Pre-launch optical tests and performance estimates of the Far Ultraviolet Spectroscopic Explorer (FUSE) satellite

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ABSTRACT

The Far Ultraviolet Spectroscopic Explorer (FUSE) is an astrophysics satellite designed to make observations at high spectral resolving power (R ~ 25000) in the 90.5-118.7 nm bandpass. This NASA Origins mission will address many important astrophysical problems, including the variations in the deuterium/hydrogen ratio in the Milky Way and in extragalactic clouds, the kinematics and distribution of O^{5+} and other hot gas species in the Galactic disk and halo, the properties of molecular hydrogen in interstellar clouds having a wide variety of temperatures and densities, and the properties of stellar and planetary atmospheres.

Between August 1997 and January 1999 an extensive series of vacuum optical tests was conducted, first with the spectrograph alone and then with the full satellite in flight-like conditions. Numerous ultraviolet spectra were obtained and found to be consistent with performance requirements. We also obtained visible light images with the Fine Error Sensor (FES) camera, whose performance will be critical for meeting the demanding pointing requirements of FUSE.

In this paper we present estimates of the performance of the instrument, including spectral resolution, line shapes, and effective area. We also present data on the visible light performance of the FES.

Keywords: Astronomy, ultraviolet, spectroscopy, Far Ultraviolet Spectroscopic Explorer, FUSE, optical testing.

1. INTRODUCTION AND SCIENTIFIC OBJECTIVES

The Far Ultraviolet Spectroscopic Explorer (FUSE) is a satellite developed as part of NASA's Origins program. Its purpose is to perform observations of astrophysical objects in the far ultraviolet (FUV) portion of the spectrum, 90.5-118.7 nm, a bandpass extremely rich in resonance and higher order spectral lines from a wide variety of ionized, atomic, and molecular species found in many space environments.

The FUSE science team has established an ambitious set of scientific goals for the mission, including investigations of molecular hydrogen in interstellar clouds of varying densities, the nature of active galactic nuclei, the properties of supernova remnants, gas in stellar atmospheres, and the atmospheres of planets in our solar system. The two preeminent areas of study for the mission are the measurements of the deuterium-to-hydrogen ratio in many regions throughout the Milky Way Galaxy; and the distribution and kinematics of hot, highly ionized gas, especially five-times ionized oxygen (O^{5+}), in the disk and halo of the Galaxy.

The importance of the deuterium (D) problem lies in the fact that this species, an isotope of hydrogen having atomic mass 2, is thought to be created in significant quantities only in the first ~3 minutes after the Big Bang, when the density of the primordial plasma was extremely high. The exact density of deuterium relative to ordinary hydrogen, a ratio that was "locked in" at this early epoch, is a sensitive measure of the density of normal (that is, baryonic) matter in the universe. In the subsequent evolution of the universe spanning approximately 13 billion years, some of the deuterium was destroyed in the

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interiors of stars, but none was created. All of the Lyman transition lines of both D and H (except for Ly-alpha) fall within the FUSE bandpass. FUSE is the first mission having sufficient sensitivity to measure the D/H ratio toward sources throughout the Galaxy. Previous measurements using the *Copernicus* satellite and *Hubble Space Telescope* have made such measurements only within about 1 kiloparsec of the sun, or about 10% of the distance to the Galactic center. FUSE will be used to measure the D/H ratio in a wide variety of environments throughout the Galaxy, which will in turn allow astronomers to extrapolate this ratio back to its primordial value.

The second investigation will address a long-standing issue of how matter and energy are redistributed in the Galaxy. Some models predict, for example, that supernova explosions cause large amounts of hot gas, at temperatures of approximately 10^6K, along with interstellar material swept up by it, to be transported to regions more than a kiloparsec away from the galactic plane. Over time, this material cools and falls back toward the plane, and may be the origin of high velocity clouds, which have already been observed using both UV absorption line and 21 cm radio emission line techniques. The origin, distance, and mass of these clouds is still unknown. They are important because they may contain matter that has been only minimally contaminated by stellar nucleosynthetic material, and may therefore be quite similar to primordial material. The dominant cooling process for this gas is emission from O^{5+}, a doublet (103.2 and 103.8 nm) which falls within the FUSE bandpass. FUSE is the first long duration mission (more than ~two week Space Shuttle based missions) with the sensitivity to observe this important cooling mechanism along many lines of sight through the Galactic halo.

FUSE was launched on a Delta 2 rocket on June 24, 1999 for a three year mission.

2. THE FUSE INSTRUMENT

The FUSE instrument[1] (Figure 1) consists of four co-aligned normal incidence off-axis parabolic telescope mirrors which illuminate four separate Rowland circle spectrograph channels. A spectrograph[2] channel has a focal plane assembly (FPA) and a diffraction grating. Each FPA contains three entrance slits, any of which may be used depending on the requirements of the observation. The slits are 1.25_20, 4.0_20, and 30_30 arcsec in size, corresponding to high, medium, and low resolution observing modes, respectively. (There is also 5 micron pinhole slit, but it is not normally supported and will not be considered further here.) The gratings are holographically ruled on spherical substrates. The spectra from two channels illuminates separate regions of one of two identical microchannel plate detectors[3] with delay-line anodes. Several in-flight adjustments are available to maximize system performance. The telescope mirror assemblies[4] have actuators for tip-tilt-focus adjustment, and the FPAs can be moved in the spectral direction to maintain channel co-alignment, and in the focus direction. The gratings and detectors cannot be moved in flight.

The four-channel design allows different optical coatings to be used on different channels in order to maximize throughput. Thus, two mirrors and two gratings are coated with ion-beam sputtered silicon carbide (SiC), which is optimized for reflectivity in the 90.5-110 nm bandpass. The remaining two mirrors and gratings are coated with lithium fluoride (LiF) over aluminum, which maximizes reflectivity from 102.5-118.7 nm.

To achieve the required 0.5 arcsec pointing stability of the satellite, a visible light fine error sensor (FES) camera with a CCD detector, views a 19x19 arcmin region around the science target at the FPA. Centroids of a selected group of field stars are computed by the FES and used by the attitude control system to keep the target properly centered in the selected spectrograph entrance slit.

3. FUV TESTING

3.1. Spectrograph Level Tests

The FUSE spectrograph was designed and assembled at the University of Colorado. An extensive series of tests was completed between August 1997 and January 1998 in a vacuum facility built for this purpose[5]. Both windowed hollow-cathode Pt-Ne and windowless H_2 emission line sources were used to align the optics and to characterize the instrument in terms of spectral resolution, line shapes, scattered light, out of band response, etc. This combination of lamps provided spectral lines through the entire FUSE bandpass.

A non-flight optical system was used to image the emitting region of the lamp onto a selected FPA slit. This optical system had the virtue of nearly filling the spectrograph optics, but the angular uniformity of light within the beam was not well characterized. Furthermore, the entrance slit was fully, but not uniformly, illuminated, which will not be the case in-flight. Nevertheless, due to the known limitations of the satellite level tests that were to follow, these tests provided the best information on spectral resolution and line shapes prior to flight.

3.2. Satellite Level Tests

Final assembly of the instrument and mating of the instrument to the spacecraft took place at The Johns Hopkins University Applied Physics Laboratory. The satellite was then taken to the NASA Goddard Space Flight Center for a series of optical end-to-end (OETE) tests[6]. These were done in the Space Environment Simulator (SES) from November 1998 through January 1999. The SES is a large vacuum chamber (~8 m diameter x 12 m tall) with thermal control provided by cold plates and liquid nitrogen temperature shrouds. The satellite was installed in the chamber with its optical axis pointed upward.

Visible and FUV light was projected into the instrument by means of a collimator assembly suspended over the satellite. This assembly consists of four separate but co-aligned Cassegrain collimators, one for each channel in the FUSE instrument. Each of collimator has a 380 mm diameter aperture, with a 100 mm diameter secondary obstruction. At the focus of each collimator is an assembly mounted on a three axis, remotely controlled translator, consisting of a windowed Pt-Ne emission line lamp with a multi-pinhole mask.

For the OETE tests we had intended to use custom Pt-Ne lamps whose beams were sufficiently fast to illuminate most of the optics in each instrument channel. Indeed, up to 55% of the mirror surfaces was illuminated with this arrangement. However, these experimental lamps failed after only a few days of use, and we were compelled instead to use a standard lamp set which significantly underfilled the collimator aperture, and therefore of the FUSE optics as well. In this case, it was possible to simulate more complete illumination by co-adding data from separate exposures using the four different pinhole apertures in the collimator lamp assembly. Figure 2 shows the lamp illumination pattern on the FUSE telescope mirror from the sum of all four individual pinholes. Unfortunately, residual misalignments and a slower beam speed resulted in only about 7% of the surface area of each telescope mirror being illuminated by each exposure, giving a co-added total of about 28%. Further discussion of the cause and effects of this illumination problem can be found elsewhere in this volume[6].

Another complication of the satellite level OETE tests was that the LiF windows on the lamps transmitted no light with wavelengths shorter than approximately 105 nm. Thus, significant regions in the FUSE bandpass were not illuminated at all during these tests. The lamp did, however, produce visible light which was detected by the FES.

3.3 Requirements of Optical End-to-End Tests

With an understanding of the limitations discussed above, we designed the OETE tests to meet these requirements:

- Show that no gross problems exist with the optical system, such as an inability to align the channels or the presence of unexplained vignetting.
- Refine flight alignment and focus methods.
- Provide FUV and visible light stimulation for mission simulation testing.

We successfully met all of these requirements, except we were not able to conclusively show that coalignment is maintained as the instrument temperature is varied, because temperature changes also slightly misaligned the collimator assembly; this misalignment could not be distinguished from instrument alignment. In addition, while we verified that the instrument focus was within the range of motion of the flight actuators, we were not able to narrow the range in order to refine our pre-flight positioning.

A significant problem with the instrument opto-mechanical system was found from the data taken during the OETE tests. Separate structural members, which support a contamination and light-tight cover, were found to be mechanically coupled into the spectrograph optical bench structure, causing image motion and defocus as the instrument temperature changed. The mechanical engineering team was able to make relatively simple structural modifications, and subsequent OETE tests confirmed that the members had been properly decoupled.

4. FUV PERFORMANCE

4.1 FUV spectroscopic results

The LiF windows on the collimator lamps limited the spectral coverage available during the OETE tests to $\geq$105 nm, approximately half of the FUSE bandpass. Furthermore, the illumination limitations discussed above meant that the Pt-Ne spectra obtained during the OETE tests would be only an incomplete representation of the spectra we will obtain in flight. Thus, it is not possible to demonstrate that the design resolution is achieved across the band. Instead, our goal was to show that the spectra are consistent with the expected resolution and format on the detector.

Figure 3 shows an image from 1 of the 2 microchannel plate segments that make up each FUSE detector, in this case segment A of detector 1. This is a composite image made by co-adding several exposures in which a point source was successively placed in all three FPA slits, corresponding to the medium, high, and low resolution modes of the spectrograph. The six horizontal lines, from top to bottom, are the three Pt-Ne spectra from the LiF channels and SiC channels. This image demonstrates that the spectral format is correct: the spectra are properly separated and fall well away from the edges of the MCP segments, where edge effects would degrade the detector response. In addition, by monitoring the location of the spectra perpendicular to the dispersion direction as the instrument temperature was changed, we were able to demonstrate that the mechanical coupling problem referred to in section 3.3 was properly fixed. This was an important achievement of our OETE test program.

In the preceding test all slits were illuminated, but for each exposure only a small portion of the telescope mirrors and gratings were illuminated. Thus, such a test did not give an accurate representation of the shape and spatial extent (on the detector face) of the spectrum which will be observed in flight, when the optics are properly filled with light. In order to best compare the measured spectra with the expected in-flight spectra as predicted using raytrace models, separate spectra from different collimator assembly illumination slits must be co-added, as described in section 3.2. A small portion of such a co-added LiF spectrum from segment A of detector 2, spanning a 1 nm range, is shown in Figure 4a. The corresponding spectrum taken during spectrograph testing at the University of Colorado is shown in Figure 4b. Differences between the spectra are almost entirely due to the distinct ways that the optics were illuminated in the two test setups. For comparison, a theoretical raytrace is shown in Figure 4c.

One of the properties of this optical design is that both the astigmatism and the image curvature are slowly varying functions of wavelength. The holographic design of the gratings greatly reduces the astigmatic height of the spectral images, an important characteristic for observations of faint sources. However, image curvature could not be corrected, and instead must be removed in data processing. Figure 5 shows a line at wavelength $\simeq$ 116.7 nm, selected from the co-added spectrum in Figure 4a, before and after line straightening. The FWHM is 6.2 detector pixels or 37 microns, corresponding to a spectral resolution of approximately 28,000. This is well within the spectral resolution requirement, given the errors in the measurement.

Because of the incomplete sub-aperture illumination during the OETE tests, it was not possible to do a precise comparison of the theoretical and measured line shapes. Instead, the best pre-flight estimate of the spectral resolution of each channel is based on data from the spectrograph level tests at the University of Colorado, and is shown in Figure 6. This is based on data taken with the gratings nearly fully illuminated by H_2 emission line lamps, and has been corrected for fact that the spectral lines are partially resolved and that the spectrograph entrance slit was filled. Details of the way in which the resolution has been estimated may be found in an accompanying paper[7].

4.2 FUV efficiency estimate

A rough estimate of the FUSE efficiency can be made from OETE test data. Prior to these tests, the flux of each collimator lamp was measured at The Johns Hopkins University on a system designed to calibrate FUV sources. This system employs a normal-incidence Rowland circle spectrograph with a microchannel plate detector. A re-imaging mirror is used to focus light from the source pinhole onto the spectrograph entrance slit. The efficiency estimates obtained are of only modest accuracy due to calibration difficulties with the laboratory detector used.

Figure 5 Spectral lines exhibit curvature, which must be corrected to maximize spectral resolution. This line has a wavelength _= 116.7 nm, corresponding approximately to pixel 840 in Figure 4a. The left panel shows the raw emission line from a Pt-Ne lamp taken during the optical end-to-end tests. The right panel shows the line after a straightening algorithm has been applied. The FUSE science data pipeline performs this on every spectrum.

The table below shows the efficiency estimate for each channel. OETE count rate data were obtained using the large 30_30 arcsec spectrograph entrance aperture, so these estimates do not include slit transmission losses associated with the high- or medium-resolution spectrograph slits. The largest source of error in estimating the efficiency is the uncertainty in the lamp calibration system. Other sources of error include: collimator source slit size, area of the collimator pupil filled by the FUV sources, source output versus current, reflectivities of the collimator optics, and variations in the detected count rate at different times during the OETE test.

We have made considerably more accurate effective area estimates based on measured efficiencies of individual components: mirror and grating reflectivities[8], grating groove efficiencies, and detector photocathode efficiency. These values are combined to give an instrument effective area curve, as shown in Figure 7. We have explicitly included in the effective area calculation losses in reflectivity of the mirror and grating surfaces that are expected from the ground handling operations prior to launch.

Channel	Efficiency	Effective Area (cm^2)	Error (percent)
LiF 1	0.030	38	32
LiF 2	0.029	37	31
SiC 1	0.007	9	29
SiC 2	0.0056	7	28

5. VISIBLE PERFORMANCE

Each of the two redundant visible light subsystems consists of a telescope mirror, the mirrored surface of its corresponding FPA, and the FES that views that FPA. There are two main requirements on the visible light subsystem: provide images to be used for attitude determination over the full 19_19 arcmin field of view (FOV) of the FES, and provide positions of up to six stars with a noise equivalent angle (NEA) of 0.2 arcsec or less at intervals of 1 second. The NEA requirement for the periodic star position updates must be met for stars as faint as V=13.5 magnitudes in order to be sure of having an adequate number of guide stars available. There is the additional requirement that field distortions must be small and correctable by means of a simple algorithm.

The NEA of the centroided star image is determined by the intensity and size of the stellar image and by the amount of noise present. The signal available from a star is limited by the aperture of a single FUSE primary mirror, the efficiency of the optical system, and the quantum efficiency of the CCD. The efficiency of the entire system could not be measured accurately during OETE tests, but in bench tests of each FES we obtained a system throughput of about 50% over 600 - 700 nm, declining to about 30% at 400 nm and 900 nm and dropping rapidly outside this bandpass (measured at a CCD die temperature of -30C). These values are in good agreement with the individual component characteristics, and will provide more than enough signal to compute accurate star positions. Point-source images obtained during the OETE test varied little in size and shape across the FOV, and were insensitive to the anticipated in-flight focus adjustments in the primary mirror or FPA. Although this is not surprising given the subaperture illumination, we expect similar results in flight. The measured image diameters of the unresolved collimator slits were typically 2.7 pixels FWHM (6.8 arcsec), providing good sampling of the images by the CCD.

The main noise contributions to the NEA are: CCD readnoise, dark current, scattered light from other stars in the field of view, and stray light from the bright earth. The CCD readnoise was measured to be only 7 electrons, well below the beginning-of-life specification of 10 electrons. The dark current was measured to be essentially negligible for CCD die temperatures below -30C. The dark current will increase significantly with on-orbit radiation dose, but predicted levels will be within the noise budget for die temperatures below -25C. The thermal vacuum tests show that the FES cooling system will maintain the CCD below -40C, even under end-of-life conditions. Scattered light from a bright point-source in the FOV was found to drop off rapidly with distance from the source: the background 2 arcmin away from a simulated V=1 magnitude star was just low enough to permit tracking of a V=13.5 star with the required NEA. If a star brighter than V=1 is in the FOV the NEA will degrade, but only slowly, if guide stars cannot be found suitably far from the bright star. The most significant background source will be scattered earthlight. Indeed, first light FES images obtained 20 days after launch indicate scattered earth light levels somewhat greater than anticipated. This new result is being evaluated but is not expected to adversely affect instrument performance, except when all available guide stars are near the faint limit, and then only during the daylit portion of the orbit.

Field distortions were measured and found to be consistent with ray trace predictions. The maximum distortion is 1.6%. The distortions are well-described by a cubic polynomial and are corrected by on-board software.

6. CONCLUSIONS

An important goal of the preflight testing of the FUSE instrument was to demonstrate performance results that were consistent with predictions. The FUSE project recognized early in the planning of ground testing that highly accurate tests were prohibitively expensive and time consuming for a mission of this scope. The tests we did perform, first at the spectrograph level at the University of Colorado, and then at the satellite level during OETE testing, have shown that the instrument either meets or is consistent with the most important requirements in terms of FUV spectral resolution, effective area, and visible light performance.

A valuable lesson learned by the FUSE team was that modest testing can often give very valuable results as long as the limits of the test program are understood in advance. Within the constraints imposed upon us, there is good reason to believe that the FUSE satellite will meet the scientific goals of the mission. Now that FUSE has been launched, we will get quantitative information by the fall of 1999.

ACKNOWLEDGMENTS

This work was supported by NASA contract NAS5-32985.

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