The *Far Ultraviolet Spectroscopic Explorer*: 1 year in orbit

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ABSTRACT

The *Far Ultraviolet Spectroscopic Explorer* (FUSE) satellite was launched on June 24, 1999. FUSE is designed to make high resolution ($\lambda/\Delta\lambda$ = 20,000 - 25,000) observations of solar system, galactic, and extragalactic targets in the far ultraviolet wavelength region (905 - 1187 Å). Its high effective area, low background and planned three year life allow observations of objects which have been too faint for previous high resolution instruments in this wavelength range.

FUSE has now been in orbit for one year. We discuss the accomplishments of the *FUSE* mission during this time, and look ahead to the future now that normal operations are under way.

Keywords: FUSE, satellites, ultraviolet, spectroscopy

1. INTRODUCTION

The *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) was designed to measure the ultraviolet spectra of astronomical objects at moderate to high resolution.[1] The last long-term mission to explore the far ultraviolet (FUV) wavelength region was *Copernicus*, in the 1970s. Since that time, there have been significant advances in fields such as optical coatings and detector technology; this allowed an instrument to be designed that was a significant advance over what was available at that time.

FUSE was built under the auspices of the NASA *Origins* program, and has served as one of the pathfinders for the PI-class concept, where the Principal Investigator has ultimate responsibility for all phases of the mission, including design and construction of the entire satellite, along with mission and science operations. The FUSE development team was led by Dr. Warren Moos at the Johns Hopkins University, and included the University of Colorado and the University of California, Berkeley, along with many industrial partners in the U.S., and the governments of France and Canada.

After numerous redesigns and reconfigurations of its design during the early 1990s - without any changes to its primary scientific goals - construction began in the mid-1990s, leading to its launch into orbit on June 24, 1999. The FUV detectors were turned on during August 1999, and a period of characterization and in-orbit checkout began. The first science observations were taken in October 1999, during this checkout period. A transition to normal science operations occurred in December 1999, and normal operations have continued since then. The mission was designed for a nominal three year lifetime in order to have adequate time to make major contributions to several scientific projects including determining the abundance ratio of deuterium to hydrogen (D/H), and studying hot gas in the Milky Way and beyond by measuring O VI transitions at 1032 and 1037 Å. In addition, a significant fraction of observing time is available to the Guest Investigator (GI) community through a competitive peer review process. The fraction of time available to GIs increases each year as the PI team projects are completed. In any extended mission, all time except that set aside for calibration will be available to Guest Investigators.

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2. SATELLITE DESIGN

2.1. Optical design

The FUSE instrument (Fig 1) consists of four coaligned optical channels. Each channel includes an off-axis parabolic primary mirror, a focal plane assembly (FPA) containing three primary spectrograph entrance apertures (1.25"×20", 4"×20", and 30"×30"); a large, holographically-ruled, aberration-corrected spherical grating with a high groove density; and half of a double delay line microchannel plate detector. The gratings and mirrors of two of the channels are coated with silicon carbide (SiC), which provides an approximately constant reflectivity across the entire FUV, while the remaining two are coated with lithium fluoride (LiF) over aluminum, which has a much higher reflectivity above ~1000 Å. Each of the LiF channels also has a visible-light Fine Error Sensor (FES) which is used for guiding. Other papers in this volume describe the design and performance of the telescope mirrors,[2] detectors,[3] and FESs,[4] so only a brief overview of the optical system is presented here. Details of the overall design have also been given elsewhere,[5] as have initial performance results[6,7].

Since the reflectivity of most materials in the FUV is poor, the optical design was developed with the goal of reducing the number of reflections while maximizing the collecting area and providing redundant wavelength coverage over most of the bandpass. In addition, constraints of the Delta II launch vehicle limited the envelope of the satellite. Lessons learned in the design, construction, and use of the optical system is covered in an accompanying report.[8]

The mirrors and FPAs are adjustable on orbit in order to maintain coalignment and focus of the channels. Once the four channels are coaligned, the satellite pointing is adjusted in order to select a particular aperture.

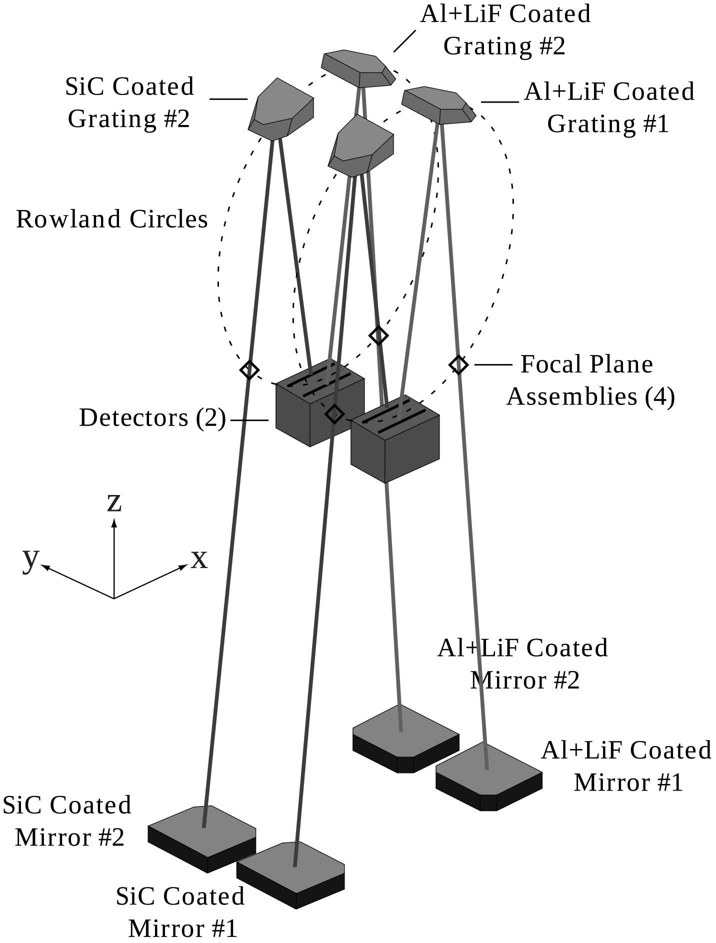

Figure 1 A schematic view of the FUSE optical system

The spectra from the four channels fall on the detectors as shown in Figure 2. Each of the four detector segments contains both a SiC and LiF spectrum from the source, in addition to background spectra from the earth's geocorona. The design ensures that the failure of a single detector segment does not have a major impact on the wavelength coverage. Differences in detector performance, grating parameters, and alignment lead to a varying two-dimensional point spread functions across each of the detectors, however, even at the same wavelength. This makes it difficult to combine data from multiple channels at full resolution.

2.2. Data handling and processing

The location of each photon that reaches one of the detectors is sent via the science data bus to the Instrument Data System (IDS). The IDS is responsible for storing this data as individual photon events (time tag or TTAG mode) with periodic time markers (typically once per second), or assembling the data into a two-dimensional histogram (spectral image or HIST mode). Targets with relatively low count rates ($\leqslant$2500 counts per second [cps]) are taken in time tag mode in order to preserve information on the arrival time of each event. At higher rates (up to ~32,000 cps), the onboard

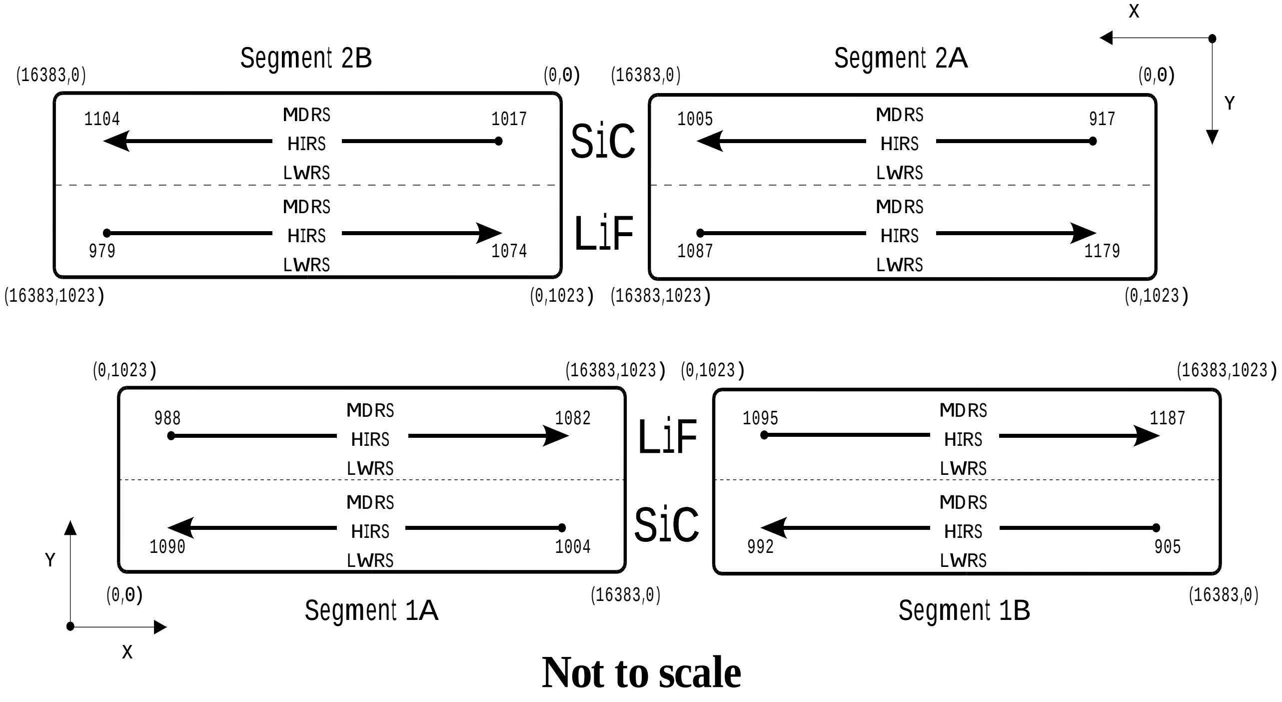

Figure 2 Location of the spectra on the detectors. Pixel coordinates and wavelength coverage is labeled on each segment.

memory would be quickly exhausted, so the data from only the relevant part of the detector is binned (typically by 8) in the y direction and stored as a two-dimensional image. Since the arrival times of the individual photons are lost in this process, Doppler corrections for the orbital velocity can only be made on the image as a whole; as a result, each observation is divided into multiple exposures during each orbit. The y binning has only a small effect on the resolution of the spectra.

2.3. Satellite pointing

The FUSE spacecraft bus, built by Orbital Sciences Corporation and located below the instrument section, contains the power, attitude control, and communications systems for the satellite. The instrument and spacecraft together make up the FUSE satellite. The spacecraft fine pointing is accomplished with the assistance of error signals supplied by the FES. The performance of the pointing and guiding system is described elsewhere in these proceedings.[9]

3. SCIENCE OPERATIONS

Science and mission operations are co-located in the FUSE Satellite Control Center (SCC) at the Johns Hopkins University in Baltimore. Planning and scheduling of observations, generation of command loads, communication with the satellite through an autonomous ground station, receipt and processing of science and engineering data, monitoring of the health and safety of the satellite and instrument, computation of the FUSE orbital elements, off-line analysis of science and engineering data, and maintenance of flight software all occur at this location.

The FUSE low earth orbit (768 km, 100 minute period, 25° inclination) adds a great deal of complexity to operations compared with a satellite in a higher orbit. Communications with FUSE is primarily through a dedicated 5 meter ground station antenna located at the University of Puerto Rico in Mayaguez (UPRM). Typically 7 passes per day, ranging in length from 6 to 12 minutes, are available for communicating with the satellite. This is supplemented by passes from a commercial facility in Hawaii, run by Universal Space Network. During the commissioning phase of the satellite, up to 7 Hawaii passes per day (using a 3 meter antenna) were used in order to supplement the UPRM passes. More recently, a 13

	Time-tag	Histogram
	Level zero processing in Satellite Control Center	
	OPUS gathers packets and converts data to FITS files	
1	Initialize header	
2	Screen data & compute Doppler	Screen data
3	Detect & remove bursts[1]	. . .
4	Compute grating drift	. . .
5	Compute image drift[1]	. . .
6	Add grating & image drifts	. . .
7	Convert list to image	Unbin hist image (if necessary)
8	Calculate drift correction	
9	Update bad pixel mask	
10	Subtract background	
11	Transform flat-field file	
12	Divide by flat-field	
13	Compute distortion shifts	
14	Compute astigmatism shifts	
15	. . .	Compute Doppler shifts
16	Apply all shifts	Apply all shifts
17	Extract 1-D spectra	
18	Wavelength calibrate	
19	Correct for dead-time[2]	
20	Flux calibrate	
21	Co-add spectra at exposure level	
22	Co-add spectra at observation level	
	Science Data Oversight Group performs quality check	
	Data archived at the Multimission Archive at STScI	

[1] Module not yet implemented.

Figure 3 Outline of the CALFUSE pipeline

meter antenna has become available in Hawaii, and approximately 12 to 14 passes per week are typically scheduled in order to improve observing efficiency by providing the ability to dump data during the daily UPRM blackout period.

Since FUSE is out of touch with the SCC for most of the day, a high degree of autonomy has been built into the satellite to allow unaided target and guide star acquisitions, instrument alignment, and health and safety checks of the instrument by flight software. Observations proceed autonomously with no intervention from the ground. Scripts controlling each observation are generated from the ground and uploaded several times per week. (Details of scripted operations have been described by Artis et al.[10]) Science data are transmitted to the ground station at 1 megabit/sec and are stored locally on disk at the ground station. The data are then transmitted to the SCC via an ISDN line after the ground station contact is over. Real-time engineering telemetry is available in the SCC during each pass.

The SCC is staffed 24 hours per day by members of the Mission Operations Team who handle real time communications and monitor satellite health and safety.

3.1. Mission planning and operational efficiency

Overall observing efficiency is limited by the low earth orbit, which results in most targets being occulted for part of every orbit. In addition, observations cannot be made during SAA passages, slewing and peakups add overhead, and the scattered light properties of the FES[4] limit the ability to acquire targets in daylight. Unplanned mirror motions due to thermal effects[8] also decrease the efficiency of observations, particularly in the narrower slits. Early in the mission, detector SEUs[3] also had a major negative impact on the efficiency. Because of these effects, and a slower than expected spectrograph outgassing rate, it took longer to begin normal science operations than originally anticipated.

Since that time, operational constraints, such as limitations on the pointing angles, have been implemented. In addition, more peakup time was allocated in order to maintain coalignment. Despite these complications, the on-orbit efficiency has now reached the level predicted before launch, and is slowly increasing as the number of calibration observations and other special tests decreases with time. For the previous one month period, the weekly efficiency (calculated by dividing the total time making science observations by the total number of seconds in 7 days) has been between 26% and 33%. Even higher numbers would be obtained if calibration observations, many of which can also be used for scientific purposes, were included in this total.

3.2. Science Data Processing

Science data sent to the ground is first processed in the SCC to remove the downlink packet structure, and is then passed through the OPUS pipeline,[11] where the telemetry packet structure is removed, the raw data is converted to FITS format, and the header keywords are populated. At that point they are passed through the CALFUSE pipeline, which is the set of calibration routines used to correct the data for instrumental effects and generate one-dimensional, calibrated spectra for scientific analysis. Figure 3 shows an outline of the CALFUSE pipeline, and the processing steps required for calibration. Details are given in the FUSE Data Handbook.[12] Later this year, the CALFUSE pipeline will be made publicly available so that observers can reprocess data at their home institutions, using the latest calibration and characterization data.

Both the raw and calibrated data are archived in the Multimission Archive at the Space Telescope Science Institute (MAST),[13] where it is available to the original proposer. After a six month proprietary period (for both PI-team and GI data; calibration data has no proprietary period), the data become public and freely available to anyone. The short proprietary period was designed to encourage quick turnaround on the data analysis, to allow astronomers to see the early data before proposals have to be prepared for later cycles. The first PI-team data became public in April, 2000.

4. CURRENT STATUS AND FUTURE PLANS

As of late July 2000, all subsystems are operating nominally. The focus of the spectrograph has been optimized in the largest spectrograph aperture, and measured resolution is in the range of 18,500 to 24,000 depending on wavelength. This is somewhat lower than had been expected, but it is adequate for most of the scientific problems FUSE is designed to address. The narrowest slit shows ~10% higher resolution.

A normal calibration plan is being interleaved with scientific observations. Much of this is identical to prelaunch plans, including monitoring of standard stars for flux calibrations, and periodic quasi-flat fields with the onboard stimulation lamps. Some modifications have been necessary in order to obtain high signal-to-noise ratio observations of bright stars for flat field determination. These tests, and other optimizations, are ongoing as normal science observations continue.

Since launch through late July 2000, roughly 8.1 million seconds worth of exposures have been made. This number includes PI, GI, calibration, and checkout observations. It includes 129 distinct programs, and 607 separate targets. Since routine operations have now truly become routine, the Mission Operations and Science Data Processing groups are now ahead looking towards more complex observation scenarios, such as observations of moving targets. In addition, attempts will be made to improve efficiency even further.

The FUSE PI-team observing program is concentrated on several large scientific programs. These include determining the deuterium abundance in a wide variety of environments, and measuring the properties of OVI in the Milky Way and Magellenic Clouds. In addition to these, however, a large number of small and medium size projects are under investigation. The first scientific results from the PI-team observations were published in late July 2000.[14]

Guest Investigator observations have been underway since early this year. These observations are being made along with the PI team observations as targets reach a favorable viewing geometry. The cycle 2 proposals deadline has passed, and the selection process will soon begin; approximately 3.6 million seconds will be available to Guest Investigators.

FUSE contains no expendable items, such as cryogens, and also is designed with redundancy in most satellite systems. As a result, we are looking forward to a long and successful life, and many years of successful scientific investigations.

More information on the FUSE mission is available at *http://fuse.pha.jhu.edu/*.

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