Optical alignment of the Far Ultraviolet Spectroscopic Explorer (FUSE)

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ABSTRACT

The Far Ultraviolet Spectroscopic Explorer (FUSE), scheduled for a summer 1999 launch, is an astrophysics satellite designed to provide high spectral resolving power ($\lambda/D\lambda$ = 24,000--30,000) over the interval 90.5--118.7 nm. The FUSE optical path consists of four co-aligned, normal incidence, off-axis parabolic primary mirrors which illuminate separate Rowland circle spectrograph channels equipped with holographic gratings and delay line microchannel plate detectors. The spectrograph comprises the upper half of the instrument structure, and was internally aligned prior to delivery to the integration team.

We describe the optical alignments carried out during integration of the satellite, including off-axis primary mirrors, system aperture stops, and baffle assemblies. Due to cost and schedule constraints, a simplified alignment procedure for the primary mirrors was implemented using a visible light, double pass system in combination with metrology of alignment references on the mirror substrates. Strict contamination and exposure requirements meant that the mirrors had to be maintained in a nitrogen-purged environment during alignment. The aperture stop in front of each primary mirror was aligned to the respective grating aperture using a laser reflected from the mirror through the spectrograph slit and onto the grating corners. Baffle assemblies were also aligned at this stage using theodolites and alignment cubes. In addition, light path checks were performed to look for obstructions, and a significant problem was uncovered early enough to be corrected without significant schedule impact.

KEY WORDS: FUSE, optical alignment, ultraviolet, off-axis parabola, contamination

1. INTRODUCTION

FUSE is a NASA satellite program intended to obtain high resolution far ultraviolet (FUV) spectra from astronomical sources. It was conceived and fabricated by The Johns Hopkins University (JHU) and an international team of corporations, universities, and government agencies. It is currently scheduled for a June 1999 launch aboard a Delta II rocket from the Cape Canaveral Air Station.

FUSE consists of four coaligned telescopes, which focus FUV photons into the slits of Rowland circle spectrographs. The spectrographs were developed and aligned at the Center for Astrophysics and Space Astronomy at the University of Colorado.[1] The four telescopes consist of 385 by 350 mm aperture off-axis parabolic (OAP) mirrors with a focal length of 2245 mm; manufactured by SVG-Tinsley Laboratories.[†] Additional descriptions of the FUSE optical system are available.[2]

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Our paper primarily covers the methods used to align the OAPs to the slits of the spectrographs. The alignment was complicated by a number of critical issues, including coalignment of the four mirrors, maintaining the particulate and molecular cleanliness of the optics, and controlling schedule and cost. This activity took place in early 1998 at The Johns Hopkins University's Applied Physics Laboratory (APL).[‡]

Other authors describe conceptually similar alignment methods for OAPs.[3,4] We concentrate here on aspects that are unique to this program, primarily those relating to the complicating issues mentioned above.

Requirements for the alignment of the FUSE telescope mirrors to the spectrograph slits were developed by top-down budgeting of overall instrument performance requirements (Table 1). The drivers for these requirements were effective collecting area of the instrument and range of motion of the flight actuators. Each mirror has three independent actuators to control focus and rotation about X and Y during flight. The two rotations allow coalignment of each mirror to its spectrograph slit. Each actuator has a range of ±1.4 mm. We define the following coordinate system: +Z along the line of sight of the instrument, and X along the direction from the mirror vertex to its geometric center.

Table 1. Telescope Mirror Alignment Requirements

Degree of Freedom	Maximum Error	Driving Factor
X Translation	± 210 μm	Collecting area
Y Translation	± 210 μm	Collecting area
Z Translation	± 100 μm	Range of actuator motion
Rotation about X	± 10 arcseconds	Range of actuator motion
Rotation about Y	± 10 arcseconds	Range of actuator motion
Rotation about Z	± 4 arcminutes	Collecting area

Collecting area driven requirements were limited by increase in image size from the telescope mirrors. The requirement on the mirrors is that 50% of the collected FUV light at 100 nm pass through the FUSE 1.25 arcsecond slit. Flow-down budgeting of this requirement allows coma from about 1 arcminute of misalignment in both rotations.

2. DESCRIPTION OF MIRROR ALIGNMENT METHOD

When the normal incidence FUSE design was conceived in 1993, the baseline method for aligning the telescope mirrors to the spectrograph slits was to use FUV light from a collimator system. A custom-built vacuum chamber and costly system for moving and locking down optical elements would have been required. This method would have had the advantage of allowing for "end-to-end" optical testing, but that requirement was fulfilled as part of the satellite level thermal-vacuum test.[5]

Cost and schedule constraints forced the abandonment of this concept in 1995. Alternative concepts were investigated, a double pass method was chosen, and procedures and GSE hardware developed in 1996 and 1997. The selected method minimized ground support equipment (GSE) development cost and effort, and allowed for alignment to be completed in approximately one month in parallel with other activities. A test bench was set up using an on-axis parabolic mirror masked down to simulate a half-scale version of the FUSE mirrors. While this test bench was useful, it was not fully exploited due to staffing limitations.

2.1. Summary of generalized alignment requirements

Simplified, the desired end result of the FUSE primary mirror alignment was to have all four mirrors' optical axes parallel to one another and passing through their respective spectrograph slits in the plane of the focal plane assemblies (FPA). These requirements allow all four channels to observe a single collimated source. While the mirrors do have actuators that

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allow coalignment to be done in flight, the amount of motion used must be kept small to avoid the introduction of significant coma into the system.

The optical axes must also be parallel to the instrument line of sight. This requirement prevents light loss through the system, by insuring that the baffles and the spectrograph diffraction gratings are aligned to the entrance pupil of the system.

The final requirement was to have the primary mirrors focused to their respective slits. Flight actuators are also provided for focus, but their usage is limited to correction of small residual errors from the alignment process, as well as changes that occur in flight such as structural shrinkage caused by water desorption.

2.2. Summary of alignment method

The method used for alignment was comprised of the following tasks:

- Determination of primary mirror optical axes and transfer of angular information to references
- Determination of instrument line of sight and transfer of angular information to references
- Rotational alignment of primary mirrors to instrument line of sight using references
- Alignment of an autocollimating flat to the instrument line of sight
- Projecting light backwards through the spectrograph slit to double pass off the mirror, and translating the mirror to move the return image onto the slit
- Examining the focus of the return image, and pistoning the mirror to produce best focus on the same plane as the slit itself

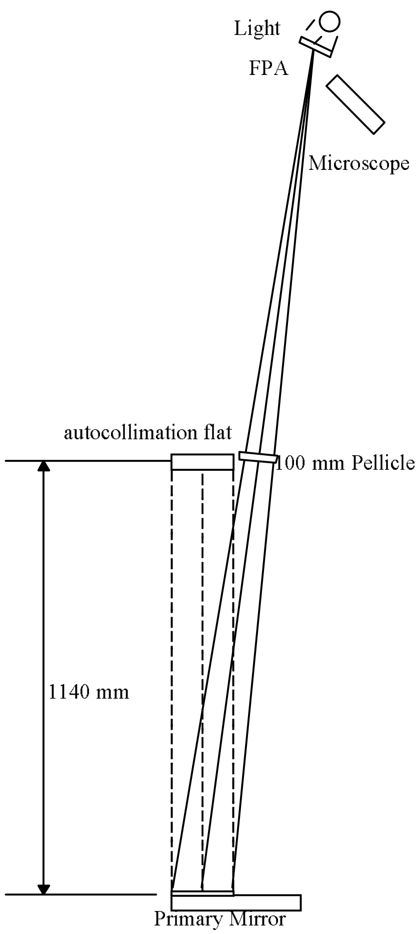

Figure 1. Optical Path for Alignment

2.3. Method used for alignment

During optical testing of the primary mirror assemblies, an interferometer was used to determine best alignment of the mirror to an autocollimating flat in double-pass mode. The normal to the flat was thereby assumed to be parallel to the primary's optical axis. Theodolites were then used to measure the angles between the normal and two alignment references attached to orthogonal sides of the primary.

A survey of the structure was conducted using theodolites and tilt levels to determine the line of sight of the instrument. Based on this data, theodolite metrology was used to place the optical axes of the instrument and the primary mirrors along the zenith vector, and align the autocollimating flat normals parallel to the gravity vector.

The spectrograph slit was then backlit. Light from the slit filled the primary mirror and was collimated. The collimated beam was autoreflected from the flat mirror back to the primary, which focused it back near the slit. A microscope was used to determine the image location. The mirror was then translated in X and Y to place the return image of the slit very close to the slit itself (Figure 1).

The return image was then examined with the microscope, and a measurement made of focus location with respect to the slit plane. The primary mirror was then adjusted in focus to correct any difference found. The process was repeated several times until all errors were within tolerance simultaneously.

2.4 Contamination control

The FUSE optics have tight contamination requirements, caused by their use in the FUV. Surface requirements are level 300 A/2, as described in MIL-STD-

1246C. This is roughly the equivalent of visually detecting 10 or fewer particles over the entire area of the mirror surface, using a strong white light in a darkened room. The limits on molecular contamination were further defined to average ≤ 0.5 nm thickness of hydrocarbons over the entire surface, which for most substances is less than one molecular layer.

Two of the mirror and grating pairs are coated with Al + LiF, which is hygroscopic. This type of coating quickly loses its UV reflectivity in "normal" room humidity of 30% or more. In order to prevent this loss of reflectivity, the optics were protected by a small, sealed, nitrogen-purged environment during the vast majority of instrument integration. Although alignment was performed in a class 10k cleanroom, with controlled humidity, requirements were imposed to not expose the optical elements to these conditions for more than tens of minutes *total*. This requirement, combined with our estimate of the time required to complete the task, forced the use of a nitrogen-purged environment for the alignment.

2.5. Risks associated with this alignment method

While this method of alignment was relatively straightforward, and much simpler in implementation than the original vacuum FUV method, it did hold significant risk. The primary risk was that it required a series of measurements, at various levels of assembly, that had limited opportunities for reverification. If any datum from any step was in error, it would have gone undetected through the alignment process, resulting in a mislocation of the primary mirror with respect to the spectrograph slit. The vacuum method directly demonstrates whether the FUV images are small enough to be within requirements. The method used on FUSE, however, forced verification to wait until the optical end-to-end test, which occurred much later in the flow, when errors would have been extremely difficult to correct.

While extreme care was used to prevent a contamination event, there was no direct method to monitor for one. Humidity of the purged environment was observed, and optical witness mirrors checked for reflectivity after alignment, but there was risk that an accident would occur unknown until well after the fact.

3. PRE-CALIBRATION OF REFERENCE FLATS

The first step of the alignment process occurred while the primary mirrors were being fabricated and assembled. At that time, measurements were made relating the mirror optical axes to alignment references on the sides of the mirror substrates.

3.1. Primary mirror configuration

The off-axis sections of the FUSE mirrors do not contain the parabola vertex. The issue of alignment references was considered early in the design of the mirrors, leading to the incorporation of alignment flats polished into the sides of the mirror substrates (Figure 2). The polished surface is on a raised boss created during grinding of the substrate, projecting 2 mm out from the substrate edge, approximately 50 mm square. The flats are located in the center of each mirror side except that nearest to the vertex. Only two orthogonal flats are needed for alignment purposes, but three were included to make the substrates interchangeable on the optical bench.

3.2. Primary mirror contamination control

Line-of-sight access to the flats is via ports in the sides of a thin, composite, thermally regulated "pie-pan" surrounding each mirror, which also forms part of the purge enclosure. The original plan was to install windows in the ports during I&T to allow the flats to be viewed with a theodolite at any time without disturbing the mirror purge. However, we decided in the end not to coat the flats due to schedule and contamination concerns, and the risk to the mirrors from additional handling. This created a problem for theodolite work, however, because equal-intensity autocollimation images would be returned from both surfaces of the port windows as well as the uncoated flats. Therefore, the port covers were completely removed during alignment measurements, but only as long as needed to actually take a theodolite reading. Relative humidity readings were taken periodically at the port openings before the covers were reinstalled, and were consistently less than 10%.

3.3. Angular calibration

Two angles are important for each reference flat: the wedge between the flat and its corresponding mirror side, and the angle between the optical axis and the surface of the flat. The wedge angle was measured mechanically to be < 2 arcminutes for any flat, which meant all could be assumed to be parallel to the mirror sides for alignment purposes. The angle with respect to the optical axis was calibrated twice: once by the mirror vendor during final acceptance testing, and again at JHU before delivery of the mirror assemblies to the I&T team. Both calibrations were performed in a double-pass autocollimation setup after optimizing the alignment of the system interferometrically. The setup used at JHU to measure the anti-vertex-side reference flat is shown in Figure 3. Alignment of the FUSE OAP to the autocollimating (AC) mirror was adjusted for minimum rms wavefront error as reported by the interferometer. This puts the optical axis of the OAP normal to the surface of the AC mirror. Theodolite T1 was then aligned to the AC mirror and T2 to the reference flat, and azimuth readings taken. The theodolites were then boresighted to each other, azimuth angles recorded, and the angle between the AC mirror and the reference flat calculated. Note that the figure error of the mirrors was degraded during assembly build-up (from ~.025λ to .050λ rms), which makes the alignment of the autocollimation setup less determinate. This most likely accounts for the typical few to several tens of arcseconds difference between the calibrations, except for an unexplained two arcminute difference for one reference flat.

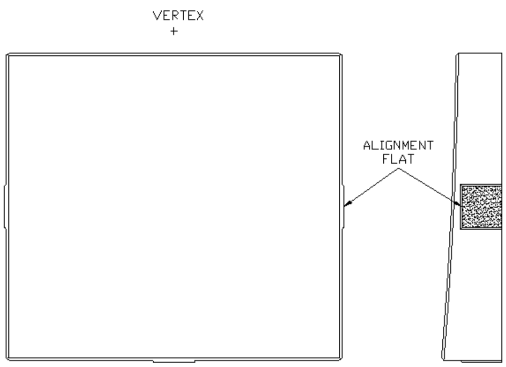

Figure 2. Mirror Reference Flats

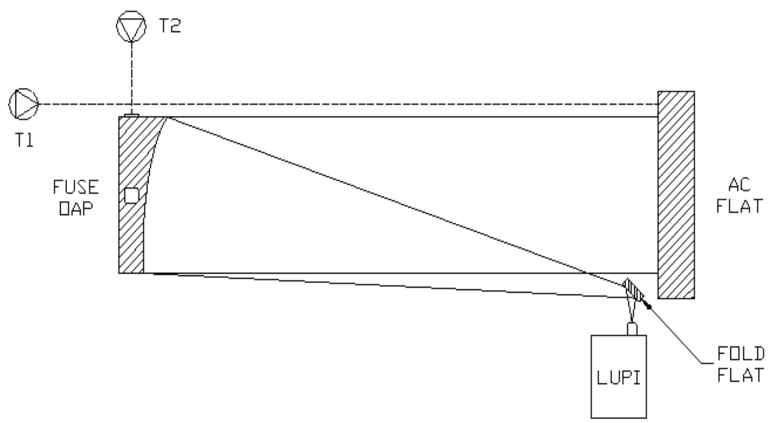

Figure 3. Reference Flat Calibration Setup

4. GROUND SUPPORT EQUIPMENT DESIGN AND IMPLEMENTATION

The alignment ground support equipment for the FUSE primary mirror alignment procedure was developed to satisfy the following requirements:

- Provide a depth of focus of less than 100 microns
- Contain the primary mirror in a nitrogen purge environment
- Image the slit and return in order to resolve 10 microns
- Establish the FUSE optical axis to within 10 arcseconds

There are four major subsystems of the entire alignment GSE: source, autocollimating mirror support assembly, FPA imaging assembly, and metrology support setup.

4.1. Source

The source chosen to back-illuminate the slit was an inexpensive fiber optic system available commercially off-the-shelf. A lamp was outfitted with a sixteen foot length of ¼ inch diameter fiber optic. This allowed the source to stay at floor level while the output was positioned above the FPA (Figure 4). A conveniently located bracket on a support strut of the spectrograph assembly allowed the fiber optic to be held by an articulating support arm. This gave great flexibility in moving and positioning the fiber source behind the FPA for maximum light transmission through the slit.

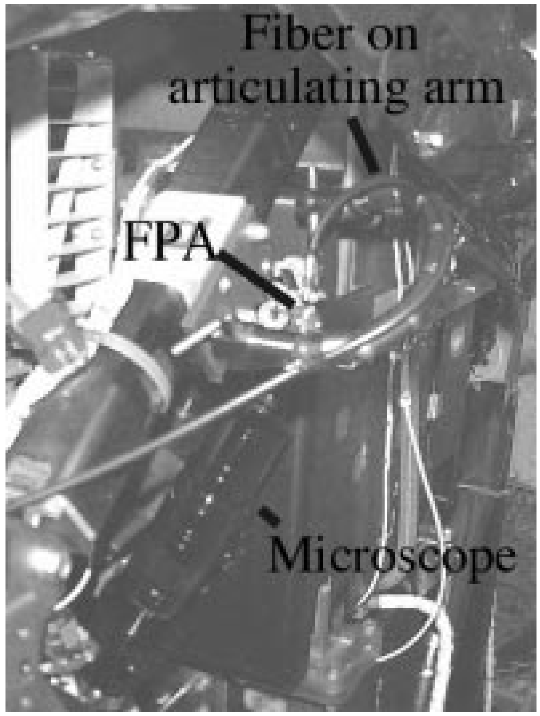

Figure 4. Fiber Source and Microscope Near FPA

4.2. Mirror Support Assembly

The largest section of alignment GSE was the autocollimating mirror support assembly. The driving design criteria of this assembly was the size of the autocollimating mirror required to achieve the appropriate depth of focus (DOF). The required F/# is given by the relationship:

$$DOF=2\lambda F/\#^2 \text{ or } F/\#=\sqrt{(DOF/(2\lambda)}$$

Assuming a wavelength of 500 nm for a white light source and a focal length of 2245 mm for the FUSE primary mirrors, this leads to at least an F/10 beam to provide the required depth of focus or a mirror of at least 225 mm in diameter. We selected a 150 mm x 300 mm rectangular $\lambda/10$ flat which would provide an approximately F/8 beam and DOF of 50 microns.

To prepare the autocollimating mirror, a one inch alignment cube was bonded onto its rear surface. Theodolite metrology was used to determine the orientation of all cube faces with respect to the flat normal. This information was later used to align the mirror to the FUSE optical axis.

The next item chosen was a 125 mm x 160 mm clear pellicle that would be mounted next to the autocollimation mirror. This would allow passage of the incoming and outgoing beams between the FPA and the primary mirror without introducing any significant focus shifts or aberrations (Figure 1). A beam map was created to determine the height at which the mirror and pellicle had to be located above the primary mirror to ensure that no part of the beam would be vignetted. The mirror/pellicle needed to be at least 1140 mm above the primary mirror.

A support plate for the mirror/pellicle and a support assembly for this plate were designed to interface with the FUSE primary structure integration dolly. An extruded aluminum support frame was developed which bolted onto the dolly and straddled the primary mirror assemblies on the mirror bench. This frame supported two aluminum plates 1150 mm above the primary mirrors. Each plate held an autocollimating mirror and pellicle next to each other with the mirror mounted face down in an aperture in the plate. Angular adjustment of the autocollimating mirror was made using three jack screws. The plate also formed a seal with the mirror rim, and included a series of aluminum angles on the underside which formed a perimeter around the area outside the mirror/pellicle. These angles allowed for a lumalloy bag to be taped to the underside of the plate. This bag was extended down to the primary mirror assembly and secured to the pie pan. This provided the sealed environment in which a dry nitrogen purge could be maintained to protect the mirror coating during the alignment process. Note that witness samples were used to measure reflectivity before and after alignment, and no changes were recorded.

4.3. FPA imaging assembly

The FPA imaging assembly viewed the FPA slit and its return from the mirror assembly. A microscope was required that was powerful enough to resolve the FPA slit and return, small enough to be mounted in the extremely tight envelope of the spectrograph structure behind the FPA, and could be placed far enough away from the FPA such that the body of the microscope would not block the incoming or outgoing light. Upon evaluation of several systems, a video microscope was chosen for its 1.5 to 2 inch focal distance and its resolving capability. Again, we were able to take advantage of some conveniently placed mounting holes on the spectrograph structure to create a bracket which held a three axis translator upon which the microscope was mounted. A small CCD camera was then attached to the microscope and its power and video output leads routed down to floor level to a video monitor. The three axis translator allowed the microscope to be moved in order to find the images as well as to focus on the slit or image as required.

4.4. Metrology set-up

Autocollimating theodolites were used to establish the orientation of all relevant components of the alignment system, with the objective of placing the optical axes parallel to the gravity vector. The spectrograph had a master reference optical cube which had been previously measured to the FUSE optical axis. Theodolites were positioned to autocollimate on the appropriate cube faces, and the leveling feet of the integration dolly adjusted until the autocollimation returns were at the known elevation values to place the FUSE optical axis parallel to the gravity vector.

Two additional theodolites were used to autocollimate on the alignment flats on the sides of the primary mirrors. The measurements described in section 3.3 had calibrated the pointing direction of these flats with respect to the primary mirror optical axis. Again, the appropriate elevation values were calculated and set on the theodolites. Manual alignment screws under the primary mirror assemblies were then adjusted in order to bring the primary mirror optical axes parallel to gravity (Figure 5).

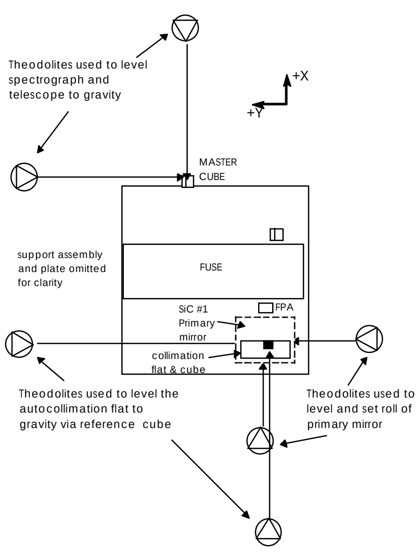

Figure 5. Theodolite Set Up

4.5. Alignment procedure flow

A detailed procedure was prepared in advance, describing all steps required to align the telescope mirrors.[6]

The first step in the procedure was to position the support framework and mirror/pellicle plates over the appropriate primary mirrors. The microscopes and illuminating fibers were also installed at the appropriate locations on the spectrograph structure. The purge bag was then constructed between the mirror/pellicle plate and the primary mirror pie pan. This allowed the removal of the lexan cover which normally protected the primary mirror surface. The theodolites were then used to set the optical axes of the instrument (via jacks under the instrument dolly), the autocollimation mirror, and the primary mirror parallel to gravity reference.

At this point, the illuminating fiber was positioned behind the FPA slits in order to project light through the pellicle to the primary mirror. The most difficult part was then to determine where the return image was located. It was usually found on or near the FPA using a piece of clean room paper as a viewing screen. Once found, the image was moved onto the FPA near the slits by translating the primary mirror horizontally along instrument X and Y axes. The video microscope could then be positioned to view both the FPA slit and its return image. The primary mirror assembly was then moved in X and Y to position the return image directly on the slit and also moved in Z to focus the image at the FPA. The X and Y motion was initially done using two translational stages, but we quickly discovered that manual motion produced better results, and the stages were discarded. The microscope images of the slit and return were recorded by connecting the video output to a frame grabber installed in a personal computer (Figure 6).

After alignment, the mirror assembly was secured in position and pinned. The same set-up and procedure was then used to verify that the mirror alignment still met all criteria after pinning was accomplished.

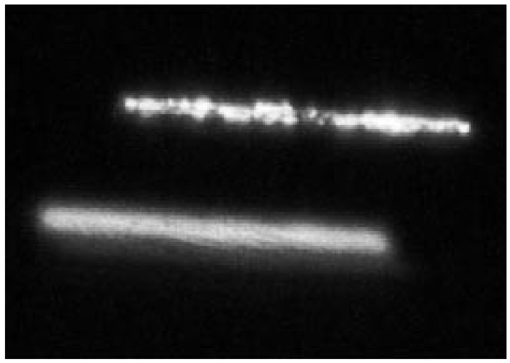

Figure 6. Slit (Top) and Return Image

5. OTHER ALIGNMENTS PERFORMED

5.1. Mirror aperture stop

The FUSE mirrors each have an adjustable aperture stop located just above their reflecting surfaces. These stops are independently adjustable on all four sides, and match the two cut-off corners of the gratings. Mirror aperture stop alignment involved mapping the projection of the gratings onto the mirrors using a laser projected through the spectrograph slits. The six corners of the grating stops were determined as critical mapping features. The FPA's contain a set of three slits (4, 1.25, and 30 arcsecond) lying along a line parallel to the Y-axis, requiring both extreme slits to be used and thereby creating two slightly offset projections. The aperture stops were therefore positioned in order to underfill the gratings through any slit.

The hardware consisted of a collimated laser source and a small adjustable turning mirror. The laser was set up away from the instrument and aimed to send its beam horizontally over to the turning mirror. The turning mirror was then aligned above the primary mirror such that it steered the beam down along the optical axis to be reflected off the mirror and up through the slit. The previous alignment of the mirror to the slit assured that the incoming beam was parallel to the optical axis in this configuration. This iterative alignment process could be quite cumbersome, as not only did the angular position have to be fairly accurate, but the beam also needed to strike the mirror at its appropriate mapping point (see Figure 7). Fortunately, viewing the laser spot on the grating was actually aided by the high levels of diffraction through the small slits, which formed 'crosshairs' that removed the guesswork of targeting the grating's radiused corners. The stops were finally positioned to overshadow the edges of the gratings by about 1 mm to provide margin for possible movement. Once all the stops were in their desired locations, they were locked into place, and verified a final time.

Again, exposure of the optical coatings was an issue, so a plexiglass cover with small, coverable ports in the desired locations was placed over the mirrors, while a simple thin sheet of transparent nylon protected the gratings. This procedure, however, was done only on the SiC channels, as it was decided that the exposure of the LiF coatings would likely degrade the signal more than simply setting the stops at their smallest aperture. We felt secure in this assumption after the SiC channel stops wound up in their predicted locations.

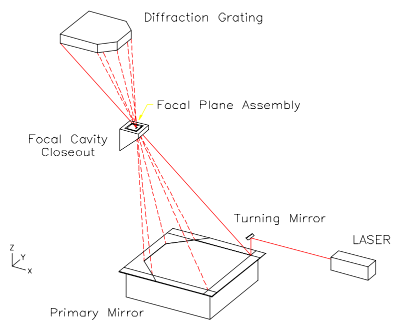

Figure 7. Aperture Stop Alignment Diagram

5.2. Baffle interference checkout and alignment

One of the objectives of the baffle verification plan was to determine if the FPA apertures and baffle vanes were placed correctly with respect to each other. A misalignment of these features could cause the incoming light from the primary mirror to be vignetted with a corresponding loss of signal. A novel way was developed to place a theodolite telescope at the exact position of the inboard and outboard edges of the primary mirror with respect to the baffle references. An operator could then view directly or shine a light through the telescope and see any potential interferences.

The first step involved placing an optical cube on the baffle structure to serve as a future reference. Once bonded, standard theodolite metrology methods were used to determine the orientation of the cube with respect to the baffle coordinate system. The baffle coordinate system was defined when the baffle was placed on its mounting points on a leveled surface table, which fixed the tip/tilt of the X axis parallel to gravity. The direction of the Z axis was determined by having a theodolite (T0) positioned to sight along the length of the baffle such that it was parallel to the structure longeron (Figure 8). Transferring this coordinate system to the optical cube provided a reference for future baffle verification measurements and alignment of the baffle to the instrument.

The vane and aperture verification procedure took advantage of the fact that the theodolites being used had a reference mark on the side of the theodolite body which is located on the telescope elevation axis and displaced a known distance from the telescope optical axis. This subject theodolite (T1 in figure) was aligned to the baffle axes by referencing the baffle optical cube, and then offset by known amounts in elevation to simulate a ray originating from one of the mirror extremes. A theodolite coordinate measurement system (Cubic Precision AIMS III, theodolites T2 and T3) was set up to measure known targets on the baffle and the reference mark on the side of the subject theodolite. The theodolite was then translated as required to put its telescope optical axis at the exact point where the mirror extremes would be. This was an iterative process that required continually re-aligning in azimuth and elevation until the appropriate coordinate location was achieved. Once aligned, the telescope optical axis was colinear with the expected light path of a ray emanating from that point on the mirror (Figure 8). The theodolite operator simply looked through the telescope and focused through the baffle aperture. Anything viewed on the theodolite reticle would be considered an obstruction. A bright light was also substituted for the autocollimation lamp such that the theodolite actually projected a beam of light through the baffle. Interferences from the baffle vanes and the FPA apertures could then be seen by observers viewing locations from where the light beam was reflecting. This process was repeated for two locations per baffle tube representing the inboard and outboard edges of the primary mirrors.

The optical reference cube was used to verify the alignment of the baffle assembly once integrated to the instrument structure. Again standard theodolite metrology methods were used to measure the orientation of the baffle reference cubes with respect to the instrument structure reference cubes. The analyzed data determined the final orientation of the baffle axes with respect to the telescope optical axis.

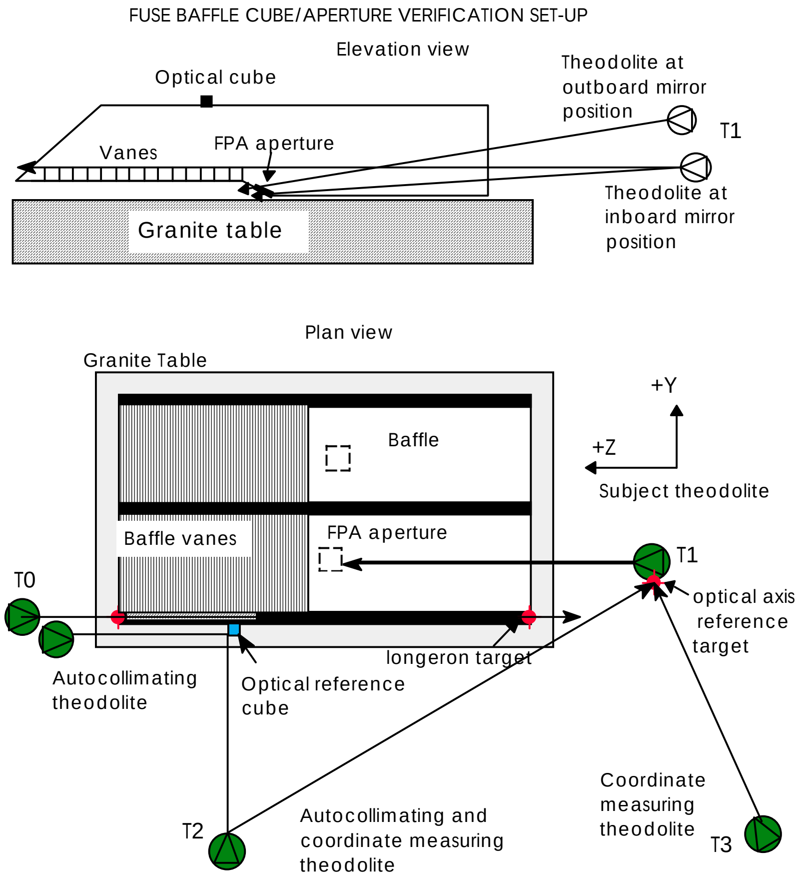

Figure 8. Baffle Aperture and Alignment Verification

5.3. Optical path checks

Upon final assembly of the optical system, the resulting optical paths were checked for vignetting or other interferences. The main path of concern was from the mirrors to the gratings, through the slits and their associated Focal Cavity Closeout (FCC) assemblies. Again, an external laser directing a horizontal beam to a turning mirror was used. This time, however, the turning mirror steered the beam directly up to the slits rather than bouncing it off the primary mirror first. All paths were then checked to look for features obstructing the beam.

The procedure for each channel was to position the turning mirror above the telescope mirror and locate the laser on it such that, viewed from the slit or the grating, the apparent source was just outside the aperture stop. This 'elbow room' was on the order of 10 mm. From each of the six corners of the aperture stop, the beam was then directed to the extents of the FPA's, as well as through each of the three slits, and evaluated as to whether it reached the grating unobstructed.

During this process it was discovered that not all combinations of ray angles had been taken into account when designing the FCC's, and that the laser was clipped by one of its internal surfaces. Note that the FCC's are a separate assembly from the baffle, and could only be checked for vignetting after installation. The parts were removed and reworked to accommodate the necessary view angles. They were then reinstalled and all optical paths were verified.

6. CONCLUSION

In general, the method and implementation of the optical alignments described herein were satisfactory. Measured results are shown (Table 2).

Table 2. Telescope Mirror Alignment Results

Degree of Freedom	Mirror LiF #1	Mirror LiF #2	Mirror SiC #1	Mirror SiC #2
X location error (uncorrectable)	-38 μm	270 μm *	-65 μm	253 μm *
Y location error (uncorrectable)	335 μm *	162 μm	-65 μm	-194 μm
Z (focus)	-200 μm *	25 μm	50 μm	-240 μm *
Rotation about X (for coalignment)	13 arcseconds *	50 arcseconds *	7 arcseconds	7 arcseconds
Rotation about Y (for coalignment)	4 arcseconds	-30 arcseconds *	-1 arcsecond	-5 arcseconds
Rotation about Z (uncorrectable)	2.4 arcminutes	1.4 arcminutes	-1.5 arcminutes	-6.9 arcminutes *

Items marked with an * are outside the original budgeted allocation. Those in the two "location error" rows were close enough to the allowable that they were accepted over schedule delays for corrective action. The focus and X and Y rotations outside of allocation were accepted by rebudgeting the range of motion of the flight mechanisms. The single Z rotation outside allocation was accepted as the original budget was determined to have been too tight.

Limited data from the optical end-to-end test indicates that no gross errors in positioning were made, but are not of high enough quality to show agreement with our measured errors. Information from in-flight alignment testing is not yet available.

Some lessons learned are described below.

6.1. Schedule

The complete mirror alignment activity, including pinning and recheck, was baselined to take approximately one month of standard working hours. Actual running time was approximately double this. There were several reasons for the delay, such as a longer learning curve than expected, the inefficiency of working rotating shifts (day/evening), and errors made during the process.

While we did some bench testing of our procedure in advance, we would have saved considerable time on the instrument schedule's critical path if we had done a high-fidelity test of the method beforehand. Our learning curve during the activity was very steep, and our last alignment took approximately one-tenth the time of the first. A test and practice session of the methods using the flight structure and an engineering test unit mirror would have subtracted a minimum of one to two weeks off the critical path.

6.2. Cost

The cost of this activity was well controlled, outside of that directly associated with schedule. With the exception of the framework to hold the flats, the microscopes, the pellicles, and the mirror translators (which were not used), all hardware used was existing or borrowed from other institutions.

6.3. Procedure

The use of a detailed written procedure was helpful for ensuring that all required hardware was in place in advance, and for establishing a basic methodology. It was also helpful for having a closeout checklist to be reviewed before the end of each major phase of the alignment. However, we quickly found that we were deviating from the procedure much more than expected, and resorted to a combination of laboratory notebook and procedure to document what was done. It is our opinion that spending somewhat less time on producing a very good formal procedure, and more time on practicing parts of the procedure on non-flight hardware would have been more beneficial to the program.

6.4. Errors Made

The most significant error we made was accidentally rotating one autocollimating flat 180° from its intended orientation, resulting in a several arcminute error in the direction its surface normal. The error was discovered after the mirror had its shear pins installed, during the final alignment check, when the image fell far from the slit. Fortunately, we were able to remove the pins and correct the alignment error, with a cost of about 2 shifts time. We were unable to determine the cause of this error (the flat was marked, and the procedure specifically had us check the rotation).

There was also a large (approximately two arcminutes) difference in the calibration of the optical axis angle to one mirror's reference flat between measurements made at the mirror vendor and at JHU. We decided to use the numbers obtained at JHU, as they had been measured with the mirror closer to its final configuration. This is also a fairly "soft" error and even if the vendor's number was correct, would result in a very slight (not measureable in flight) loss in performance.

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REFERENCES

[1] E. Wilkinson, J. Green, S. Osterman, K. Brownsberger, and D. Sahnow, "Integration, Alignment, and Initial Performance Results of the *Far Ultraviolet Spectroscopic Explorer* (FUSE) Spectrograph," SPIE, vol. 3356, pages 18-29, 1998

[2] J. Green, E. Wilkinson, and S. Friedman, "The design of the Far Ultraviolet Spectroscopic Explorer spectrograph," SPIE, vol. 2283, pages 12-19, 1994

[3] C. Bond, C. Pipan "How to Align an Off-axis Parabolic Mirror", SPIE volume 1113, pages 236-248, 1989

[4] M. Ruda, *Introduction to Optical Alignment Techniques*, class notes from College of Engineering, University of Wisconsin-Madison

[5] S. Conard, K. Redman, R. Barkhouser, D. McGuffey, S. Smee, R. Ohl, and G. Kushner, "Hardware and methods of the optical end-to-end test of the Far-Ultraviolet Spectroscopic Explorer (FUSE)," SPIE, vol. 3765 , 1999 (this volume)

[6] S. Conard "Mirror Installation and Alignment," FUSE-TAP-0003, internal FUSE document