The Far Ultraviolet Spectroscopic Explorer optical system: lessons learned

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ABSTRACT

The Far Ultraviolet Spectroscopic Explorer (FUSE) is a NASA astrophysics satellite designed to produce high resolution spectra in the far-ultraviolet (90.5--118.7 nm bandpass) with a high effective area (20--70 cm^2) and low background detector. It was launched on a three-year mission in June 1999 aboard a Boeing Delta II rocket. The satellite has been performing routine science observations since December 1999.

FUSE contains four co-aligned, normal incidence, off-axis parabolic primary mirrors which illuminate separate Rowland circle spectrograph channels equipped with holographically ruled diffraction gratings and microchannel plate detectors. Fine error sensors (slit jaw cameras) operating in the visible on two of the channels are used for target acquisition and guiding.

The FUSE mission was first proposed in the late 1980s, and experienced several major conceptual changes prior to fabrication, assembly, and testing, which lasted from 1996 through 1999. During the program, we realized both positive and negative aspects to our design and processes that may apply to other space missions using telescopes and spectrographs. The specific topics we address are requirements, design, component specification, integration, and verification.

We also discuss on-orbit alignment and focus. These activities were complicated by unexpected levels of motion between the optical elements, and the logistical problems associated with limited ground contact passes in low Earth orbit. We have developed methods to characterize the motions and mitigate their resultant effects on the science data through a combination of observing techniques and modifications to the data reduction software.

Keywords: FUSE, satellites, ultraviolet, contamination, scattering, reflectivity, spectroscopy, optical systems

1.0 INTRODUCTION

The Far Ultraviolet Spectroscopic Explorer (FUSE) is a NASA satellite program that obtains high resolution ($\lambda/\Delta\lambda$~20,000), far-ultraviolet (FUV; 90.5--118.7 nm) spectra from astronomical sources. It was conceived and fabricated by The Johns Hopkins University (JHU) and an international team of universities, government agencies, and corporations. It was launched in June 1999 aboard a Delta II rocket from the Cape Canaveral Air Station.[1,2]

FUSE was one of NASA's first "better, faster, cheaper" missions, and the first time for an Explorer-class mission that overall responsibility was given to a university. The FUSE team learned a great deal during the early life of the mission.

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We convey those experiences relating to the FUSE optical system in this paper. This discussion will be limited to optical systems issues, optical hardware developed at JHU, and flight operations.

FUSE was first proposed in the late 1980s. The original baseline was a single grazing incidence telescope feeding three different diffraction gratings via slit selection. This version was to be launched on the Space Shuttle and mounted to the Explorer Platform, a reusable spacecraft, in low earth orbit (LEO). In 1992, FUSE was changed to have its own spacecraft, and to be launched on an expendable rocket. At the same time, the trajectory was changed to a 24-hour period highly elliptical orbit (HEO) from the LEO baseline. In 1993, the optical design was changed to four parallel normal incidence telescopes, each feeding their own grating. The optical design remained essentially unchanged after this time. The program was radically restructured in 1995. The budget was sharply decreased and the schedule reduced by two years. As part of the restructuring, the orbit was changed back to LEO. No further significant changes were made to the mission.

Integration of the satellite was completed in the summer of 1998 at JHU's Applied Physics Laboratory. The completed satellite was environmentally and optically tested at NASA Goddard Space Flight Center in late 1998 and early 1999. FUSE was launched from Cape Canaveral Air Station on June 24, 1999. FUSE has collected data on over 500 astronomical targets, with total on target integration time of 7 Msec as of early July 2000. Since December of 1999, the on target efficiency has been at or above prelaunch requirements. A special issue of the *Astrophysical Journal Letters* will be published July 20, 2000 containing papers based on the FUSE early release observations obtained in November 1999.

The FUSE mission was developed in an environment of constrained resources, with the goal of preserving the premier science. This required the assumption of risk to both non-essential performance characteristics and schedule. The first year on orbit has demonstrated that FUSE is able to perform its prime objectives, the measurement of deuterium abundances and the measurement of hot ionized gases between the stars.

2. DESIGN DEVELOPMENT

2.1. Early designs

Early FUSE designs used a multiple element grazing incidence telescope (Wolter-Schwarzschild type II) to direct far-ultraviolet (FUV) light into one of three slits. Two of these slits had pick-off mirrors behind them which served to direct light onto diffraction gratings that covered different sections of the band-pass. Only one of these channels could be used at any one time. Two additional channels were also proposed: an extreme ultraviolet (EUV) channel (10.0--40.0 nm), and a survey FUV/EUV channel (40.0--160.0 nm), which extended the band-pass at much lower resolution. These channels would have added two additional slit/pick-off mirror sets to the focal plane.

2.2 Arrival at current design

As discussed in section 1, financial and schedule constraints placed upon the program in the early 1990s led to the as-flown normal incidence design. During the design phase, we realized that the schedule of a large grazing incidence telescope was not practicable for an Explorer-class budget. Advances in coating technology, primarily the availability of SiC, now allowed reasonable normal incidence reflectance down to 90.0 nm. Acceptable effective area could be obtained by using four parallel prime focus telescopes, which direct light into matched spectrographs. In additional, the entire band-pass could be observed simultaneously, further improving instrument efficiency. Although we expended considerable effort on the grazing incidence design, in the end, the flexibility of the FUSE program saved money and time, and mitigated risk by willingness to re-evaluate the basic design.

Limits in grating size and Rowland circle diameter and requirements on resolution dictated a system focal ratio of f/6 or slower. The shroud size of the expendable launch vehicle, combined with the third stage required to achieve HEO, limited total instrument length to about 4 meters. The resulting telescope mirror size was about 0.4 meters square for each channel. Fairing shape limitations also forced the spectrograph to extend up above the end of the telescope baffles (Figure 1 and 2) and the corners of the gratings to be removed. The baffle length issue was a known scattered light problem for the fine error sensor (FES), a CCD-based star tracker and slit jaw camera, but was acceptable since the bright Earth was not expected to be a significant problem in HEO.

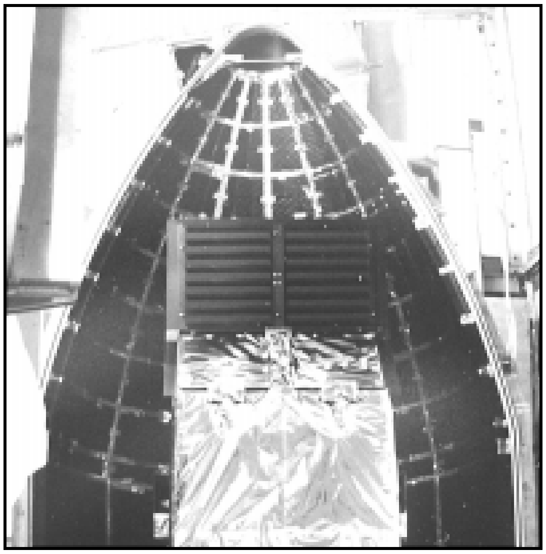

Figure 1 FUSE in Fairing Shroud

Figure 2 FUSE Side View

When the change was made back to LEO, cost and schedule constraints precluded changing the optical design. The new spacecraft was designed to mount below the instrument, rather than wrapping around it. This took the space formerly occupied by the third stage for the HEO mission, so the baffles could not be extended to the top of the spectrograph. Analysis showed that the scattered light should be sufficiently low in LEO.

Communication between engineering staff and scientists was extremely important during the design evolution described above. Complex trades between effective area, resolution, and bandpass were required. Engineering staff generally identified requirements that drove the design to additional complexity, and the scientists were made aware of the cost of these requirements. The EUV channel was an example of this on FUSE. Maintaining it as a requirement of the design would almost certainly have forced a grazing incidence design, as the efficiency of the normal incidence coatings decreases dramatically below 90.0 nm.

3. OPTICAL SYSTEMS ENGINEERING

3.1. The Systems Engineering Team

FUSE had a large number of university, corporate, and US and foreign government partners involved in the design, fabrication, and testing of the optical system. These partners brought unique skills to FUSE that were required to construct the instrument. These groups were widely separated geographically, hampering face-to-face communication. This challenged the systems engineering team, as communication of requirements was difficult and in-person verification of requirements infrequent. The FUSE team worked to mitigate this problem via frequent telecons and document distribution via the world-wide web. The use of modern communications and documentation techniques significantly enhanced the activities of the systems engineering team.

3.2. Schedule

Optical integration and test contributed to delays in the baseline schedule. Some optical elements were delivered late, and others were found to be out of specification during component level testing, requiring corrective action. This caused the optical alignment process to begin late, and also required changes to the alignment plan to account for the arrival order of the hardware which was different than originally anticipated. Major tasks, such as mirror installation and alignment and the optical end-to-end test also took significantly longer than expected. We believe that this was caused by attempting to estimate durations for unique, complex tasks that cannot be realistically practiced in advance. For FUSE, the complex optical tasks generally took 1.5 to 2 times longer than anticipated. Short and simple tasks that were repeated, such as optical reference checks and witness mirror measurements, were typically on schedule.

In general, the FUSE team did a good job in not allowing the schedule to force bad decision making. However, assumptions made about the schedule had repercussions later. A good example of this was the selection of lamps used in the optical end-to-end test. Near the originally scheduled time for the test, a significant problem was discovered with the nearly off-the-shelf FUV lamps.[3] There were several possible modifications available to correct the problem, but due to the anticipated required start date for the test and limited personnel resources, only the two easiest methods were pursued. These methods proved only to be marginally satisfactory. In the end, delays to the schedule caused by other factors would have allowed sufficient time for alternative fixes.

3.3. Tolerancing and Budgeting

Before launch, scientists regularly met with the structural design team in order to assess the expected performance of the structure. The scientific requirements (primarily the resolution and throughput) were the main drivers for the structural stability performance. A structural thermal optical performance (STOP) analysis was done using a simple spreadsheet raytrace model of the spectrograph, along with a finite element model of the satellite. The effects of the initial (ground) alignment of the spectrograph, plus short term (primarily orbital) and long term (including ground to orbit shifts, and changes due to pointing) were included. Fairly detailed models were made for an initially coaligned system. However, this analysis was done before fabrication of the structure and most of the optical mounts. Ideally, during and after construction, these calculations would have been repeated with as-measured values, but schedule and personnel limitations prevented this from occurring.[4]

The range of motions required for each optical actuator were originally determined from the tolerance analysis and the baseline methods planned for focus and alignment, and some safety margin. In flight, the mirror actuators' range of motion are utilized at less than a 20% level, while the FPA X and Z adjustments are used over their full range. Additional range for both FPA adjustments would have been helpful in flight, due to the image motion problems discovered after launch. Note that increasing this range would not improve performance, but make the system simpler to use. However, decreasing the range of the mirror actuators would not have changed schedule or cost.

3.4 Coordinate System

A significant amount of time and negotiation went into the determination of the FUSE instrument prime coordinate system. The difficulty was in the four channel design, two channels focused onto each detector, leaving no "natural" placement for a single coordinate system. The FUSE coordinate system was placed near the center of one of the detectors, with one axis perpendicular to its curved surface at that point. This proved unsatisfactory in that there was no easy way to directly measure from that point, and it was difficult to use even during the optical design process. We believe that the other possible locations considered were also flawed in various ways, and there would have been no ideal system to use on this instrument.[5]

4. OPTICAL ELEMENTS

4.1. Optomechanical Design

FUSE did not have an optomechanical systems engineer on staff at the start of the program. This proved to be a weakness in a variety of ways. In a program of this size and type, there should be a minimum of one full-time optomechanical engineer throughout the design and integration process, in addition to the nominal contingent of mechanical engineers. This person should be experienced in optomechanical design prior to joining the program. FUSE did include a senior level consulting optomechanical engineer as part of relevant reviews. Starting early in the design process, these reviews were done at both the subsystem- and instrument-levels.

A key problem, both during integration and, we believe, during flight, was the coupling of the secondary structure to the optical bench. The optical bench consists of very low coefficient of thermal expansion (CTE) composite material. The secondary structure consists of relatively high CTE materials, and is used, among other things, to support light-tight cavities and baffles. While the interfaces for these structures to the optical bench typically consist of flexures, several problems have nevertheless been identified, which are caused by:

a. Failure of flexures to be "soft" enough--both by design and due to assembly problems such as flexure blade misalignment
b. Failure to fully model all of these interfaces
c. Design of "unmodelable" interfaces

Both the “cruciform problem” (dimensional change versus temperature in the aluminum secondary structure causing motion of the gratings; Section 6) discovered during thermal vacuum testing and the in-flight alignment problems indicate that coupling of secondary structure to the FUSE composite structure was particularly problematic. This was caused partially by pressure to maximize mirror aperture in the HEO design, resulting in limited space for the interfaces between the support and secondary structures.

One possible pre-assembly mitigation strategy for the motions would have been to continue the STOP analysis for the duration of entire integration and test (I&T) effort. The STOP analysis effort ended at the start of optical bench fabrication due to funding considerations, before much of the secondary structure was designed. If more analysis funding were available, the STOP model could have been updated on a semi-annual or annual basis throughout hardware development (up to thermal vacuum testing of the satellite). An important element to maintaining the STOP analysis throughout I&T is that the model could have been correlated at various points in the flow. For example, as optical components were installed, the model could have been compared to the optical metrology for a correlation of stiffness/1-g effects. Additionally, a correlation of the structural model to the optical end-to-end test could have been attempted. It is possible that this ongoing analysis would have flagged issues such as the cruciform problem.

Most critical materials were completely evaluated prior to fabrication and assembly. However, a few seemingly insignificant materials that were not evaluated sufficiently caused problems later. An example of this was the bonding agent used for attaching flexures to the mirror ribs. This epoxy shrank upon cure, stressing the mirrors and distorting the optical surface. The epoxy also has a glass transition temperature that is close to the temperature initially used for the mirrors during component-level thermal vacuum testing. This also caused small figure changes in the mirror measured after component-level thermal vacuum testing. These effects were time consuming to diagnose and mitigate.[6]

FUSE used open back weight-relieved mirrors.[7] While in the end this design met requirements, we feel that other designs would have required less engineering effort. FUSE carried a substantial weight margin; it would have been advantageous to use a more rigid design, such as a double arch or something similar. This would have saved significant time and money associated with design, fabrication, and assembly. A sandwich design would have been cost prohibitive. The use of the open back design was originally introduced to meet the low weight margins of the HEO instrument combined with cost limitations.

Venting of the spectrograph was a subject that was problematic. Early in the design phase, venting methods were considered, and a design was baselined. While this design would have worked well for light rejection, it would have failed to remove gas from the system to maintain low enough pressure for detector operations. We failed to consider the gas load caused by water evolving from the composite structure. This error was discovered during integration, while investigating the composite material’s moisture absorption properties. At this point in the flow, we were limited in our options. There was no reasonable new location for the vents, and the original location was limited in the additional volume and mass which could be supported. Pumping speed and scattered light rejection behave inversely: increasing the pumping speed generally trades directly with the stray light flux. Furthermore, vent location was very near the FUV detectors, so scattered light was a significant issue. Many potential designs were evaluated before arriving at the final solution. Other flight optical programs have also had problems with the issue of venting, and extra care should be taken by future programs not to underscope this effort.

Another critical design issue was the lack of feedback from the mirror actuator mechanisms. It was decided early in the program that there would be no feedback, such as from an encoder, of the mirror mechanism positions. This was justified as a cost savings measure, and with the hope that optical data from focus and alignment would indicate where the mechanism was positioned. Additionally, it was thought that these mechanisms would be seldom used. This lack of feedback forced the use of very tedious methods for tracking position by motor step counts on the ground, which hampered our ability to make simple motions without optical verification. In practice, motions are also required much more often than envisioned during design, compounding these complications. Note that this increased usage does not cause concern for the health of the mechanisms, as there is adequate margin in their predicted lifetime. The lack of feedback has not in any way compromised the performance of the mirror actuators, or the instrument as a whole. This is an example of an early minor economy that actually increased cost over the duration of the mission.

4.2 Procurement of Optical Hardware

The FUSE team began evaluating vendors very early in the design process. For optical hardware, we were surprised by large variations in estimates and bids. The management team emphasized that we should not be driven solely by cost, and we decided several times not to award a contract to the lowest bidder. We found it was a significant advantage to deal with a local vendor, allowing quick "check-up" type visits and easy transportation of hardware.

5. ASSEMBLY AND ALIGNMENT

5.1 General

As originally envisioned, the alignment of the FUSE mirrors to the spectrograph would have been done in vacuum using FUV light. One of the first descopes was to remove this requirement, and replace it with a visible light alignment system.[8] This single change saved the program a great deal in both direct cost and schedule and appears to have been successful.[9]

During installation and alignment of optical elements, the optical and mechanical teams required close interaction. Interspersed with this was electrical testing that required “hands-off” for substantial lengths of time. Close teamwork allowed corrective optomechanical changes to be made very late in I&T. The mechanical team made a point to understand the optical system, and was aware of the close coupling between mechanical design and optical performance. This interaction allowed on the spot review of work from both the optical and mechanical point of view.

5.2 Alignment Monitoring

Most optical elements on FUSE had optical alignment references used for installation and alignment monitoring throughout integration. These typically consisted of optical cubes or reference mirrors, which were measure using optomechanical or “surveyor” techniques. The timing of the alignment checks was done in an event-driven way, with a “full shoot” of the references done prior to and after major assembly steps, tests, and shipment. One problem with the overall system design was the blockage of the line of sight to some of these references as the instrument was assembled. Near the end of processing, the gratings, mirrors, and detectors could only be checked on a single face of their reference cubes, giving knowledge in only 2 of the 3 possible rotations. The only significant motion that was detected was that of the detectors rotating about their long axes. We believe this was caused by a thick composite bracket absorbing and releasing water in response to the various levels of humidity encountered. Analysis showed that the approximate one-arcminute level of maximum rotation would have no impact to flight operations.

5.3 Visible light focusing

Our installation procedure for the FES made use of measuring fixtures to determine where to match drill bushings. While this method appeared to be straightforward, it was lacking in that there was no verification of focus immediately after installation. The addition of such a test would certainly have had a significant cost and schedule impact. While this was nominally part of thermal vacuum testing, lack of confidence in the collimator focus due to thermal variations in that GSE assembly weakened our confidence in the test results.

5.4 Contamination

One of the most impressive achievements of the FUSE program was in the area of contamination control. The FUSE instrument is extremely susceptible to molecular contamination. A single Angstrom of hydrocarbon contaminant on any optical surface would decrease the FUV efficiency of that channel by an estimated 10%, depending on wavelength.

Instead of employing a team of full time contamination personnel, FUSE had an experienced contamination engineer develop and document methods and processes early in the design. This engineer then taught the methods to the engineers and technicians working on the program. Later in the process, the contamination engineer was reduced to part time, and mainly audited the compliance with the documented processes.

One of the unique challenges for FUSE was preserving the LiF over aluminum coatings on the gratings and mirrors of two of the channels. This coating is quickly damaged by typical humidity levels found in cleanroom air, especially at the integration location in the Baltimore-Washington area and the launch site in Florida. In order to prevent exposure, the gratings and mirrors were kept under local purge for a period of up to two years between coating and launch. The grating and mirror cells had covers that were removed only for brief periods when testing required. The optics were *never* exposed to relative humidities above 50% at room temperature, and the total exposure to humidities above 10% was less than 10 days.

Pairs of witness mirrors were kept inside the grating and mirror cells at all times. These samples were made of the same material as the optics, and coated at the same time. One of these samples was removed for measurement at regular intervals, primarily driven by events during integration. The second sample was measured less frequently in an attempt to minimize the effect of the measurement process itself. The redundancy of the samples proved critical when a set of grating samples sent to JHU from Colorado for measurement was lost by the shipping company during spectrograph integration.

A weakness of the witness mirror program was the usable wavelengths and accuracy of the JHU reflectometer used to measure their reflectivity. The radio frequency lamp used was bright enough to allow measurement at only three wavelengths reliably, and the shortest was 104.6 nm (above the LiF cut-off). There were also detector problems that caused the system to be difficult to operate. Even with these shortcomings, the witness mirror program did show that the losses of reflectivity during ground processing were well within the budgeted loss, and calibration in flight seems to show similar results.[10]

As well as employing a full-time purge to the optics, the entire FUSE instrument was double bagged during much of I&T. This allowed the instrument to be shipped and be tested in sub-optimal facilities. This bagging process initially took a large amount of time, but later bags were “pre-assembled” allowing the process to be done in less than 4 hours by a crew of 5.

Loss of sensitivity in-flight over a 7 month period is 5 to 10% depending on wavelength, less than the budgeted amount. Most of this loss can be attributed to detector aging, as the effect is greatest where effective area is largest.[11]

5.5. Facilities

The facilities chosen for assembly of the FUSE instrument were generally satisfactory. The cleanroom at JHU used for mirror assembly and alignment had problems with the airflow causing vibration. These were “solved” by temporarily depowering the fans during critical interferometric tests.[12] Other cleanroom facilities were satisfactory, but it was found that having exclusive use rather than sharing with other programs was highly desirable.

The Space Environment Simulator (SES) vacuum chamber at Goddard Space Flight Center was used for the optical end-to-end test. This chamber was the appropriate height for the satellite and collimator assembly (Figure 3). In the Figure, the space around FUSE appears generous, but it allowed room for personnel access during the set-up process. We conclude that the use of such a large chamber and its associated higher operating cost was justified.

6. OPTICAL TESTING

6.1 General

Optical testing the FUSE satellite consisted of component-level testing, subsystem-level testing, and system-level testing. Examples of component-level testing were efficiency and resolution testing. Subsystem level performance testing was performed on the Fine Error Sensor and the spectrograph.

The FUSE management team made difficult trades between optical test requirements and schedule and cost. A minimal, but adequate, test program was baselined early on, and was fully described in documentation. This minimal program saved resources early in the program. Considering the schedule and cost constraints of the final FUSE program, any additional testing would have been descoped and preparation would have been wasted.

The optical test plan was evaluated by standing review committee at several meetings, over the period of several years. By having a standing committee, FUSE was continually reviewed by persons familiar with the program. One weakness in the review committee was several of the reviewers most versed in optical hardware left the panel that early in the process for various reasons. We made it our policy to point out to the reviewers the known weaknesses inherent in the FUSE optical test program.

The FUSE system-level test philosophy was to show that there were no problems that would prevent reaching the minimum performance floor, but not to perform an extensive calibration. We erred in two significant areas:

We did no visible stray/scattered light tests, as we believed that we could not do an adequate test with the schedule and funding available. This was justified by the belief that any problems in this regard would not cause a significant impact to the mission. As it turned out, the visible stray light performance is poor and even a moderate test would have had a possibility of uncovering it (Section 6.3). However, it is questionable whether a fix for the problem could have been implemented within the scope of the program if it had been found. While this problem does not effect the ability of FUSE to achieve its science goals, it reduces the efficiency of the observing program. However, even with this constraint, FUSE is more time efficient recently than anticipated prior to launch.

We did no test that would have detected motions of optical elements with thermal variations. This was justified by the belief that even if we were outside of specification, we would simply be able to correct the problem with a slight loss of time efficiency. As it turned out, the initial performance was over an order of magnitude worse than the requirement (Sections 4.1 and 7.2). This caused a loss of observing time early in the mission while the problem was characterized, although now, approximately one year after launch, it has a minimal impact. A test that would have produced time variable gradients would have been very difficult and costly to implement, and we were unable to develop a moderate test for gross effects.

While the test program was designed early, not enough resources were devoted to early preparation. Ancillary items, such as light sources and calibration standards were left out of the early planning, with the assumption that they were "off-the-shelf" hardware. Another result was that the optical ground support equipment was underscoped, and required contingency money to complete on time.

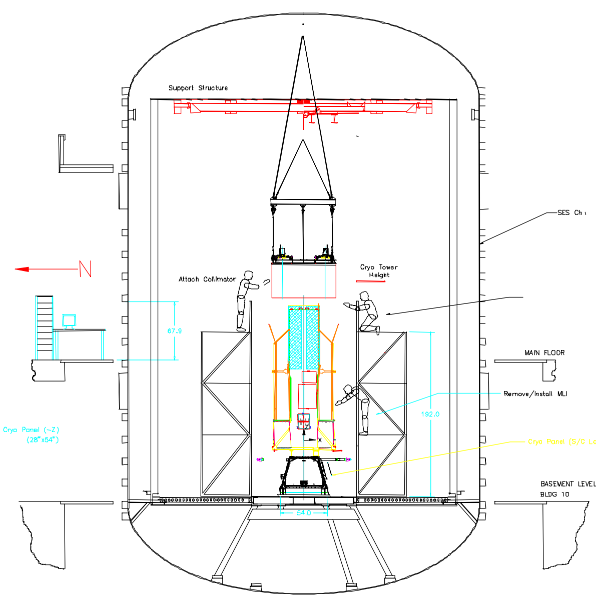

Figure 3 FUSE in Vacuum Chamber

The FUSE system level testing combined satellite thermal-vacuum testing with the optical end-to-end test.[13] This had several significant advantages:

a. FUSE was optically tested in close to its final, flight configuration
b. Cost and schedule reduction was achieved by combining two major tests
c. Optical test hardware provided high fidelity stimulus for flight operations testing
d. Interleaving electrical and optical testing allowed time for data to be reviewed

We also found that there were a number of disadvantages as well:

a. Loss of control of the test by the optical engineering staff
b. Increased levels of staffing required, due to the increased complexity of the system

FUSE was under vacuum for approximately 60 days, with the majority of that time requiring around the clock support from optical engineering, electrical engineering, and science staff. As the program was only 2 or 3 persons deep in most positions, the 3 shift, 7 day per week schedule caused a strain on personnel.

6.2. FUV Testing

The major problem with testing FUSE in its science bandpass was having to operate in vacuum. This was required for two reasons: 1) FUV light in the FUSE bandpass does not transmit through any gas at atmospheric pressure and 2) the FUSE open face detectors required high vacuum to operate. This forced us to limit FUV testing to several specific times during integration. At the component-level, the gratings and detectors were tested with FUV light for resolution and efficiency. The mirrors were tested for point spread function (PSF) in visible light and longer UV wavelengths at ambient pressure, with analysis which extrapolated the PSF to FUV wavelengths.[14] For both the gratings and mirrors, FUV reflectivities were measured using a system of small witness mirrors, coated with the same materials and exposed to the same environment.

The assembled spectrograph was aligned and tested for resolution using FUV wavelengths. This was done in a custom manufactured vacuum chamber at the University of Colorado.[15] System level FUV testing was done at the GSFC in the SES chamber.[16] System-level FUV testing was limited to wavelengths longer than about 104.0 nm due to the use of windowed lamps. While this almost entirely covered the bandpass of the LiF channels, only about a third of the SiC bandpass could be stimulated. This was a reasonable compromise made in light of the added complexity of using windowless sources. The optical design places multiple spectra on the same detector, allowing verification of the entire length of the detector.

Problems with the lamps were a major difficultly with FUV end-to-end testing. Several of the lamps failed due to leakage through their window seals, and others had too large an f-number to allow full illumination of the collimator optics. The latter forced us to combine a number of exposures illuminating different parts of the collimator aperture to estimate spectral resolution. The lamps used were known to be narrow emission line sources in the region of interest (relative to the spectral resolution), so the widths of the spectral lines provided a direct estimate of the instrument resolution.[17]

Efficiency during the optical end-to-end test was measured by calibration of the lamps at several power levels prior to the test, and knowledge of the reflectivity of the collimator optics as determined from witness samples. This was not intended to be a rigorous test, but primarily provide a coarse check. The data matched predictions to about 25%.

One significant worry for the spectrograph was light leakage. While multiple layers of covering and blanket were used to seal off the cavity, the large number of interfaces that required sealing caused concern. There was no reasonable way to determine if a leak existed, and to know where it was to allow rework after assembly. Rather than perform this test in the UV, requiring a vacuum environment, we installed temporary visible light lamps inside the spectrograph cavities, and visually inspected for light leaks in a darkened room. Many leaks were identified and corrected. In-flight performance indicates that there are no significant leaks.

6.3 Visible Light Testing

Visible light PSF measurements were made for the Fine Error Sensor at the subsystem-level, and at the system-level after the vacuum portion of the optical end-to-end test. Subsystem-level testing consisted of a point source fully illuminating the FES mirrors. The resulting images were compared to ray-trace models to determine internal FES alignment and focus. It was not intended to verify the instrument visible PSF, but showed that the FES alone performed as designed. During the optical end-to-end test, the FES entrance pupil was 67% filled. This test was successful, but it revealed a large difference in focal position for visible and FUV light for both FESs. A collimator assembly was used to provide light during the end-to-end test. Post-test checks revealed that the collimators changed focus with thermal variation. The temperature of the collimator assembly was significantly different in vacuum than in air for the visible light testing, and the difference in focal distance was attributed to this. In flight it was found that the visible and FUV foci were nearly coincident for LiF 1, but differed by about 600 microns for LiF 2, approximately halfway between the desired position and that measured during thermal vacuum testing. As only FES 1 is used in normal operation, this slight defocus has no impact at this time.

Trade studies indicated that there was little risk in not performing efficiency testing on the complete visible light system. The FES was measured at the subsystem-level, and the telescope mirror's witness samples were measured at a single visible light wavelength. In-flight visible light sensitivity is close to the pre-flight predictions.

Visible scattered light testing was performed on the FES at the subsystem-level. The telescope mirrors and focal plane assembly's (FPA) reflective surfaces were measured for surface roughness, and analysis was used to estimate visible light scattering. Measurements performed during thermal vacuum demonstrated that the visible light system met its scattered-light requirements; in-flight measurements show even better results, indicating the ground data were dominated by scattering within the optical ground support equipment.

One of our most significant in-flight problems is visible stray light in daylight. No instrument-level visible light stray light testing was performed. Instead, a complete stray light analysis was done on FUSE, which showed that it would meet requirements with a reasonable margin.[18] A minimal amount of ground testing--as opposed to testing to the specification, which would have been very costly--may have uncovered the problem early enough to take some type of mitigating action.

Visible light leakage tests were made on the baffle tubes, using methods similar to those described above for the spectrograph cavity. A significant number of leaks were discovered and patched, especially along the rivet lines.

7. FLIGHT OPERATIONS

7.1 Early Operations

Early flight operations were more of a learning process than the FUSE team had expected. After the doors were opened, it was discovered that the visible light performance was limited near noon of the orbit due to stray light, particularly at low earth-limb angles. While the FUSE team found that the satellite would track on previously acquired star fields throughout the orbit, acquisitions could not be done reliably for a fraction of each orbit, resulting in an acquisition timing constraint.

Another early mission problem was that the pressure in the spectrograph cavity took significantly longer to reach detector operating level than was expected. The complex trade between vent size, FUV light leak, and pumping speed was the root cause of this. It was not practical to use the flight vents during the thermal vacuum test, as the test duration would have been lengthened significantly. As a result, there was not a good data set to estimate time after launch to reach the required pressure. Operational pressure was achieved in 47 days rather than the design specification of 24 days. This time was used very constructively to do acquisition testing, among other things. This illustrates the uncertainty in the performance of this type of baffle when applied to a complete system. Note that there is no evidence of FUV light leak.

Before any light from astronomical targets was focused into the spectrograph, airglow, primarily Lyman beta (102.6 nm), was intentionally observed as an "extended source" through the low resolution spectrograph slit. It was quickly determined that the spectral line was shifting on the detector over time throughout each orbit. This motion was in both the spectral and spatial directions, and roughly sinusoidal in shape. Further, it was discovered that the phase and amplitude of these motions varied with the beta angle (line-of-sight to anti-sun angle) and orbital pole angle (line-of-sight to orbital pole) of the pointing direction. This motion appeared to be very repeatable, and eventually the data processing pipeline was modified to remove most of the effect. We believe this may be another example of the complex thermal environment interacting with the secondary structure, although there are other possible explanations.

Overall, instrument in-orbit checkout took longer than was anticipated prior to flight, and required significantly more effort from personnel as well. The use of personnel who were experienced in the integration and test of the instrument was critical to this effort, and in hindsight it would have been advantageous to have had a small number of additional personnel with this experience available. Note that a number of flight operations personnel participated throughout integration and test, which was similarly beneficial.

7.2 Alignment

The FUSE plan for initial coalignment was to direct FUV light into the LiF1 channel's low resolution slit using Fine Error Sensor A. Then while guiding with that channel, perform a spiral search by monitoring for FUV counts in the remaining 3 channels using mirror actuators. This method required that a point source be used in a fairly isolated star field, to prevent a nearby field star from causing confusion. The source also needed a moderate FUV count rate in all channels. Overall, this method worked extremely well, although there was some confusion initially caused by a second star. It was used to coalign channels to the 15-arcsecond level.

After data analysis, the spiral search was followed by rotations to mirrors on the three other channels, to take out the measured alignment errors relative to the LiF1 channel. After the first mirror adjustment was performed, one of the channels was still not in alignment with LiF1, and a second spiral search was performed. After its misalignment was again measured, and a second mirror motion performed, all channels were within 15 arcseconds of coalignment. Initially, this second motion was thought to have been required due to a bad mirror motion, or an incorrectly measured position. As further alignments and observations were attempted, it was found that all of the channels were moving with respect to each other, by as much as 40 arcseconds. The misalignment varied from observation to observation, and was found to depend strongly on beta angle and orbital pole angle. Over time, empirical data were tabulated that allowed the images to be held in coalignment within the 30 arcsecond size of the low resolution slit without the need of active realignment. FPAs and mirrors are now moved to predicted alignment positions in advance of each observation, and loss of data due to alignment error is fairly uncommon.

Finer coalignment was performed by stepping the roughly coaligned images across the edge of low resolution slits. This method allowed for coalignment to about 2 arcseconds. Note that early attempts to use this method were hampered by the fact that the measurement and adjustment were not closed loop. Scans were made and mirrors adjusted, but no recheck was made. FUSE would then slew to another target, which often resulted in coalignment being lost due to changing the thermal load on the instrument. Early on, it was not known if bad mirror motions or some other cause was to blame. This worked to mask the misalignment problem.

In order to maintain coalignment of the channels at the arcsecond level required for the medium and high resolution slits, an on-board peak-up procedure is employed. This procedure uses small slew steps to move the images over the narrow slit, and monitors the FUV count rate at each point. When complete, the centroid for each channel is calculated, and FUSE is slewed to the peak position for the guiding channel. Then the other three channels' FPAs are moved to the calculated location for each of their peak count rates. In performing this operation, it was quickly determined that the images moved over an orbit even while pointing at a single target. This motion appears to be extremely repeatable, and does not seem to vary from target to target. This has allowed us to track orbital motion for doing science exposures through the narrow slits by either using a series of peak-ups or a single peak-up, with predictive FPA motions used to hold coalignment. Both methods have worked, with the predictive method seemingly holding an advantage in efficiency.

There were plans for the early mission to attempt to minimize coma caused by misalignment of the mirrors, if measurement of the mirror PSFs indicated it was necessary. This was not required, but based on other alignment and focus methods, we believe it would have been extremely difficult to perform this measurement.

7.3. Focus

In order to properly focus the FUSE instrument, it was required that the mirror-to-grating and mirror-to-FPA distances be adjusted based on measured data. The baseline plan for performing this task was to focus the mirrors to the gratings by measuring absorption line widths on point source astronomical targets. The low resolution slit (which is an essentially slitless mode, so the mirror to FPA distance does not have any effect) was used, and the mirror focus stepped through a range of positions. After this was complete, knife edge testing, by moving the telescope images over the slit edges, was used to measure the image size as a function of FPA position.

Unfortunately, this plan had a number of problems which slowed progress. Using absorption line sources requires a very high flux in order to achieve the signal-to-noise ratio required to measure line widths. This requires either a very bright source, or long integration times. Due to the image motion, taking long integrations requires the exposures be adjusted to compensate, which is an imperfect process. The first several focus attempts did not have enough total signal to measure the line widths, especially in the SiC channels with their inherently lower sensitivity. Each focus test would take several days, due to the amount of exposure time required at each position for adequate signal-to-noise ratio.

The second, and more critical problem with the use of absorption sources is that, for most targets, the inherent line width is not known. After several unsuccessful attempts at using targets that were believed, but not proven, to have narrow lines, data from the Hubble Space Telescope was used to assess other potential targets in advance. Eventually, approximately five potential sources were found, and two were used for focus runs. Of the two, one was found to have enough narrow features to allow focusing on all channels. Best focus was found to be within 250 microns from the launch position on all channels. The launch positions had been corrected for 1-g and other expected early mission effects.

While the spectrograph focusing was being attempted, a parallel effort was made to determine the correct mirror to FPA focus positions. This was complicated by the alignment problems causing data loss on certain channels when the knife edge scans were attempted. Best focus was found to be within 200 microns for each channel from the launch position. By measuring spot size with knife edge scans and ratios of signal through various slits, it appears that each channel is currently within ~±100 microns of focus.[19]

Current instrument performance is described elsewhere.[20]

7.4. Science Observations

Several months into the instrument on-orbit checkout phase of the mission, it was decided to discontinue exclusive test operations and mix science observations with the test process. These science programs did not require the full system performance. This had two great advantages to the FUSE team. First, it allowed additional time between tests for data analysis, and to make improvements to follow-on tests. Secondly, by doing actual science observations, we were able to discover additional problems earlier, allowing them to be mitigated in a timely fashion.

It was immediately recognized by the scientists planning to use FUSE that with the four-channel design it would be improper to simply co-add the spectra from separate channels if the highest resolution was to be maintained. The primary reasons for this are that each channel has slightly different dispersion relations, and that the statistical independence of the pixels would be compromised. Instead, when fitting models, the spectra are treated independently, even over common wavelength intervals, and the errors are carefully propagated forward during the fitting process. This allows the scientist to take full advantage of the effective area of the co-added channels. Occasionally, when the channels are misaligned, the signal levels in some channels are so low that they are not included in the data analysis. In these cases the inherent redundancy in the instrument usually results in full wavelength coverage anyway, but at lower sensitivity, as long as light from at least one LiF and one SiC channel are present.

For those cases in which the science observation requires only low resolution data, the spectra can be binned and the channels co-added directly to produce the greatest possible signal/noise spectra.

Currently, science observations are planned such that beta and pole angles change only a limited amount from target to target, to minimize the effects of the image motion problem. Equator crossings are also minimized. These constraints place a large burden on the mission planning team, as it limits the target selection. We are currently attempting to improve our predictive abilities to allow for a larger target pool at any one time.

A large fraction of the FUSE team at JHU is involved in the observing loop, from the planning stage through the initial stages of data analysis. This has allowed the staff members involved with instrument optimization to have a view into the actual way the data is used, giving an opportunity to make improvements which are better matched to the observations.

8. CONCLUSION

FUSE has produced outstanding scientific results, and the productivity of the mission continues to increase with time.[21] However, the first year of this mission has been difficult. The large number of problems encountered had the unfortunate effect of masking each other, making diagnosis and corrective action difficult and time consuming. As some of these problems were cleared, the pace of progress became much faster on the remaining issues. The limited ground station contact time associated with LEO hindered the diagnosis and correction of the problems encountered.

The design of FUSE was flexible enough to allow work-arounds to be found for most of the problems encountered. Additionally, there are levels of redundancy (both complete redundancy and “soft-failures”) that have not yet been used in flight, which will allow an extended mission.

ACKNOWLEDGMENTS

FUSE is supported through the Explorers Program office at the Goddard Space Flight Center, and managed within the Center for Astrophysical Sciences at The Johns Hopkins University. The authors would like to thank Dennis McCarthy and JB Joyce for their help in preparing this paper. This work was supported by NASA contract NAS5-32985.

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