

Designing, Constructing, and Testing an X-ray Polarimeter

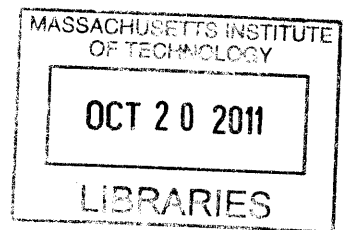
by

Kevin P. Jenks

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL
FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2011



© 2011 Massachusetts Institute of Technology. All Rights Reserved.

ARCHIVES

Signature of Author: _____

Department of Mechanical Engineering
May 6, 2011

Certified by: _____

Herman Marshall
Principal Investigator, MIT Kavli Institute
Thesis Supervisor

Accepted by: _____

John H. Lienhard V
Samuel C. Collins Professor of Mechanical Engineering
Undergraduate Officer

Designing, Constructing, and Testing an X-ray Polarimeter

by

Kevin P. Jenks

Submitted to the Department of Mechanical Engineering
on May 6, 2011 in Partial Fulfillment of the
Requirements for the Degree of Bachelor of Science in
Mechanical Engineering

ABSTRACT

X-ray astronomy has been an important field since its birth 50 years ago. However, X-ray polarization measurements have been almost non-existent, especially when compared to the amount of polarimetry being performed in the other bands of the spectrum. One method of filtering a specific energy of polarized X-rays involves reflecting these X-rays off of a correctly tuned multilayer mirror at a specific grazing angle. A design for a small spacecraft incorporating this type of instrument has been proposed, but the effectiveness of using multilayer mirrors as polarization filters has never been tested in a laboratory setting. A design for using an existing X-ray beamline as a means of testing this method was developed. The necessary modifications to both the source and detector end were made, but due to an inability to completely eliminate small misalignments in the system, the full tests of the multilayer mirrors could not be performed. Further research could be performed to identify and correct the cause of the misalignments and continue the evaluation of the multilayer mirrors as a polarimeter.

Thesis Supervisor: Herman Marshall
Title: Principal Investigator, MIT Kavli Institute

Contents

1 Introduction	5
2 Background Info	6
2.1 Polarization Mechanisms.....	6
2.2 Multilayer Mirror.....	7
3 The NE80 X-ray Lab	8
3.1 Initial Hardware.....	8
3.2 Control System.....	10
4 Polarimeter Construction	11
4.1 Overview of Design.....	11
4.2 Modifications required to existing beamline.....	12
4.2.1 The Multilayer Mirrors.....	13
4.2.2 Source Modifications.....	14
4.2.3 Detector Modifications.....	17
4.3 Alignment and Testing.....	20
5 Conclusion	23
References	24
Appendix	25

List of Figures

Figure 1: Photograph of CCD Detector.....	10
Figure 2: Schematic of Polarimeter Design.....	13
Figure 3: Reflectance Response of Multilayer Mirrors.....	14
Figure 4: Schematic of Source Assembly.....	15
Figure 5: Photographs of Completed Source Assembly.....	17
Figure 6: Photograph and Schematic of New Detector Design.....	19
Figure 7: Alignment Verification Measurements.....	22

Chapter 1 Introduction

Since 1962, when the first extrasolar X-rays were discovered, X-ray astronomy has been used to increase our knowledge of many cosmic phenomena, including black holes, supernovas, and neutron stars. From missions such as the Einstein Observatory in the late 1970s and the ongoing mission of the Chandra X-Ray Observatory, X-ray observations have shown us the flow of gases when galaxies collide, given us estimates of the sizes of neutron stars, and have given us hints as to what is at the center of our galaxy [1]. When combined with measurements from other parts of the spectrum, X-ray observations can also help distinguish between different types of active galactic nuclei (AGN), important for determining what the underlying physical phenomena are [2].

In addition to photometry and spectroscopy, polarimetry is an important technique for discovering new phenomena. Radio and optical polarimetry observations have led to important advancements such as the currently accepted model for pulsars [3], and the unification of the many theories of a certain class of AGN [4]. However, to this date, only one object, the Crab nebula, has had X-ray polarization measurements taken at a significant level [5]. It has been theorized that by making X-ray polarimetry measurements of other objects, we will advance our knowledge even more, such as by learning new information about the extreme magnetic fields around neutron stars and the structure and geometry of accretion disks close to a black hole [6].

Marshall has proposed a system for an X-ray polarimeter that could be flown on a spaceflight, but the feasibility of this design has not been proven in a lab setting [7]. Therefore, we propose to design, build, and test this system using the existing beamline in building NE80.

Chapter 2 Background Info

2.1 Polarization Mechanisms

Radiation can be polarized by one of two general methods. It can be emitted in a polarized state, e.g. synchrotron radiation, or it can be polarized at a later time by only allowing radiation with a certain polarization to be transmitted. The most common method of filtering one polarization out of unpolarized light is to use a set of thin, parallel wires. If the distance between the wires is smaller than the wavelength of the incident light, the filter will only pass light which has an electric field component perpendicular to the wires. This is practical for visible light with wavelengths on the order of 600 nanometers, but is not practical in the soft X-ray band with wavelengths on the order of 2 nanometers. The other method of polarizing radiation is by reflecting it off of a dielectric surface, such as a glass mirror. The Fresnel equations describe the fraction of light reflected off of the surface and the fraction of light transmitted into the other medium. The equation for the fraction of light reflected is also a function of the polarization of the incoming light wave. For light which is s-polarized, i.e. the electric field component is perpendicular to the plane formed by the incoming and reflected rays of light, the fraction of light reflected, R_s , is given by

$$R_s = \left(\frac{n_1 \cos \theta_i - n_2 \cos \theta_t}{n_1 \cos \theta_i + n_2 \cos \theta_t} \right)^2, \quad (1)$$

with n_1 and n_2 the index of refraction of the two materials, θ_i the angle of incidence, and θ_t the angle of refraction. For light which is p-polarized, i.e. the electric field component is parallel to the plane formed by the incoming and reflected rays of light, the fraction of light reflected, R_p , is given by

$$R_p = \left(\frac{n_1 \cos \theta_t - n_2 \cos \theta_i}{n_1 \cos \theta_t + n_2 \cos \theta_i} \right)^2 . \quad (2)$$

The angle of incidence and angle of refraction can also be related by Snell's law,

$$n_1 \sin \theta_i = n_2 \sin \theta_t . \quad (3)$$

By combining these, it can be shown that R_p goes to zero for a specific angle of incidence, while R_s is non-zero at that same angle. Therefore if the incoming light is incident to the surface at this specific angle, known as Brewster's angle, all of the light that is reflected will be polarized in the s-direction.

2.2 Multilayer Mirror

Reflecting light off of a dielectric will polarize the light regardless of its wavelength, providing that the surface will reflect, and not absorb, the wavelength of interest. For the soft X-ray band, a normal glass mirror will not reflect the incident photons at such a high angle of incidence; they will be absorbed or re-radiated at a lower energy due to inelastic scattering. However, by coating the surface of the mirror with alternating layers of specific materials, it is possible to construct a mirror that will reflect a certain energy of X-rays at a certain angle of incidence. If the thicknesses of the layers are chosen correctly, placing many of these layers on a surface will cause the reflected beam to constructively interfere. If constructed accurately, these multilayer mirrors can have reflectances of over 10%, sufficiently large to be used as a polarizer in many experimental setups.

Chapter 3 The NE80 X-ray Lab

3.1 Initial Hardware

The 17 meter X-ray beamline located on the 6th floor of Building NE80 was built in the early 1990's to test and calibrate transmission gratings for the Chandra telescope. It is divided into three sections that can be isolated from each other and each have their own vacuum pump: the source end, the grating chamber in the center, and the detector chamber. The X-ray source is a Manson model 5 which allows for up to six anodes to be installed at one time. It can operate at a maximum voltage of 10 kV and a current of 0.6 mA. The spectrum of X-rays produced is determined by the material of the anode and the operating voltage, while the flux is proportional to the current. Also located at the source end is a laser alignment system. A laser is vertically placed in an adjustable mounting block that allows the laser to be tilted in two directions. Inside of the pipe, a movable beam splitter directs the laser both towards the detector and back towards the source. The beam splitter can be adjusted in both the vertical and horizontal directions which combined with the degrees of freedom in the tilt of the laser allows for the laser beam to be directed through any two points in the beamline.

The grating chamber contains the equipment that was used to test the gratings for Chandra. These include a baffle plate with a square opening, a movable collimating slit, and a movable stage for holding gratings. In future experiments, the gratings will be used, but for this work, the slit and movable stage were moved out of the path of the beam as to not interfere with the experiments. Also located in the grating chamber is a grazing mirror that was used to increase the flux in the Chandra tests. This mirror is not used in the current experiments, but it did influence the original design of the beamline in an important manner. In order to be able to use

this mirror, the incoming rays had to come from a slight horizontal direction. To accomplish this, the source pipe is connected to the main pipe with a 3" horizontal offset.

On the back end of the detector chamber is the CCD detector. It has a 1" square photosensitive region and is positioned to have the same 3" offset as the source so that the X-rays can travel straight from the source to the detector. The CCD mount contains cooling lines so the detector can be chilled with liquid nitrogen to reduce thermal noise along with a thermistor for measuring the temperature of the device. Attached just in front of the CCD is an optical blocking filter which filters out visible and infrared light while allowing the X-rays to pass through. Figure 1 is a picture of the CCD mount as it is attached to the detector chamber. The data from the detector are read out with a set of ACIS electronics and onto a SPARCstation20 where they are saved for later analysis.

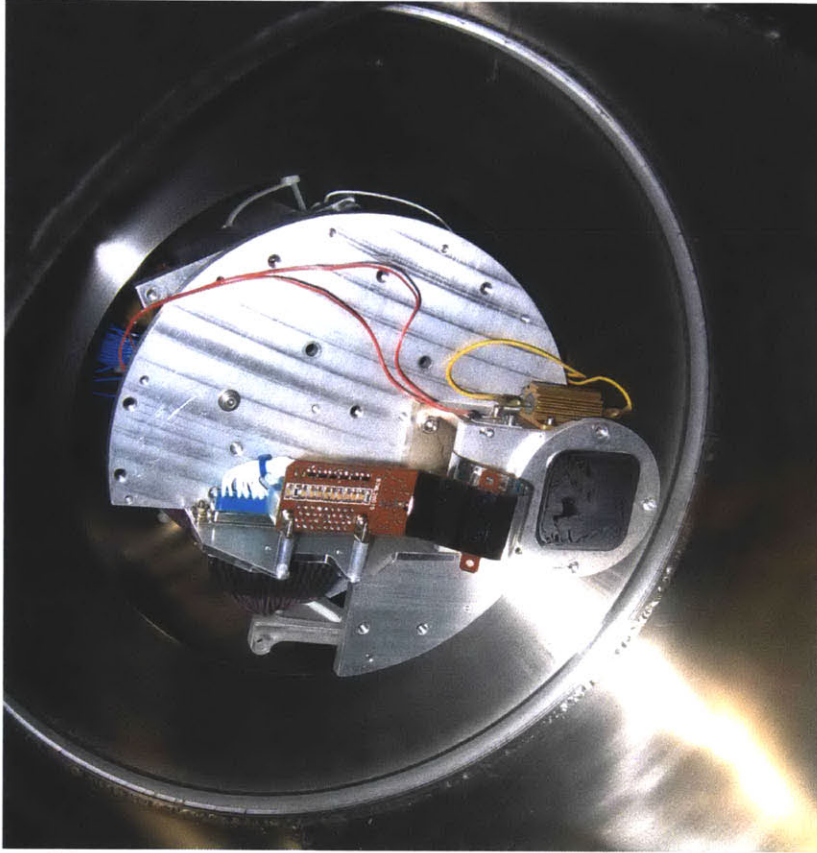


Figure 1: Photo of the CCD mount inside the detector chamber. The CCD is located underneath the optical blocking filter, seen as the small black square on the right. Note how the CCD is offset from the center of the mount. The top plate of the mount is seen in light silver with a corner missing, and is approximately 7" in diameter. The larger tube into which the CCD protrudes slightly is 12" in diameter.

3.2 Control System

The current control system is a Linux workstation which mainly runs a custom LabVIEW program. The parts of this program that control the original hardware, such as the grating chamber stages and source anode selection, were closely modeled from the original LabVIEW control program, but there were several significant changes. The first was the addition of code to control the new motors at the source and detector ends. The code for the source motor was

written all by hand, while the code for the detector motor uses the sample code provided with the motor. The program also communicates with the high voltage source and reads the current values of the high voltage and beam current. The other important task the program performs is to write the current state of the system to a log file every 10 seconds. This includes information such as the voltage and beam current of the source, the polarization angle, and the source anode being used. A separate script also runs on this computer to serve the most recent data about the state of the system to a client running on the SPARCstation20 machine which inserts this data into the header of the FITS data file for the current CCD frame. This allows each data frame to have the important information about the state of the experiment so that the data may be analyzed easier.

Chapter 4 Polarimeter Construction

4.1 Overview of Design

The functional design of the polarimeter, as proposed by Marshall (2008) [7], consists of a multilayer mirror to polarize the X-rays produced by the source, and a second multilayer mirror in front of the detector to filter out only one polarization of the incoming X-rays. To change the polarization angle of the X-rays relative to the detector, the source along with the source multilayer mirror (SML) would be able to rotate about the axis connecting the two multilayer mirrors, while the detector multilayer mirror (DML) and the detector would stay fixed. Theoretically, this would produce a sinusoidally varying flux at the detector, with a maximum flux when the mirror surfaces were parallel and a minimum flux when the source was rotated 90° from the maximum.

4.2 Modifications required to existing beamline

A schematic of how this polarimeter design would be implemented using the existing beamline is shown in Figure 2. On the source end, a 5-way cross is needed to hold the mirror and provide an attachment point for the source at a right angle to the optical axis. The other necessary component is a rotating flange. This is a piece that would allow the source to rotate relative to the rest of the beamline while still keeping the entire beamline at vacuum. If this component were not in place, the source end would have to be brought up to air every time the polarization angle was to be changed, which would be very impractical. At the detector end, a large elbow is required so that the CCD can be mounted perpendicular to the optical axis as well. This elbow would also have to be large enough to fit the DML and a rotation table inside. The DML would be mounted on this rotation table so that future measurements could be made as to the effectiveness of this type of polarimeter when small misalignments in the angle of incidence on the DML are introduced.

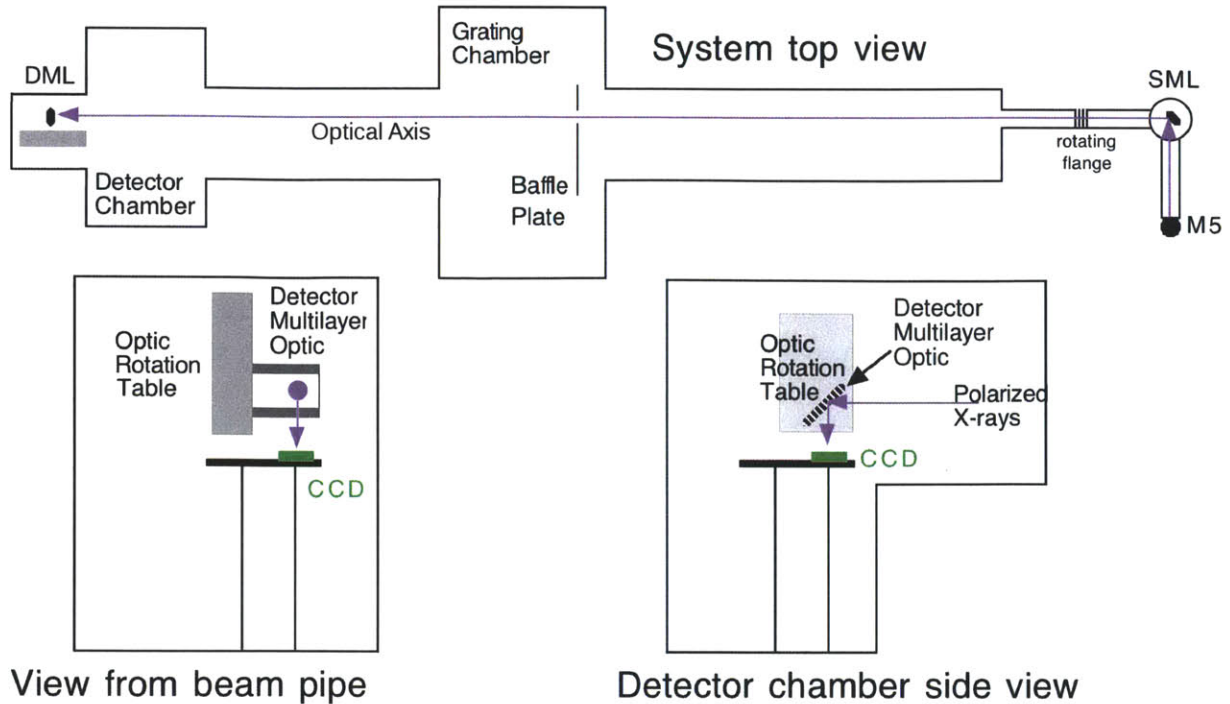


Figure 2: Schematic of the necessary components of the polarimeter design. The top view shows the Mason 5 source, the two multilayer mirrors and the optical axis connecting the two mirrors. Since the SML and DML are rotated by 90° with respect to each other in the position drawn, the detector should not receive any X-ray flux. (Adapted with permission from Marshall)

4.2.1 The Multilayer Mirrors

It was decided to operate this experiment at an energy of 0.525 keV, corresponding to the oxygen K-line emission. This emission line would be produced by using a small piece of sapphire (Al_2O_3). A small circle of sapphire was placed on the top of an existing copper anode. The abundance of oxygen would produce a clear line at this energy. The multilayer mirrors were designed to reflect X-rays of this energy with an incident angle of 45° . These mirrors were built by Reflective X-ray Optics and are of a sufficiently high quality. Figure 3 shows the reflectance of 8.05 keV X-rays as a function of the graze angle, the compliment of the angle of incidence. Even though these mirrors will be operated under different conditions, the shape of the reflectance curve will be similar. The peak reflectance meets the requirements of this experiment, but the width of this curve is on the order of $\theta/100$, where θ is the angle of peak reflectance.

Deviations greater than this width will lead to reflected fluxes that are too low to be of use in this experiment. This leads to the condition that the mirrors can be misaligned by no more than 0.5 degrees when installed in the beamline.

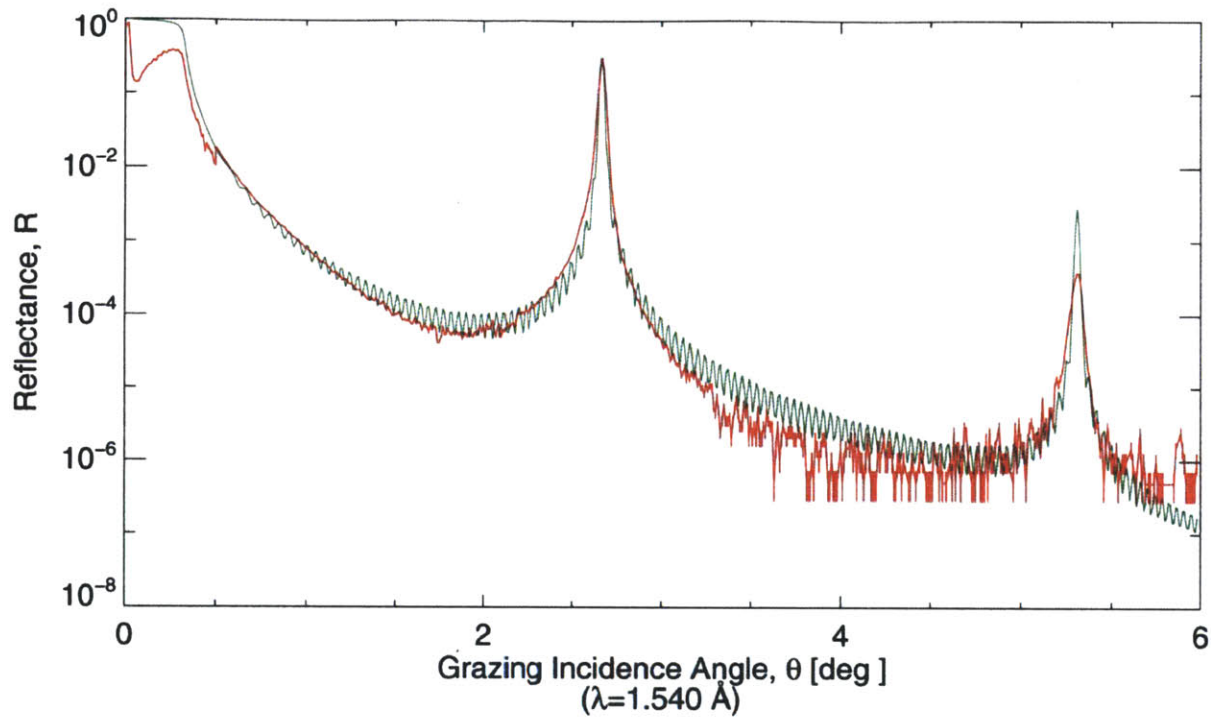


Figure 3: Measured (red) and modeled (green) reflectance of the multilayer mirrors used in this experiment. Note the extremely narrow peak at 2.5 degrees. At longer wavelength X-rays, the angle of the peak will shift, but the width will stay the same. (Produced by RXO)

4.2.2 Source Modifications

The modifications to the source end were the most extensive due to the requirement that the source be able to rotate. The source also had to be mounted perpendicular to the beamline so that the X-rays could reflect off of the SML at 45° and be directed down the beamline. This required the mirror to be mounted at 45° rotated around the axis perpendicular to the plane defined by the

source and the optical axis. To be able to control this angle, and therefore be able to aim the polarized X-ray beam down the beamline, the mirror was placed on a rotary motion feedthrough manipulator. This would allow alignment corrections in one direction to be made without breaking the vacuum. To control the direction of the beam in the other dimension, the mirror was mounted on a small tip-tilt stage which was attached to the manipulator. The tip-tilt stage allows for adjusting the angle of the mirror to within 10 arcseconds, well within the required accuracy of 0.5° . Figure 4 shows a drawing of the source configuration and mirror positioning.

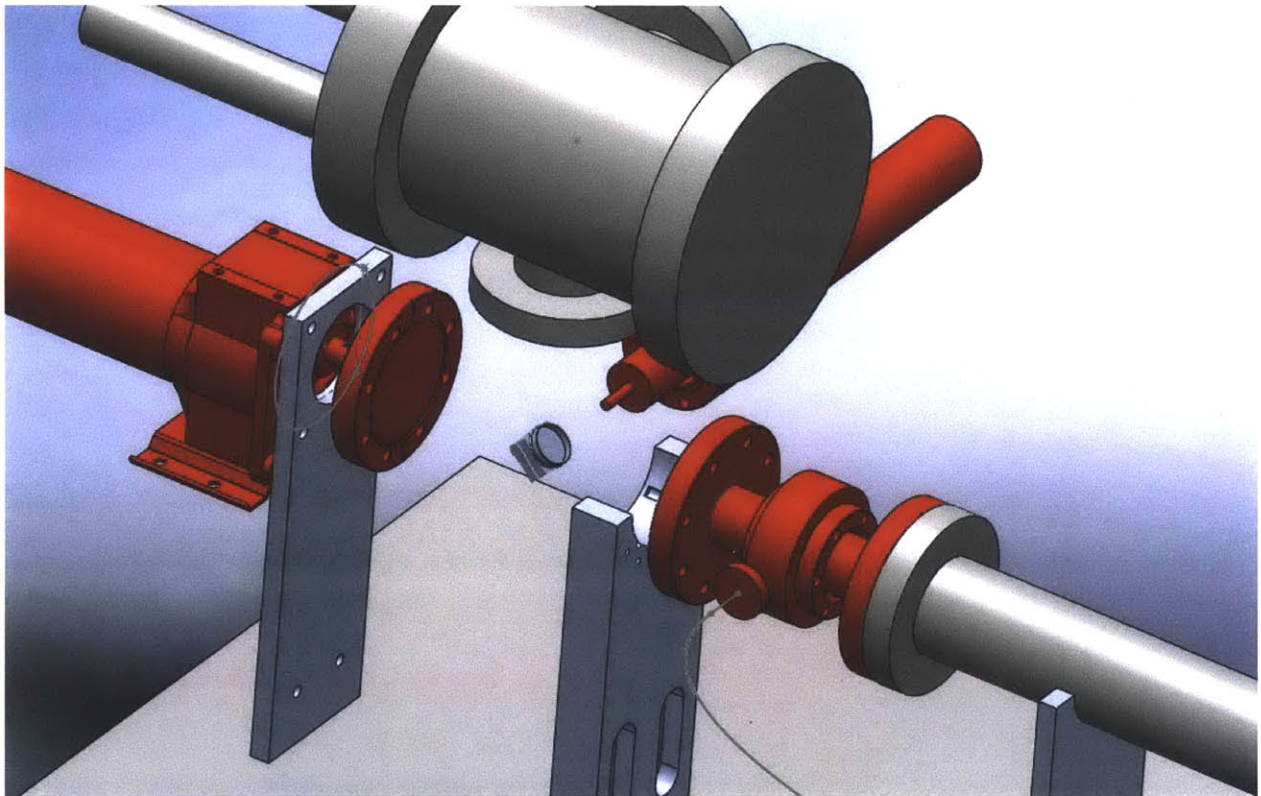


Figure 4: Source assembly configuration. This figure shows the configuration of the source (top, gray), the mirror manipulator feedthrough (back, red), the rotating flange (right, red), and the source motor (left, red). Also shown in the center is gray is the mirror and tip-tilt stage. The beamline continues off to the lower right.

To control the polarization angle of the X-rays, a motor was attached to the port of the 5-way cross opposite the rotating flange. There were four important requirements for this motor:

sufficient torque to rotate the source assembly, the ability to hold the source assembly in position even during a loss of power, small resolution and high repeatability for accurate measurement of the polarization angle, and the ability to be computer controlled. The source chamber itself weighs approximately 50 lbs and is located 8 in. from the axis of rotation, therefore the motor had to be able to produce at least 500 lb-in. of torque. Based on these requirements, the motor selected was an Oriental Motors part #AR98MA-N50. It has a maximum torque of 530 lb-in, a step size of 0.0072° , and is equipped with a fail-safe electromagnetic brake. Connecting the motor to the 5-way cross required an extra collar since any connection could not compromise the integrity of the vacuum. A small collar was designed and fabricated that would fit around the motor shaft and attach to the cross at six points. By having many attachment points, the bolt holes only needed to be drilled part way into the wall of the cross, keeping the integrity of the vacuum.

In the original configuration of the beamline, the source end of the beamline was supported by the Manson source chamber sitting on a table. In the polarimeter design, this is not possible due to the movement of the source. A set of three supports was designed to hold the beamline fixed while allowing the source assembly to rotate. One support holds up the stationary portion of the beamline, one support attaches to the motor, and the other support holds one of the arms of the 5-way cross. These three supports can be seen in the bottom of Figure 4. Each support is made to be adjustable in both the vertical and horizontal directions to have as many degrees of freedom as possible during alignment. There were no other requirements for the stationary and motor supports, but the cross support had to allow the source assembly to rotate on top of it. To reduce friction between the support and the cross, two small, cylindrical pieces of

delrin were embedded within the semicircular cutout at the top of the support. The cross only touched these delrin pieces, greatly reducing the amount of friction and therefore reducing the torque required to rotate the source assembly. Photographs of the completed source assembly are shown in Figure 5.

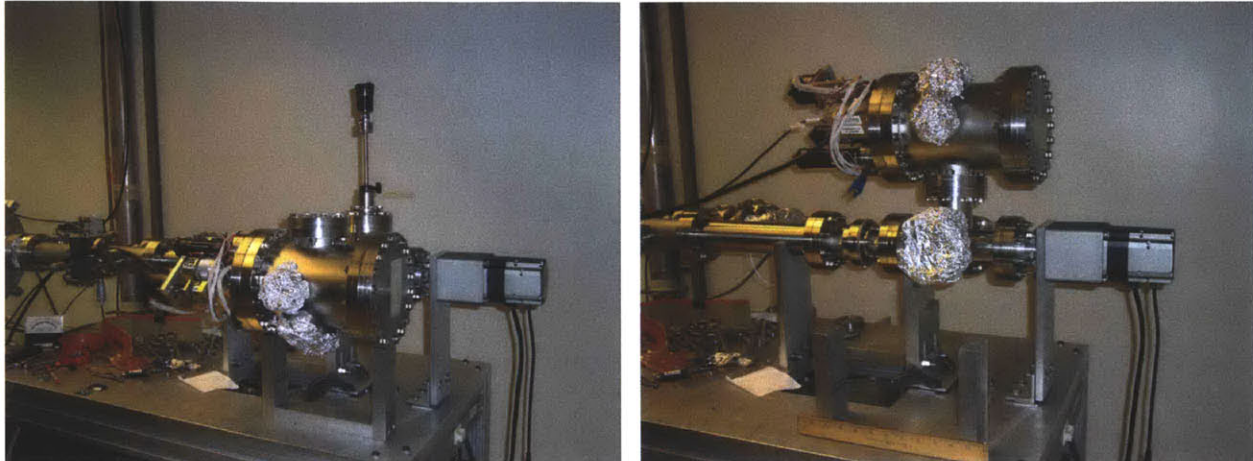


Figure 5: Photographs of the completed source assembly. On the left, the source chamber is shown in the front and the handle of the mirror manipulator feedthrough can be seen at the top. This is defined to be a polarization angle of 0° and the polarization vector of the X-rays will be vertical as they travel down the beamline to the left. On the right, the source has been rotated to a polarization angle of 90° . The three supports can now be seen, along with the rotating flange located just below the left side of the source chamber. (Used with permission from Marshall)

4.2.3 Detector Modifications

The main requirements for the detector modifications were as follows:

1. The CCD and its corresponding mount had to be moved so that the CCD faced perpendicular to the optical axis.
2. The DML had to be centered on the optical axis, which is offset horizontally by 3" from the center of the beamline pipe.
3. The DML had to be mounted on a rotational stage with the axis of rotation perpendicular

to both the optical axis and the direction the CCD faced.

4. All materials added to the system to support these modifications must fit within an 8" diameter mitered elbow pipe.
5. These materials can not be attached to the elbow pipe in any way.

The first two requirements were necessary to reflect the filtered X-rays onto the CCD. The third requirement was to provide the ability to perform tests on the effectiveness of this polarimeter design to misalignments in the grazing angle. The fourth requirement was simply due to budget restrictions, and the fifth requirement was due to the requirements of maintaining a vacuum. The wall thickness of the elbow piece was only 0.120" thick, so any screws or bolts used for attachment would completely pass through the wall, compromising the vacuum in the beamline. Tape or other adhesives would not be allowed because at such low pressures they would leave a residue which would outgas and then possibly condense onto and contaminate the surface of the mirror or CCD.

Requirement 1 does not specify the angle at which the CCD is relative to the beamline, however, the other requirements effectively constrain it to be mounted vertically. If the CCD were to be mounted horizontally, the axis of rotation for the stage would have to be vertical. Since the mirror must be located 3" off center, there would not be enough room to fit a rotational stage under the mirror and still have it fit in the 4" radius elbow pipe. If the CCD were to be mounted vertically, the axis of rotation would be horizontal, and there would be plenty of room to fit a stage in the center of the pipe. If the CCD were to be mounted above the optical axis so that the other opening of the elbow pointed up, the bottom and back of the elbow would provide a flat, square surface to help constrain the location of the DML. If a large sheet of metal exactly

8" tall were to be inserted into the horizontal section of the elbow, it would be constrained in all but two degrees of freedom. It would be able to translate in and out as well as rotate about the axis of that section of the elbow. In order to constrain these last two degrees of freedom, a hole in the top plate of the CCD mount was used. The CCD mount is fixed to the other end of the elbow, so a pin was attached to the metal sheet that would fit in the hole in the CCD mount. This pin would completely fix the metal sheet in the elbow, so the DML and rotation stage could be attached to this sheet and be located in an exact position. Figure 6 shows a schematic of the new detector configuration as well as a picture of the sheet and rotation stage.

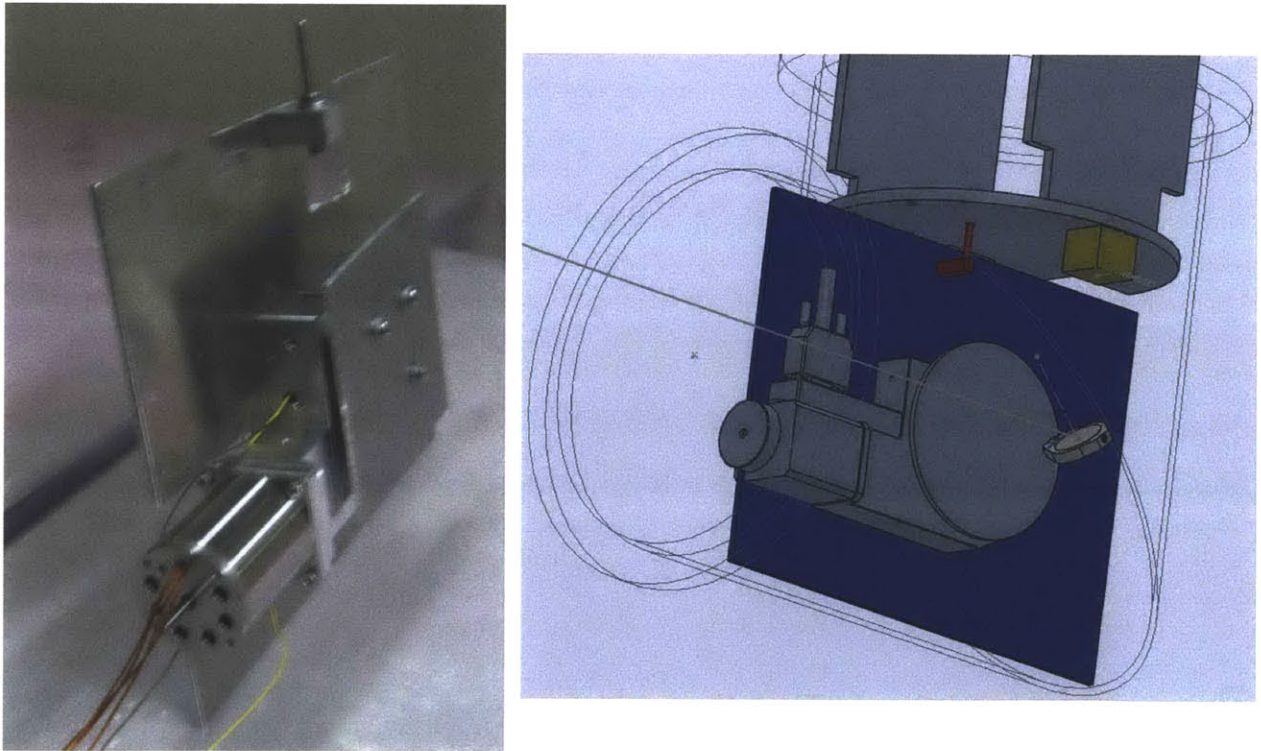


Figure 6: Left: a picture of the alignment sheet with the rotation stage attached. On the right of the rotation stage is the piece to which the DML is mounted. Also note the pin sticking up from the center of the sheet. The notch cut in the top of the sheet behind the pin is for the ribbon cable (see Figure 1) to fit through. Right: A schematic of the new detector configuration. The yellow cube represents the location of the CCD, the pin is in red, and the alignment sheet is in blue. The wire frame is the outline of the elbow and the single line going off to the left is the optical axis back towards the source.

4.3 Alignment and Testing

After the source modifications were complete but before the detector modifications were installed, the source assembly was aligned and tested to ensure that it could consistently produce an adequate flux. The source could be misaligned in two possible ways: the SML could be tilted at the wrong angle, or the supports could be in the wrong position causing the axis of rotation to be different from the optical axis. If the SML was misaligned, the X-ray beam would trace out a circle on the plane of the detector centered around the optical axis as the source assembly rotated. If the supports were misaligned, the X-ray beam would point at the same spot on the detector plane as the source rotated, but this spot would not be at the center of the CCD. However, due to the dispersion of the X-rays as they traveled the length of the beamline, the spot they produced was over twice as large as the CCD, making it hard to detect the motion of the center of this spot.

Instead of using X-rays produced by the source, the alignment laser was used instead. The laser had two major advantages over the X-rays for alignment purposes. First, the system could be aligned without having to be pumped down to vacuum. This meant that adjustments could be made to the mirror instantaneously, drastically reducing the feedback cycle time. Second, the laser was used “backwards”. The laser was first aimed along the optical axis by adjusting it until it passed through the center of the square in the baffle plate and also hit the center of the CCD. The laser spot was observed on the anode in the source as the source assembly was rotated. This was possible due to a secondary beam monitoring port on the Manson source chamber. Usually, a second detector is placed on this port, which has an unobstructed view of the anode. Any fluctuations in the intensity of the X-ray beam will be captured by this beam monitor and can be

subtracted from the data collected by the primary detector. During the alignment procedures, a vacuum-compatible glass window was installed over this port so the anode could be directly observed. By running the laser “backwards” during alignment, the distance the laser traveled was much smaller, and the spot did not disperse and so could clearly be seen to move around on the surface of the anode. During alignment, the anode was also switched to carbon which provided a dark, dull surface on which the laser spot could be safely and easily observed.

Since any misalignments would affect the X-rays on the CCD in the same manner as the laser on the anode, the alignment procedure was relatively straightforward in principle. The laser spot was observed on the anode to trace out an arc as the source was rotated. The radius of this arc was proportional to the misalignment of the SML, while the incorrect placement of the center of the arc was due to a misalignment of the supports. Adjustments could be made to correct these misalignments, and this process was repeated until the arc was sufficiently small and centered about the center of the anode. To verify the alignment, the source was turned on and the flux was measured as a function of the polarization angle. The results of one such set of measurements is shown in Figure 7.

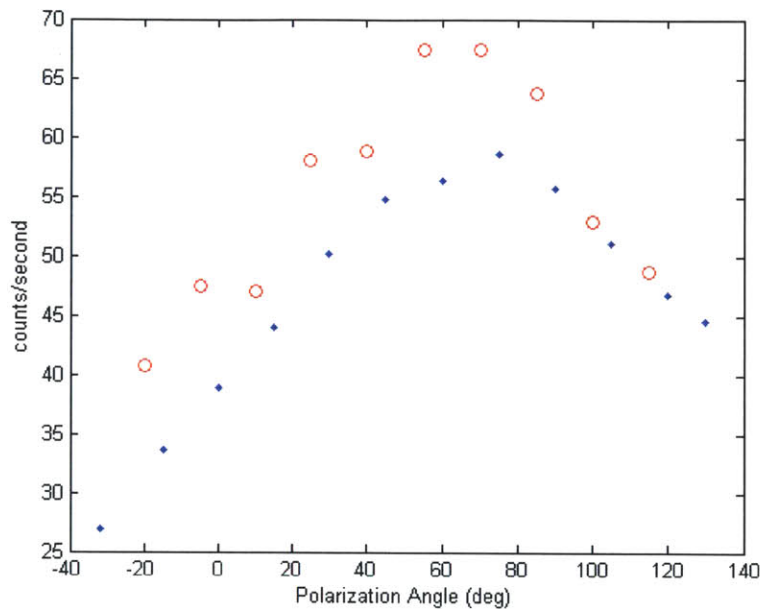


Figure 7: Alignment verification measurements. The blue data points represent measurements taken when the source was moved in a positive direction and the red circle data points are measurements taken when the source was moved in a negative direction. The cause for the large increase between 100° and 85° is not known. The data points for negative movements at 40° and 10° do not follow the pattern of the rest of the negative movement data. This is because the source was moved in a negative direction too far past these angles and then was moved slightly in a positive direction to get to those angles. These slight positive movements caused the flux to decrease to a point somewhere between the expected negative movement flux and the positive movement flux.

The flux is not uniform across all polarization angles, and it is also not repeatable. The two different sets of data points correspond to data taken when the source was moved in the positive direction to that angle and when the source was moved in the negative direction to that angle. There is a large, unexplained increase in flux when the source is moved down from 100° to 85° relative to the flux when the source is moved in a positive direction. This difference in flux remains for all subsequent negative movements. The cause of this discrepancy is unknown, though one possible explanation is that there is something moving within the source chamber. Because this increase happens when the source passes through 90° , it is likely that gravity is causing something to move from one side to the other. Very late in the project, it was noticed that

the beamline was moving off of the cross support at polarization angles close to 0° . This was due to the large imbalance of weight caused by the source being directly horizontal to the beamline. A cap for this support was made to keep clamp the pipe down into the support, but data were not able to be taken with this in place. Because of the inability to produce a repeatable flux, the detector modifications were never installed.

Chapter 5 Conclusion

Due to issues with alignment and repeatability, the entire system was not tested as a whole. However, if the cause for the sudden increase in flux when rotating in the negative direction is determined and fixed, testing of the full system could begin. It would not be ideal to operate the system when the flux varies as a function of angle, but as long as the flux at a particular angle was consistent, well-known, and did not depend on the direction of approach, this variance could be divided out and measurements of using a multilayer mirror as a polarization filter could be made.

To proceed with development of this system, a small amount of funding would be necessary to accurately build more precise support and alignment parts. Most of the non-purchased parts were made by using whatever material was available in the lab, not necessarily what material would be best. Once this simple system has been proven, more multilayer mirrors can be obtained that would reflect different energies, so that this system can be tested across a variety of conditions. The transmission gratings can also be used to attempt polarization and spectroscopy measurements at the same time [7]. Such an instrument would prove valuable on a small spacecraft where space is limited and multifunction instruments are important.

References

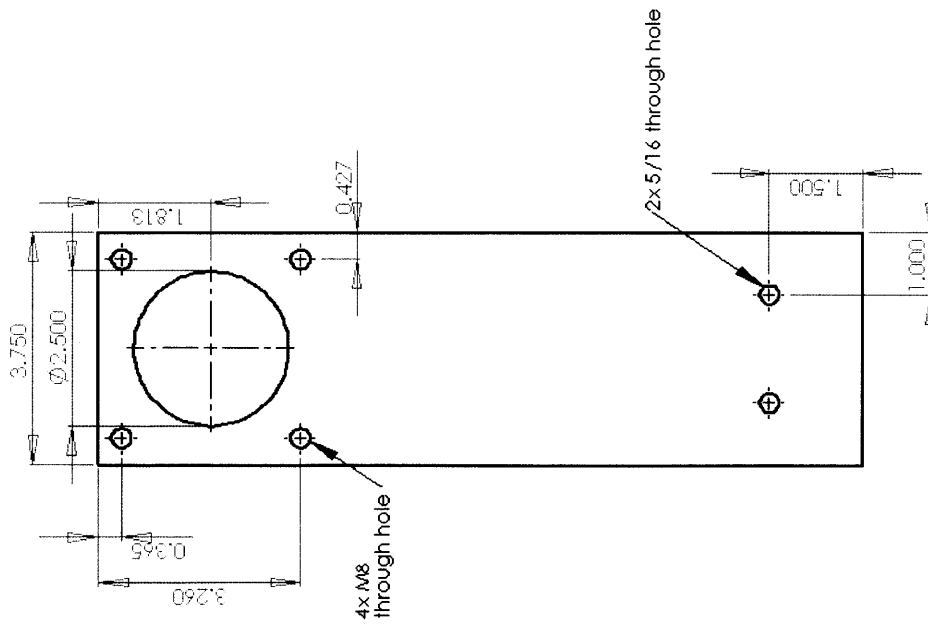
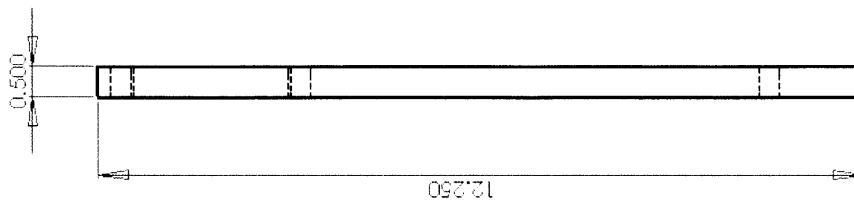
- [1] F. K. Baganoff, M. W. Bautz, W. N. Brandt, G. Chartas, E. D. Feigelson, G. P. Garmire, Y. Maeda, M. Morris, G. R. Ricker, L. K. Townsley, F. Walter, "Rapid X-ray flaring from the direction of the supermassive black hole at the Galactic Centre". *Nature* **413** (6851), pp. 45–8, Sep. 2001.
- [2] C. M. Urry, P. Padovani, "Unified Schemes for Radio-Loud Active Galactic Nuclei," *PASP* **107**, pp. 803-845, Sep. 1995.
- [3] J. H. Taylor and D. R. Stinebring, "Recent progress in the understanding of pulsars," *ARA&A*, **24**, pp. 285-327, 1986.
- [4] R. R. J. Antonucci and J. S. Miller, "Spectropolarimetry and the nature of NGC 1068," *ApJ* **297**, pp. 621-632, Oct. 1985.
- [5] R. Novick, M. C. Weisskopf, R. Berthelsdorf, R. Linke, and R. S. Wolff, "Detection of X-Ray Polarization of the Crab Nebula," *ApJ* **174**, pp. L1-+, May 1972.
- [6] R. Blandford, E. Agol, A. Broderick, J. Heyl, L. Koopmans, and H.-W. Lee, "Compact objects and accretion disks," in *Astrophysical Spectropolarimetry*, J. Trujillo-Bueno, F. Moreno-Insertis, and F. Sánchez, eds., pp. 177-223, 2002.
- [7] H. L. Marshall, "Polarimetry with a soft x-ray spectrometer," in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7011**, Aug. 2008.

Appendix

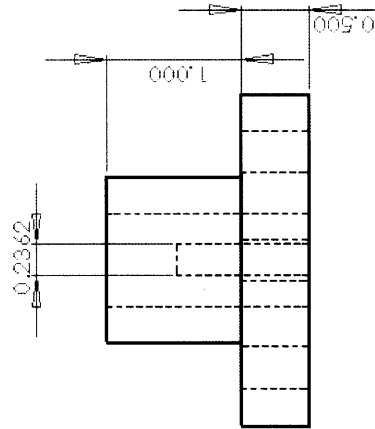
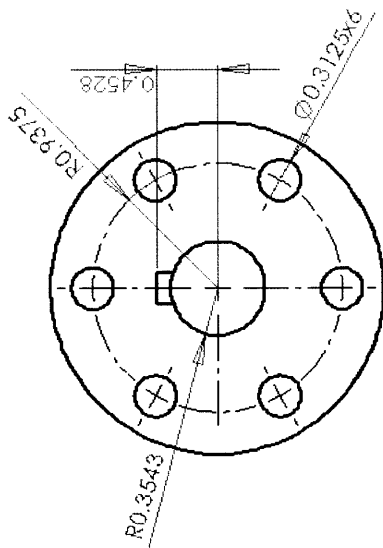
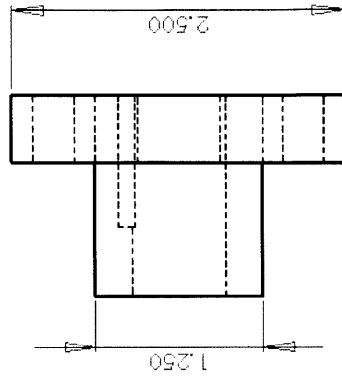
Important Parts List

<u>Name</u>	<u>Company</u>	<u>Part Number</u>
Source motor	Oriental Motors	AR98MA-N50
5-way cross	Huntington Mechanical Labs	VF-5250
Rotating flange	Huntington Mechanical Labs	VF-174-275
Mirror manipulator	MDC Vacuum	672002
SML tip-tilt stage	Siskiyou	RM80.1H
Detector elbow	MDC Vacuum	823003
Detector rotational stage	Micos	DT-80

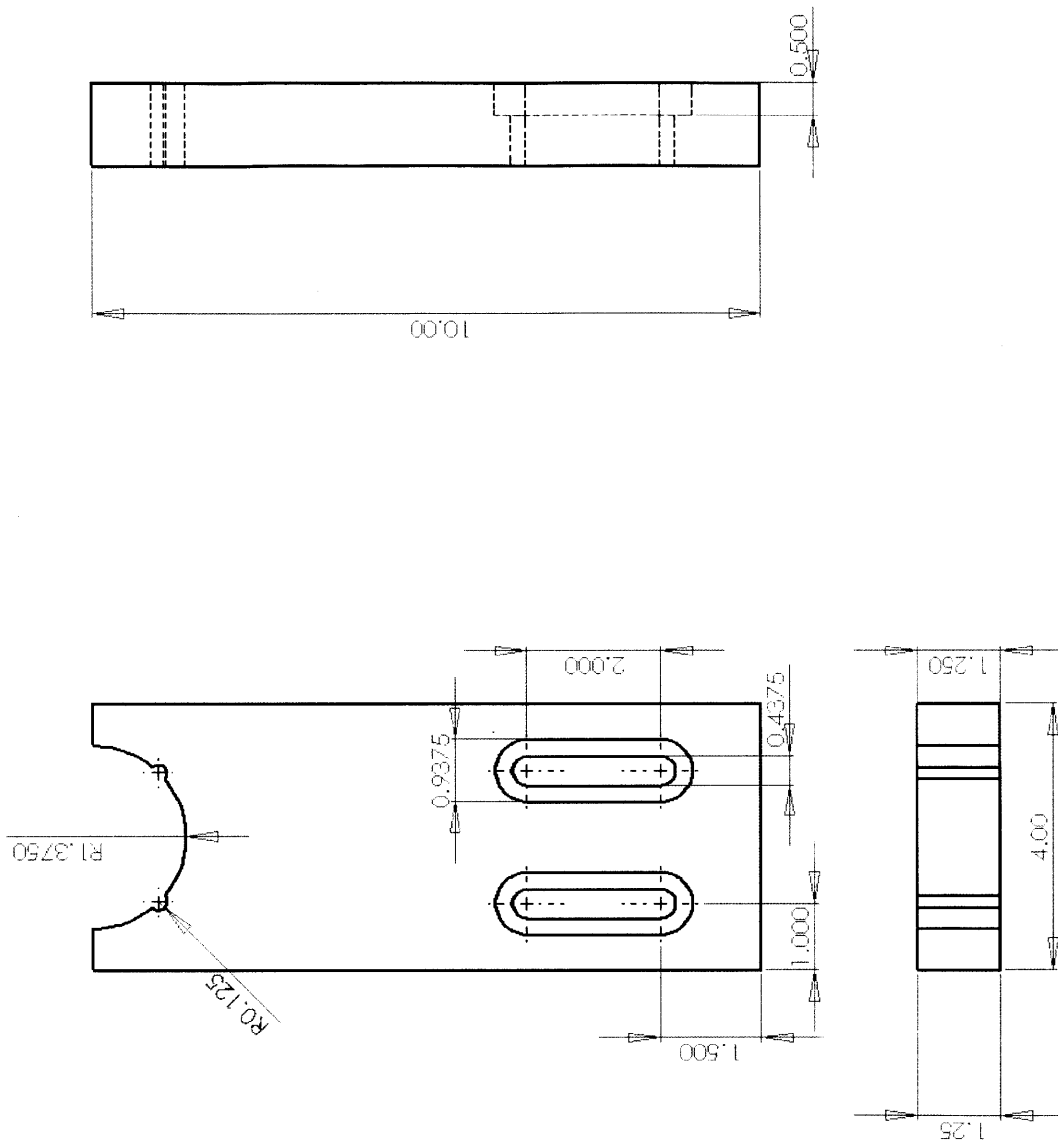
Drawings for Custom Parts



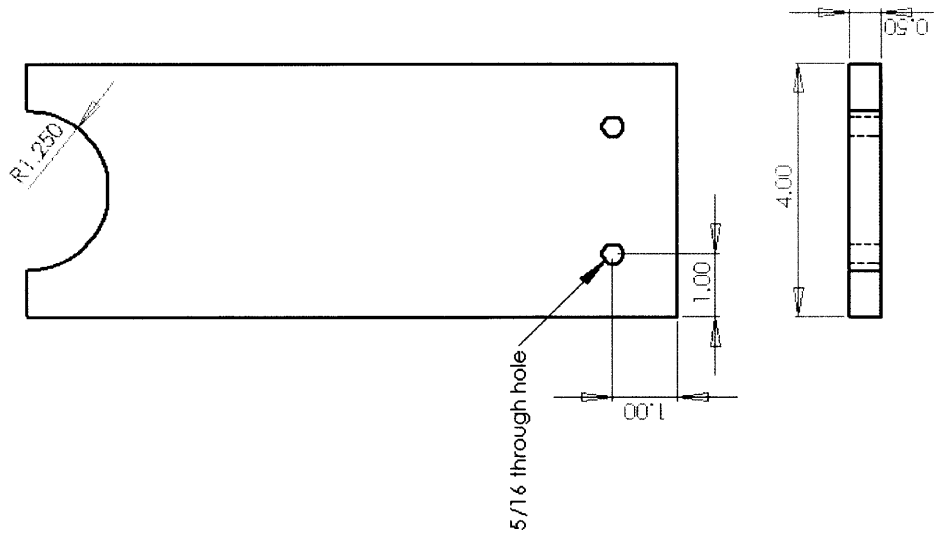
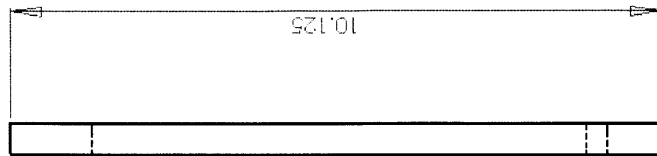
Motor Support



Source Motor Collar



Rotating Holder



Stationary Support