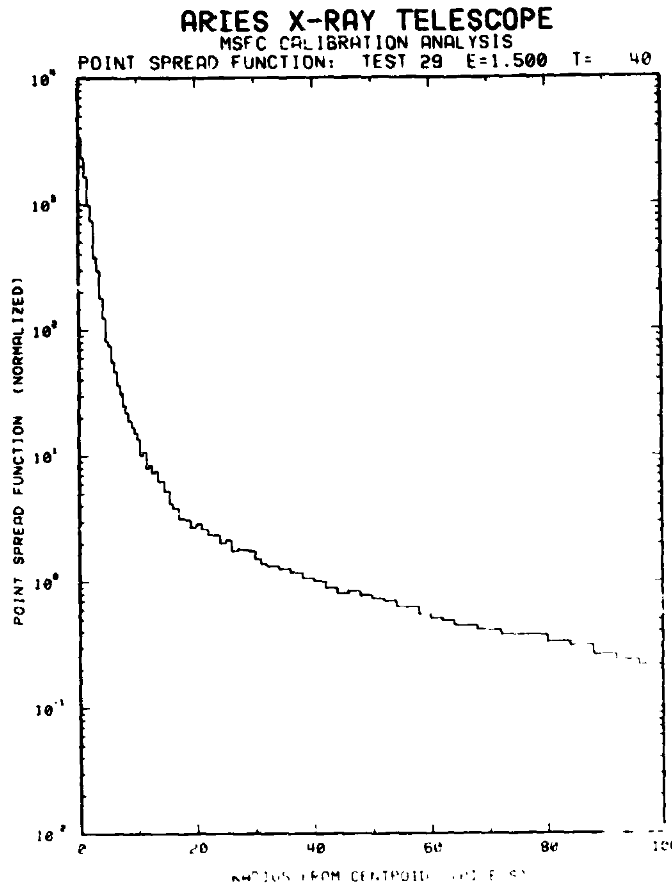

Figure 5. Point spread function for the Aries telescope, including IPC, at an energy of 1.5 keV.

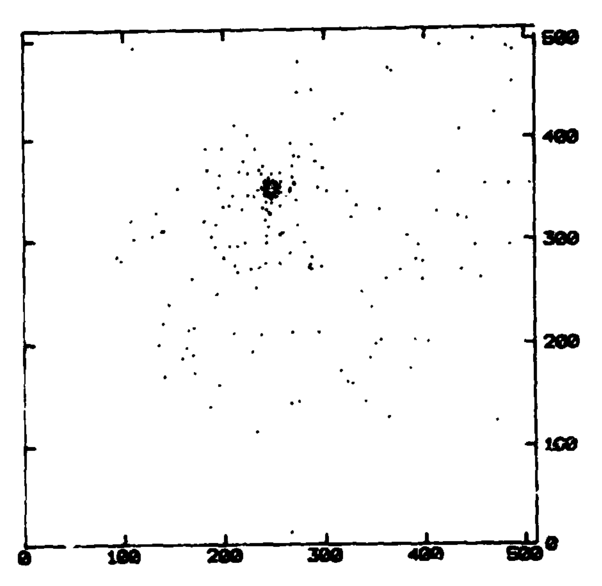

Figure 6. An image of Cyg X-1 obtained during the Aries rocket flight.

grating spectroscopy later in this workshop.

Another telescope fabrication effort, also utilizing diamond turning to figure Wolter I mirrors, is being carried out in parallel by Gordon Garmire at Penn. State University. This effort differs from that described here in the preparation of the X-ray reflecting surfaces. The diamond-turned mirrors are coated with an acrylic lacquer which provides a very high quality surface finish. This thin (~ 10 μm) lacquer coating is then overcoated with a metal deposit to provide the final X-ray reflecting surface. Peter Serlemitsos, here at GSFC, has pioneered this technique of fabricating X-ray reflectors and will describe it in more detail later in this workshop.

IV. A Wolter Type I LAMAR

The definition phase of a NASA funded Spacelab investigation has recently been completed, in which a single Wolter-I LAMAR module was designed. This definition study was carried out by a consortium of seven institutions including Penn. State University, University of Washington, Mullard Space Science Laboratory, University of Leicester, The U.K. National Physical Laboratory, University of Cambridge and Lockheed Palo Alto Research Laboratory. The design goals for the telescope were to maximize the effective area of the module and provide the best possible angular resolution over the broadest telescope field within the cost constraints. The resulting High Resolution LAMAR (HRL) module is shown in Figure 7 and consists of a ten element nested array of Wolter-I mirrors. The HRL focal length is 3.6 m and the mirror diameters range from 90

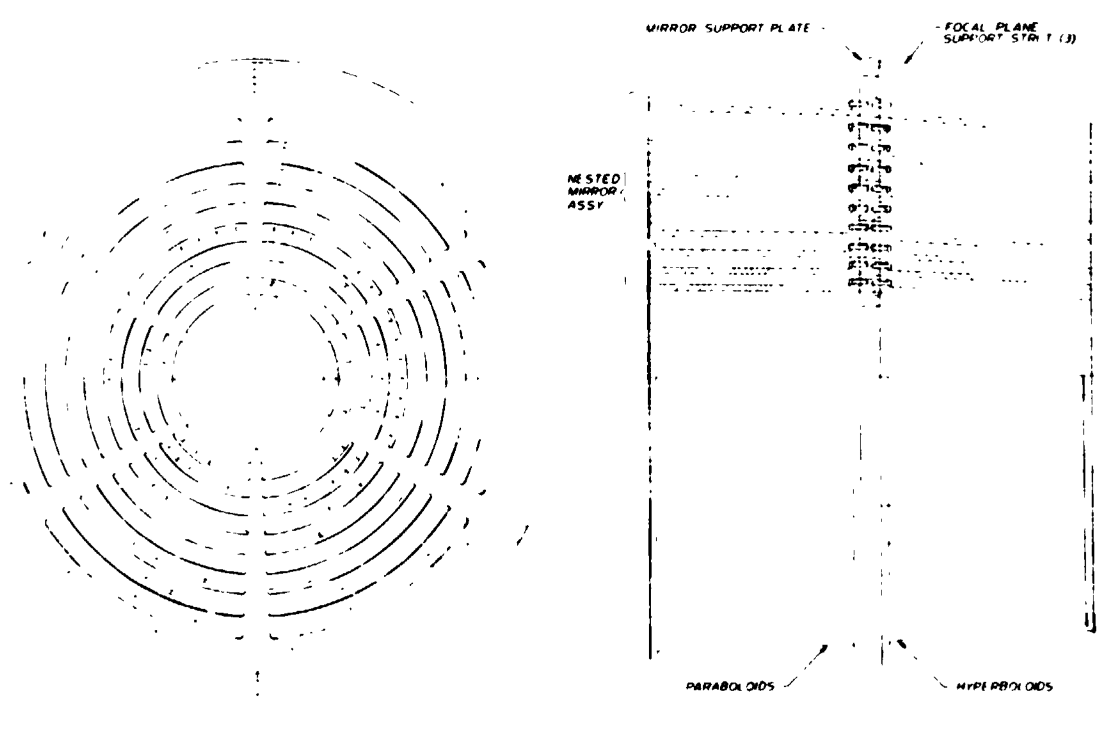

Figure 7. The High Resolution LAMAR (HRL) mirror assembly utilizing Wolter-I X-ray optics.

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cm to 30 cm with grazing angles between 1.7° and .56°. The mirrors are 36 cm long in their axial dimensions, the telescope has a geometrical area of 1350 cm^2 and the design goal was to achieve an on-axis image blur of 20 arc sec radius or less. It is anticipated that these mirrors would be fabricated in the same manner as described earlier for the Aries rocket telescope. However, if the technique of coating the diamond turned surfaces with acrylic lacquer proves effective in preserving the 20 arc sec figure, it would be utilized to reduce costs. As shown in Figure 7, the mirrors are attached to a cental support plate, which also serves as an alignment fixture for the nested array. This alignment is obtained by utilizing the precision machining capability of the diamond turning facility to machine the mating surfaces of the paraboloids, hyperboloids and the support plate. The mating flange surfaces of each mirror are machined at the same time as its interior surface is figured and thus the flange provides a true reference for the mirror axis. Surfaces of the support plate are diamond turned to be flat and parallel, for axial alignment, and the inner surfaces of raised lugs, present on the six radial webs are also diamond turned to provide mirror alignment in a direction normal to the telescope axis. This alignment technnique utilizes the precision of the diamond turning machine to greatly reduce, what otherwise would be a time consuming and expensive effort in the telescope production. This method is being utilized in fabricating the three mirror nested array for the Aries rocket program.

Figure 8 is a schematic of the HRL telescope showing the mirror assembly on the left and the focal plane on the right. The focal plane assembly, which includes a rotary interchange mechanism to position either of two IPC detectors at the HRL focus, is attached to the mirror support plate by a tripod structure. A shutter door, which seals the telescope entrance aperture, also serves as a sun shade when observations are being conducted. This payload, which is 1.1 m in diameter and slightly over 4 m long, is designed for flight on the Space Shuttle utilizing a pointing control system. Further details of the HRL Payload have been discussed by Catura et al. (1981).

The calculated response of the HRL mirror assembly is shown in Figures 9 and 10, assuming the outer 3 mirrors are Ni coated and the inner 7 mirrors have Au reflecting surfaces. The effective area as a function of energy, which the

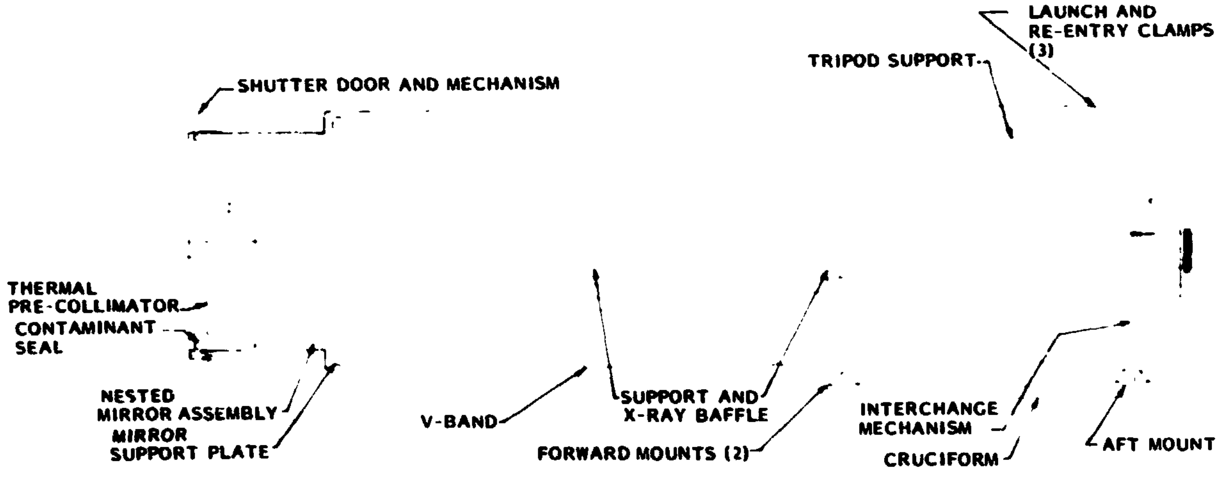

Figure 8. A drawing of the HRl payload designed for Spacelab observations.

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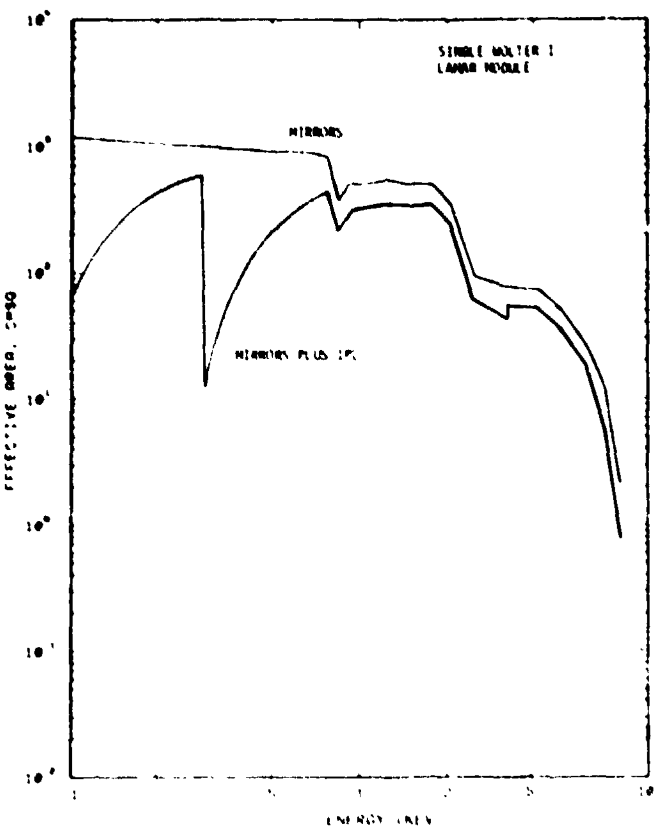

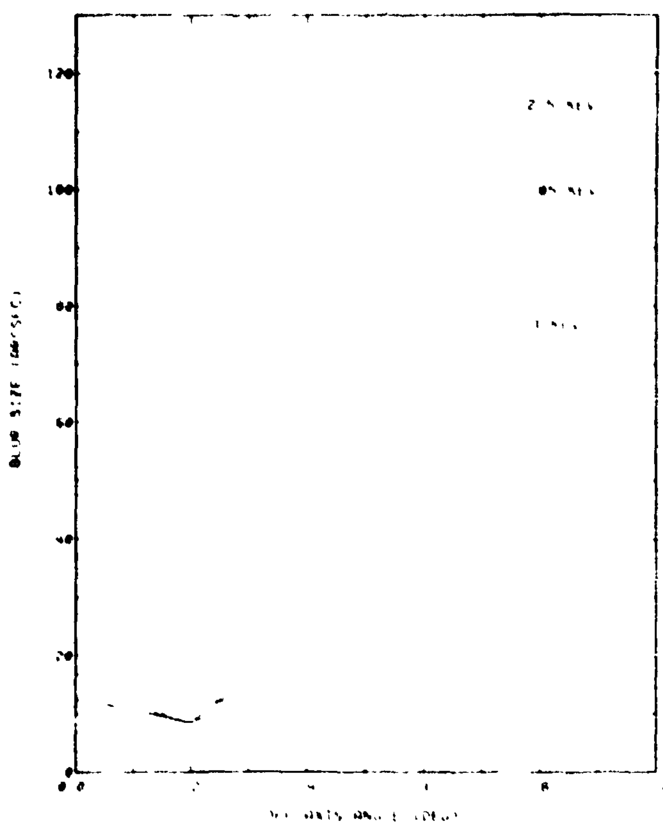

Figure 9. Effective area of a single HRL module as a function of energy.

Figure 10. Image blur as a function of field angle in the HRL focal plane.

mirrors present to a focal plane instrument, is shown in the top curve of Figure 9 along with the response of the HRL telescope when a Xenon filled IPC is utilized as an image sensor. The mirror assembly has ~ 1000 cm^2 effective area below the Ni L-shell absorption edges at .85 keV and provides nearly 20 cm^2 at the Fe line energy of 6.7 keV. Figure 10 shows the radius of the image blur as a function of field angle in the focal plane. It is somewhat energy dependent but, by defocusing the detector slightly (trading on-axis resolution for a larger telescope field), it is possible to maintain an image blur of < 20 arc sec out to a field angle of nearly 0.4^o in radius.

Figure 11 shows how HRL telescopes could be conceptually arranged in a 4 module subassembly of the LAMAR. Such a subassembly could be flown as a Spacelab facility instrument or assembled into a full scale LAMAR. Figure 12 schematically illustrates a 24 module LAMAR, shown here as a free flying satellite. The Wolter-I LAMAR illustrated in Figure 12 could be placed in orbit by a single shuttle launch. However, it would be possible to establish the array with a smaller number, for example, on the Space Platform and add further modules as budgets and shuttle availability permitted. In this way the overall array performance could be progressively enhanced and the specific capability of array members could be altered to reflect changing scientific priorities and developments in the instrumentation field.

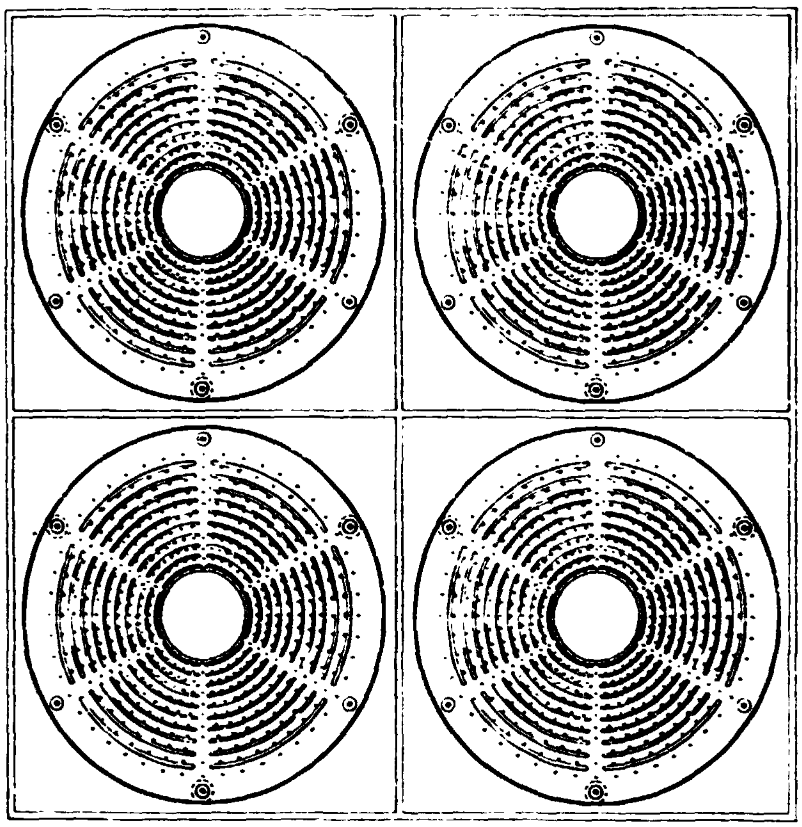

Figure 11. 4 Module LAMAR Subassembly.

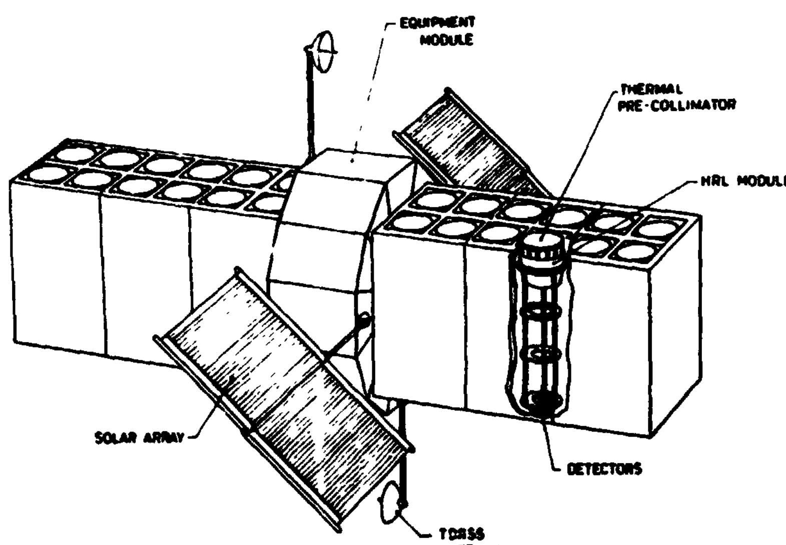

Figure 12. Schematic of a 24 module free flying Wolter-I LAMAR.

The effective area of a 24 module LAMAR as a function of X-ray energy is compared in Figure 13 with the effective areas of the Einstein Observatory and the future Advanced X-Ray Astrophysics Facility (AXAF). The areas shown are for the mirrors alone, as presented to a focal plane instrument. The data of Figure 13 has been used to compare sensitivities of these three observatories as a function of observing time. For purposes of this comparison, unit detector efficiency is assumed. Charged particle counting rates were taken to be 5 x 10^{-5} counts s^{-1} mm^{-2} and the extra-galactic diffuse X-ray intensity (the largest background for the LAMAR) was represented as $11E^{-1.4}$ ph cm^{-2} s^{-1} keV^{-1} sr^{-1}. A Crab-like energy spectrum was assumed for the source and was folded through the telescope responses given in Figure 13. The relative sensitivities for detecting faint point sources with the three observatories, under the above assumptions, are indicated in Figure 14. The dashed curve indicated for the LAMAR would result if the entire extra-galactic diffuse X-ray back-ground could be resolved into discrete sources and only the detector noise from charged particles remained. The three horizontal lines indicate the source confusion limits for three different values of pixel sizes determined by the telescope angular resolution. These limits are independent of the observatory and use only the number-flux relationship:

$$N(>S) = 2.7 \times 10^{-16} S^{-1.53} \text{ sources sr}^{-1} \qquad (6)$$

determined by Maccacaro et. al. (1981) and the confusion limit defined as 1 source per 40 pixels. It is apparent that confusion becomes a problem for an observatory with 3' angular resolution at the sensitivity which Einstein achieved in a 10^{3} sec observation. Results of the Einstein deep survey (Giacconi, et al. 1979) show no apparent turnover in the

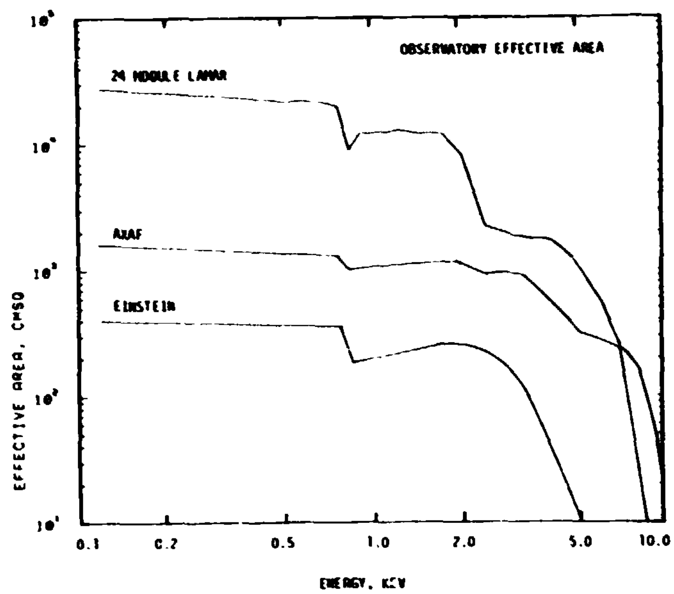

Figure 13. Effective collecting area of three observatories as a function of energy.

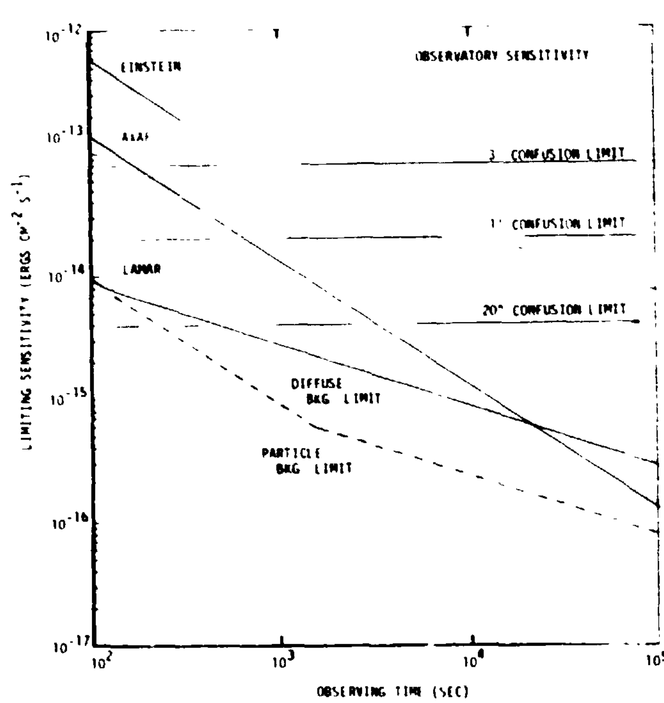

Figure 14. Sensitivity for detecting point X-ray sources as a function of observing time for three observatories.

number-flux relation for extragalactic sources down to ~ 2×10^{-14} ergs cm^{-1} sec^{-1}, so that the confusion limit for 1' resolution is observationally verified. Even with 20" pixels, the 24 module Wolter I LAMAR will be at its confusion limit in a 600 sec observation, unless there is a turn over in the number counts between 2×10^{-14} and 4×10^{-15} ergs cm^{-2} sec^{-1}. One must conclude that angular resolution is a critical factor for extragalactic studies in a highly sensitive observatory such as the LAMAR.

V. X-Ray Reflectivity Enhancement with Multilayers

The technology for depositing extremely thin alternating layers of high and low density materials, which act as Bragg diffractors, is now becoming well established (Underwood, Barbee and Keith, 1979; Spiller and Segmuller, 1980 and Barbee, 1981). These coatings are applied by vacuum deposition with highly uniform layer thicknesses down to 10A, essentially replicating the surface finish of the underlying substrate. Deposition of these multilayer diffraction coatings on the reflecting surfaces of a Wolter-I telescope offers the potential of increaasing its effective area in a selected bandpass at high energy. If the underlying mirror finish is preserved by the multilayers, the low energy specular reflection of the telescope will not be diminished. However, it is necessary to arrange the high energy band pass well above the energy at which the normal mirror reflectivity cuts off, since interference effects will otherwise degrade the specular reflection. Since the outer mirrors of the HRL module reflect efficiently only below about 2.5 keV, they will in principal allow reflectivity enhancement for Fe-line emission at 6.7 keV by multilayer deposition without disturbing their low energy response.

The Bragg reflectivity of gold-carbon multilayers of various thicknesses and number of layer-pairs has been calculated with the aid of a computer code which predicts their response as a function of wavelength. A result of these calculations is shown in Figure 15 for 15 layer pairs of gold and carbon optimized for 1.85A X-rays at a grazing angle of 1.7° (appropriate for the outer mirror of the HRL module). The peak reflectivity of this rocking curve is 42% and its FWHM is .14A, which has an angular equivalent of .13° from the Bragg equation. Since the grazing angle varies slightly along the length of a Wolter I mirror, the width of the rocking curve should be broad enough to encompass this variation

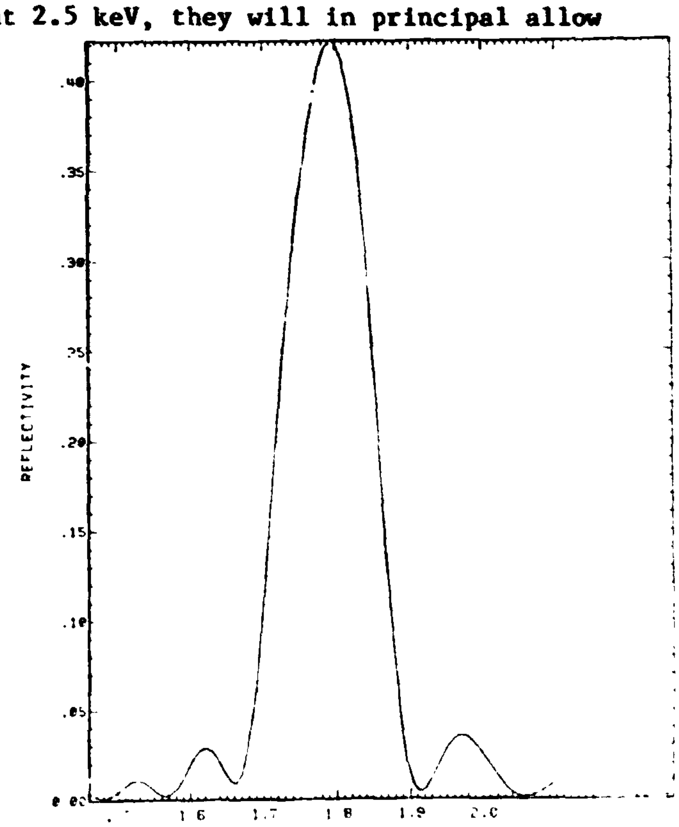

Figure 15. Reflectivity of a Gold-Carbon multilayer with 15 layer-pairs as a function of wavelength. The layer thickness is 16Å.

Also, because two reflections are involved, the telescope efficiency depends on the square of the multilayer reflectivity. However, peak reflectivity and rocking curve width are competing parameters in the multilayer design and so they must be optimized. Figure 15 is the optimum in this case and represents a structure having 15 layer pairs where each layer is 16A thick. This provides a peak efficiency for double reflection of ~ 16% and has a rocking curve wider than all but the largest mirror.

For purposes of calculation, the outer 4 mirror pairs were assumed to be coated with multilayers of appropriate layer spacing such that the rocking curve peaked for the grazing angle at the center of each mirror. The computer ray tracing program used for the calculations of Figure 9 was modified to include the angular dependence of the Bragg reflectivity of the multilayers, assuming no degradation of the low energy specular reflection. Figure 16 indicates the HRL response when the multilayers on all four outer mirrors are appropriate to reflect 1.85A X-rays. The multilayers increase the response at 6.7 keV over that from specular reflection on the inner mirrors by a factor of 7, providing a peak effective area of 125 cm^2 in a band pass which is .5 keV FWHM. For a 24 module LAMAR, one would obtain ~ 3000 cm^2 at this energy. The off-axis response of the telescope is also shown in Figure 16 at angles of 0.1^o and 0.3^o and indicates that the multilayer response degrades approximately the same as that for specular reflection at this energy.

It is possible to broaden the band pass of the telescope at the expense of peak response by tuning each mirror pair to reflect a slightly different energy. Figures 17 and 18 show results of these calculations where the peak wavelengths for each of the four mirror pairs are separated by .04A and .08A respectively.

While the results of these calculations are encouraging, a number of practical matters need to be addressed. These include the practicality of depositing uniform multilayers on such large surfaces and whether the low energy specular response can be maintained after multilayer deposition.

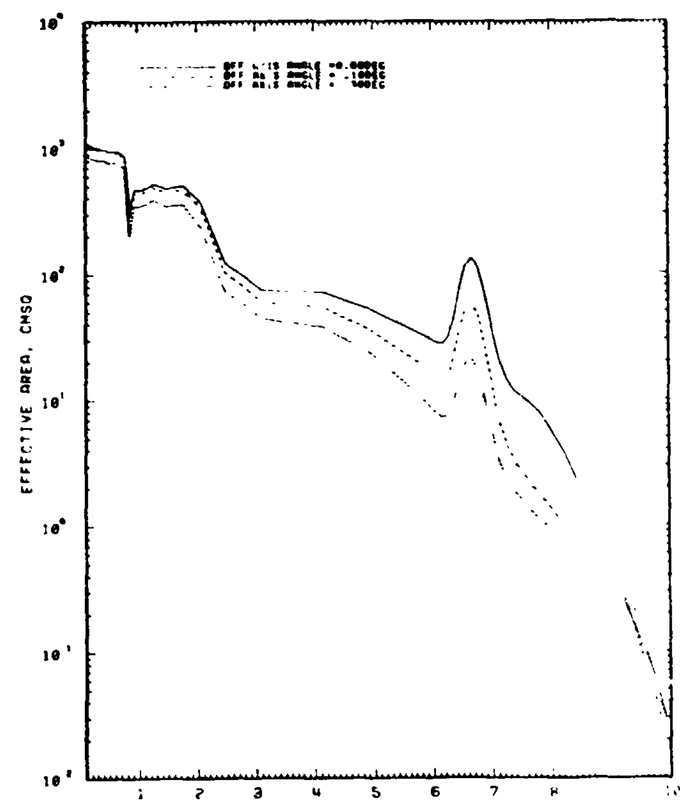

Figure 16. Effective area of an HRL module with the outer 4 mirror pairs coated by multilayers and optimized for 1.85A X-rays. Three off-axis angles in the telescope field are shown

VI. Conclusions

Angular resolution of the X-ray optics in a LAMAR most strongly influences its performance. A LAMAR with 20" resolution has a factor of 10 better sensitivity than one of the same effective area but with 3' angular resolution. Also, a LAMAR with 10^4 cm^2 effective area and 3' angular resolution will be source confusion limited in about two minutes of observing time at the sensitivity level reached by Einstein in about 800 sec. The comparable confusion limit for a LAMAR of 20" resolution is 20 times better, at a sensitivity 3 times below the level of the Einstein deep surveys. The spectral resolution achievable with objective gratings is linearly related to angular resolution of the X-ray optics. Consequently, it is critically important to the LAMAR Observatory's performance to utilize the highest angular resolution possible within the mission cost constraints. The technology for producing Wolter Type I X-ray optics with 20" angular resolution is rapidly reaching maturity and a detailed design and a development plan now exists for a high resolution LAMAR module which utilizes these optics. Deposition of multilayered diffraction coatings on the outer mirrors of this telescope module appears to be a promising way of enhancing the high energy performance in a selected bandpass.

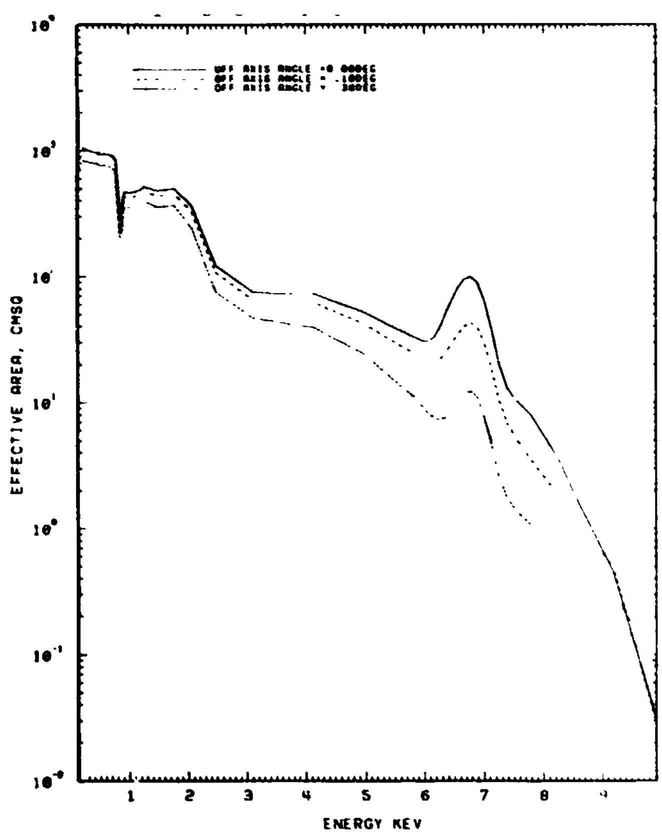

Figure 17. Response of the HRL module when the peak wavelengths for multilayers on the outer 4 mirrors differ by .04Å.

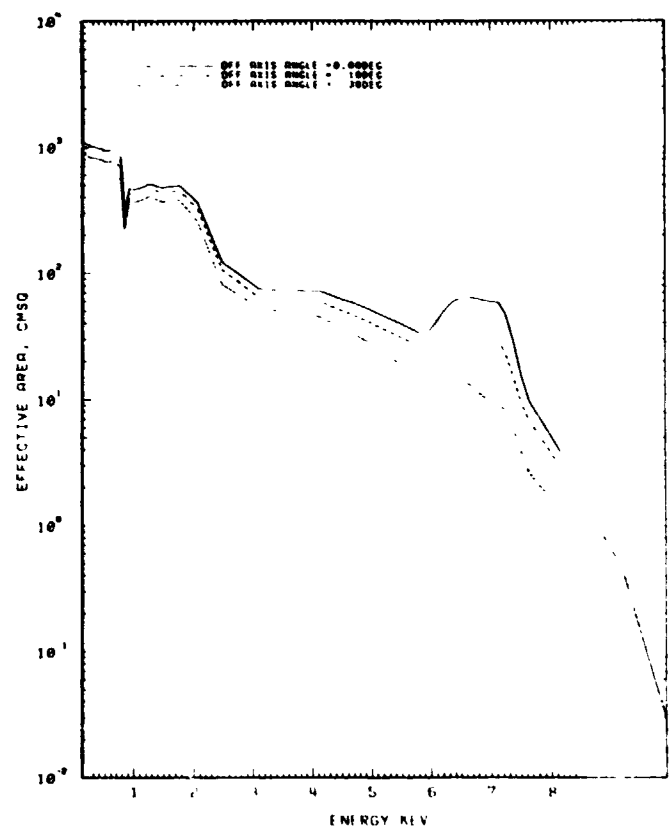

Figure 18. Response of the HRL module when the peak wavelengths for multilayers on the outer 4 mirrors differ by .08Å.

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