A GALEX Instrument Overview and Lessons Learned

Patrick Morrissey

California Institute of Technology, MS405-47, 1200 E. California Blvd., Pasadena, CA, USA

ABSTRACT

GALEX is a NASA Small Explorer mission that was launched in April 2003 and is now performing a survey of the sky in the far and near ultraviolet (FUV and NUV, 155 nm and 220 nm, respectively). The instrument comprises a 50 cm Ritchey-Chrétien telescope with selectable imaging window or objective grism feeding a pair of photon-counting, microchannel-plate, delay-line readout detectors through a multilayer dichroic beamsplitter. The baseline mission is approximately 50% complete, with the instrument meeting its performance requirements for astrometry, photometry and resolution. Operating GALEX with a very small team has been a challenge, yet we have managed to resolve numerous satellite anomalies without loss of performance (only efficiency). Many of the most significant operations issues of our successful on-going mission will be reported here along with lessons for future projects.

Keywords: Ultraviolet, Detector, Microchannel plate, GALEX, Lessons learned

1. INTRODUCTION

The Galaxy Evolution Explorer (GALEX) is a NASA Small Explorer mission[*] currently performing an all-sky ultraviolet survey in two bands.[1] GALEX was launched on an Orbital Sciences Corporation (Dulles, VA) Pegasus rocket on 28 April 2003 at 12:00 UT from the Kennedy Space Center into a circular, 700 km, 29° inclination orbit. While small in size, the instrument is designed to image a very wide 1.25° field of view with $4'' - 6''$ resolution and sensitivity down to $m_{AB} \sim 25$ in the deepest modes. This is achieved with a pair of photon-counting, microchannel plate (MCP), delay-line readout detectors differing mainly in choice of cathode material (CsI and Cs_2Te). The detectors are completely sealed tubes, relying on internal getter pumps to maintain vacuum pressure. The far ultraviolet (FUV) channel sensitivity peaks at 155 nm, while the near ultraviolet (NUV) channel peaks at 220 nm; both detectors are solar blind, a requirement for reliable ultraviolet photometry.

GALEX makes science observations on the night side of each orbit (to keep sky background to a minimum) during "eclipses" that are typically in the range of 1500 − 1800 s in length. Each field is observed with a dither pattern 1 arc-minute in diameter spiraling at a rate of approximately one revolution per minute in order to minimize the effects of fatigue due to bright objects on the MCPs. Ground pipeline software reconstructs sky images using a combination of Attitude Control System (ACS) telemetry and point source tracking. Our global hardware count rate limits are 100,000 cps[†] ($m_{AB} \sim 7.5$), with the planning system restricting point sources to less than 5,000 cps FUV and 30,000 cps NUV. The mission includes several parallel surveys with different depths and aerial coverage, among them an All Sky Survey at 100 s/field, a Medium Imaging Survey at 1500 s/field and a Deep Imaging Survey at 30,000 s/field. The program also provides a significant amount (30%) of Guest Investigator time, which is allocated by the Goddard Spaceflight Center.[‡]

In three years of operation thus far, we have observed over 14,000 square degrees of sky and accumulated 3.3 terabytes of science data, which is downloaded in ∼ 1 GB segments approximately 4 times per day to one of two Universal Space Networks (Newport Beach, CA) ground stations, which are located in Australia and Hawaii.

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[*] See http://www.galex.caltech.edu for more information.

[†] The FUV global limit is generally programmed lower, at 30,000 cps, because there have been a number of FUV issues and because the count rates are low enough that the limit does not restrict the observing program.

[‡] See http://galexgi.gsfc.nasa.gov for more information.

Figure 1. A multiwavelength view of the nearby galaxy M51 showing striking morphological differences from the UV to IR resulting from the distribution of different stellar populations.

Because GALEX measures the light from massive, short-lived stellar populations, by its nature it detects areas of active star formation in galaxies. As was already known before GALEX, the morphology of galaxies in the ultraviolet can vary substantially from that observed in the visible as shown in Figure 1, however the sensitivity of GALEX has enabled the discovery of active star formation in regions far removed from the main body of the galaxy,.[2] The growing database of nearby objects in the GALEX surveys will help disentangle the poorly-resolved sample that will be obtained at high redshifts in the rest-ultraviolet by the James Webb Space Telescope.

2. INSTRUMENT OVERVIEW

The instrument comprises a 50 cm Ritchey-Chrétien telescope with selectable imaging window or objective grism feeding the detectors simultaneously with a multilayer dichroic beamsplitter. A cross section of the instrument is shown in Figure 2. The imaging window and grism were provided by our French partners at the Laboratoire d'Astrophysique de Marseille. The instrument integration, central processor, thermal control, test and project management were all provided by the Jet Propulsion Laboratory (Pasadena, CA). The detectors[3,4] are each sealed tubes containing a "Z" stack of three 75 mm diameter (65 mm active diameter) MCPs and a 2-dimensional delay-line anode readout. They were fabricated by the Space Sciences Laboratory, University of California at Berkeley in collaboration with the California Institute of Technology. The two are basically identical, differing primarily in cathode choice and location as shown in the schematic diagram of Figure 3. The FUV detector has a CsI cathode on the front MCP, several millimeters below a QE-enhancing grid of wires that is on the inside of the MgF_2 tube window. The NUV detector has a Cs_2Te cathode deposited over a thin metal layer on the inside of its fused silica window. Because the NUV cathode is proximity focused, it requires the window to be in close proximity to the front MCP. In this case, the NUV window/cathode is 300 μm from the plate, compared to about 6 mm in the FUV window/grid configuration. NUV resolution ($6''$) is degraded by about 20% compared to FUV ($4.5''$) due to the proximity focusing. The tubes are run between 5200 V (NUV) and 6200 V (FUV), which is temperature-dependent since the resistance of the MCPs varies significantly over the 0 – 30 °C operating range. In flight, the detectors have only been operated close to 20°C in order to fix their calibration.

3. GROUND TESTING

While anomalies during assembly and test of a spacecraft are normal and probably too numerous to recount, it is worth noting a few issues for the benefit of future programs. Of the general issues that affected the

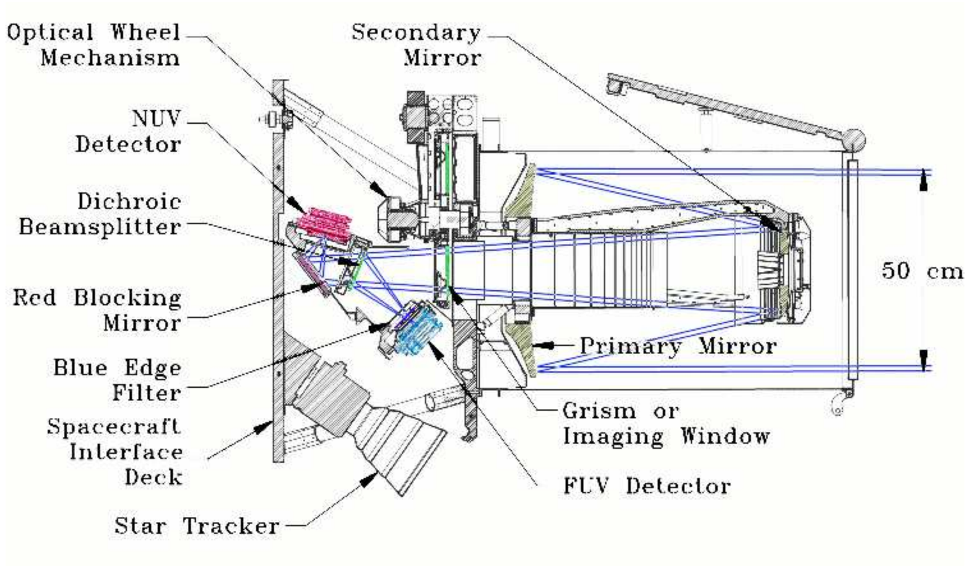

Figure 2. A cross section of the GALEX instrument showing 50 cm primary mirror, optics wheel, dichroic beamsplitter, red-blocking mirror, and a pair of photon counting microchannel plate detectors.

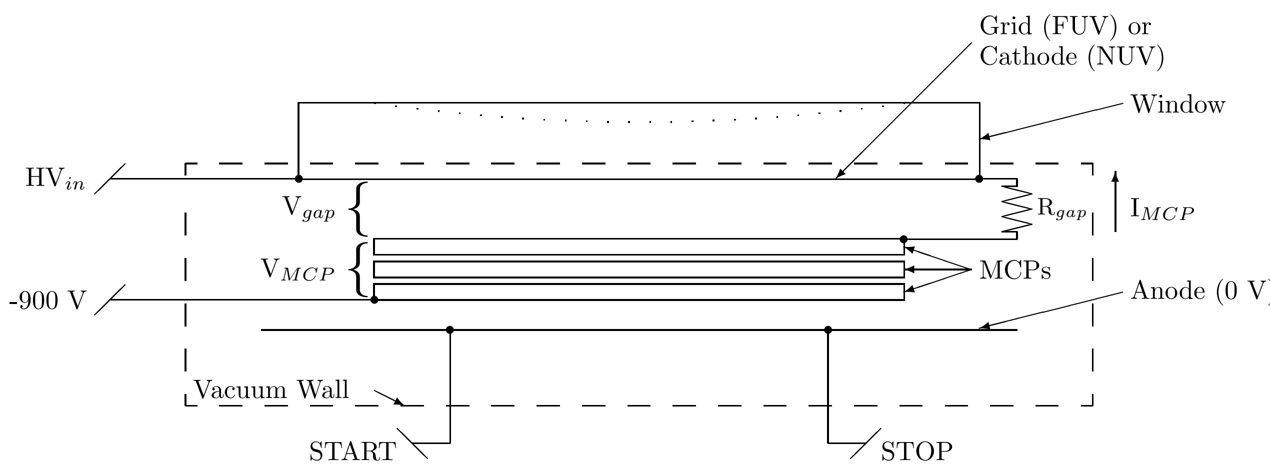

Figure 3. GALEX sealed tube detector head electro-mechanical block diagram. The NUV and FUV tube heads are nearly identical with the principal differences being in the choice of photocathode material (CsI for FUV and Cs_2Te for NUV) and window material (MgF_2 for FUV, SiO_2 for NUV). Also, the cathode material is deposited on the detector window in the NUV channel but directly on the MCP in the FUV channel. Instead of a cathode, the FUV window has a charged grid of wires that enhances the sensitivity of the detector. The other practical difference between the two channels is that the NUV cathode is proximity focused on the front MCP, thus the window-MCP gap in the NUV channel is much smaller (and the electric field at a given voltage much higher) than in the FUV.

GALEX development schedule, we will focus on the large detectors since they represent a significant investment in technology development.

3.1. Tube Issues

The tube program was generally successful, delivering four flight quality tubes on a relatively small budget. Nonetheless, as with any significant technology development (the GALEX detectors are the largest-format sealed tubes on orbit), there were numerous hurdles on the path to a flight-quality system. The FUV detector QE is one example; while the delivered GALEX detectors perform comparably with STIS, the value ($\sim 10\%$) at the key GALEX FUV wavelength of 1560 Å is still well below pre-program estimates, illustrating the complexities of extrapolating performance to a detector with fundamentally new design in terms of size and sealing processes.

A more significant development hurdle was encountered by the team shortly after the first detector deliveries to JPL; the infant failure of one detector, FUV02, during system-level gain-resolution testing. This particular tube had suffered an overcurrent during pre-delivery tests, however it recovered after exhibiting an initially elevated background as a result of the event. At JPL, a second larger overcurrent event proved unrecoverable. The post-event tube exhibited a large, persistent bright feature in the field of view at many thousands of cps. We choose to mention this event because this tube and its unusual characteristics have been illuminating in terms of understanding issues with the detectors that are now on orbit. For example, lab experiments with FUV02 have been suggestive that the window-MCP interface has a high voltage issue (which will be discussed in Section 4.3). This detector was the only problematic unit delivered to JPL; all the others behaved flawlessly on the ground.

The failure of FUV02 led to the implementation of new detector software that monitors the current at high speed (up to 200 samples per second), compared to the test version of the detector code, which monitored the current only every three seconds. We also implemented a procedure in preparation for thermal vacuum testing to set the detector voltage based on the internal voltage distribution of the tube rather than the applied voltage, because the internal voltages can vary significantly as the temperature of the MCPs changes. The effect is largest in the NUV, where the 300 μm gap between the cathode and front plate places a tight requirement ($\pm$few degrees) on the thermal stability of the detector (requiring a special heater nearby the NUV detector).

One of the aspects of the FUV02 failure that helped debug a later flight issue was the following odd electronics behavior: prior to the large overcurrent event, the digital side of the detector electronics would intermittently cease to produce valid counts as the operating voltage was increased, while the analog input side continued to operate normally. The fast event counter, or FEC, which is located at the discriminator input of the electronics, would continue unchanged, but the telemetered event counter, or TEC, would drop to zero. The TEC represents events that have a valid position computed and telemetered to the DPU and is thus a "back end" measurement of the system health. The TEC dropouts, or "FEC without TEC," thus appeared to be an electronics issue since pulser-supplied "STIM" events (that are independent of the high voltage) were also affected. Unfortunately the issue was not resolved before the event and could not be reproduced until a chance recurrence event occurred several years later in the lab. The FEC-without-TEC count rate anomaly was then traced to a benign oscillation in the analog pulse-height measurement circuitry at the front end of the digitizer electronics. The oscillation was most likely set off by occasional large pulses produced by the problematic FUV02 detector, but was not reproducible with other tubes. Because the pulses were occasional, the charge sum circuit would come in and out of oscillation making the problem very difficult to detect.

3.2. Electronics Issues

Finally, we will mention several design issues resolved with operational changes. The first of these involved the command interface of the detector Front End Electronics (FEE), which generates a clock that is used by the DPU to synchronize data transfer. The GALEX detector system has fully redundant electronics; each channel operates independently. As a simplification, the DPU command interface uses a command clock generated by one FEE (selectable) for both interfaces. This choice has placed requirements on scripts and the regular observing command sequence that add significant command overhead. The reason is that if one set of detector electronics shuts off for some reason and happens to be the set supplying the command clock to the DPU, then the functioning command interface will crash. This led to the requirement that all commands to a new detector be preceded by a clock switch to that particular unit, which represents a significant command overhead. While completely resolved operationally, the problem simply illustrates the types of design issues that can come up when assumptions are made about the way the electronics will be used (in this case an assumption about both sets of electronics being on or off together, rather than independently).

A second issue involves a design choice that was made early on for the detector digitizers. Normally, positions are measured in delay line systems using a time-to-amplitude converter, or TAC, with a simple scheme for which the TAC output is directly proportional to the timing difference between the pair of pulses arriving from either side of the delay line. In such a system, non-linearities in the TAC translate to spatial non-linearities in the resulting detector images. The GALEX detectors are so large that a conventional TAC would not have the resolution to meet the detector requirements across the field of view, so a novel design was implemented that uses a coarse counter to divide the field into a 3×3 grid, with the fine resolution achieved by the TAC within each grid section. In this design, the coarse clock runs asynchronously from the photon input, and the TAC measures the phase of the coarse clock relative to the photon arrival time. The beauty of this design is that it is highly scalable, however it does have the pitfall that the value of the TAC output does *not* correlate with detector position. Thus TAC non-linearities translate into *blur* in the GALEX digitizer design. Initially, this was a dominant effect, but by careful parts selection and layout it was reduced dramatically. To assure the effect was completely mitigated, we also augmented the digitizer output word with 5 additional bits that measure the TAC value, information that otherwise would be lost but which is very useful for image analysis. These extra bits measure what is referred to as "wiggle," an effect reminiscent of detector walk in appearance and resolution.

3.3. Optics Issues

The final design issue we will discuss was the fact that the GALEX optics had significant astigmatism, which varied as the instrument made its way through environmental testing. The initial third-party optical design was not kinematic, relying on workmanship with very tight mechanical tolerances to produce high resolution imaging. Testing at JPL indicated that the delivered system was optically pinched, which led to a complete mounting redesign by JPL at a large additional cost. A JPL-designed kinematic primary mirror mount was installed, although time and budget did not allow installation of a kinematic secondary mount. Further complicating the picture was the fact that the ground test collimator, a nearly-identical twin of the flight telescope, had a significantly larger thermal coefficient of focus than the flight telescope. This lead to uncertainties during thermal vacuum focus testing. After multiple vibration tests and a collimator-only thermal vacuum autocollimation test, the team concluded that the problem was reasonably enough bounded to assure that the optics would not dominate the overall instrument resolution budget, and flight performance has closely followed our expectations.

4. FLIGHT OPERATIONS

GALEX has met all of our pre-flight requirements for performance in terms of sensitivity, resolution, photometry, bandwidth and astrometric accuracy. However, the one area where the program has suffered has been efficiency, largely due to downtime from detector issues, but also a variety of other issues from different subsystems. In all cases our small team has taken advantage of the flexible design of the instrument to recover as will be shown in this section. Thus far we have been lucky that *all* of the issues encountered in flight have been completely resolved with operational changes or software patches without loss of performance. This section will describe unexpected situations that occurred during flight and the steps taken to resolve them.

4.1. Data Processing Unit (DPU) Flight Software

The JPL-built DPU has performed essentially flawlessly since launch. There was one significant flight issue with it that was a consequence of a known hardware flaw in the DPU-FEE digital interface board. This interface employs asynchronous timing that occasionally (roughly 1 in 10,000 words) corrupts data from the FEE into the DPU. The error was detected on the ground at a late enough time in the development program that the project elected only to verify that the consequences were not harmful to the electronics. Since the primary data flow into the DPU from the detector is in the form of photons at an integrated rate of roughly 25,000 per second, the corruption amounts to a very small effect with negligible impact on science quality. However, this error eventually had a significant ($\sim$monthly) impact on operations efficiency when it started to trigger the DPU fault protection into shutting the detectors down as a result of apparently dropped commands. Since the detector

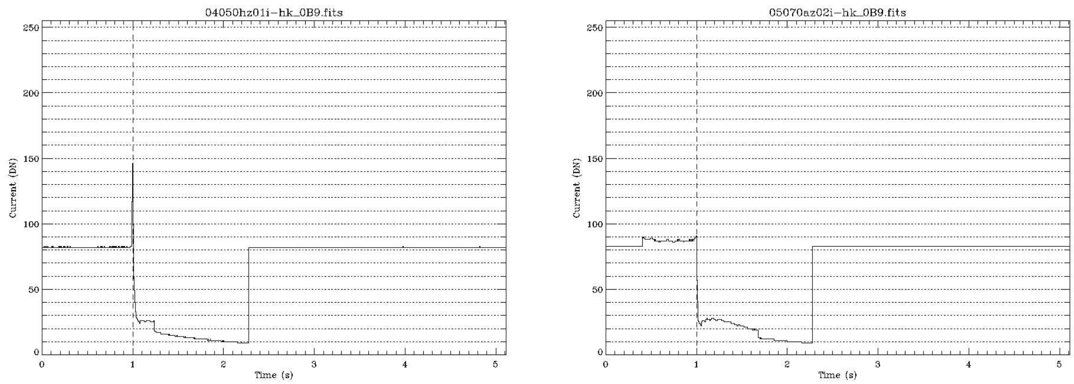

Figure 4. *Left panel:* A high-speed trace of the FUV MCP current during a "fast" shutdown event. As is typical of this type of event, the amount of overcurrent is large, almost doubling the normal current for a very brief interval. GALEX fault protection only allows the event to persist for 10 ms (2 samples) before shutting down the HV. *Right panel:* A high-speed trace of the FUV MCP current during the "slow" shutdown event of 11 March 2005. In this type of event, the current increase is so small that even the very conservative fault settings used by GALEX do not trip for a large fraction of a second. Both panels are ring buffers that stop recording shortly after the overcurrent; each event is arbitrarily placed at 1 s for clarity (the current does not turn back on after the events). The current scale is in engineering units, the normal draw of the detector is about 50 μA and the scale is about 1 μA-DN^{-1}.

only transmits housekeeping to the DPU on changes, certain housekeeping values do not change often but are critically important (such as the command counter) are very sensitive to corruption. In this case, the DPU requests a detector power-off from the spacecraft bus to protect the detectors if a command is dropped, and it did so roughly monthly when the command counter housekeeping from the FEE to the DPU was corrupted. We solved this problem with a DPU software patch that uses three essentially redundant telemetry points to measure the command count in a majority vote scheme.

4.2. Early-mission detector current transients

Immediately after GALEX began detector operations in May 2003, we began to observe transient overcurrent events, a typical example of which is shown in the left panel of Figure 4. This was a surprise since both detectors had run for over 1000 hours on the ground with extremely stable current (± 1 μA). We still do not understand what caused these events, which occurred both in the NUV and FUV detectors. We do know that a number of them were remarkably well correlated with the active space weather of 2003 in the form of protons bursts and x-ray flares, and also that the frequency of the events diminished from one or more per month to one per year after the space weather subsided. We observed 5 events (2 FUV and 3 NUV) from 29 May 2003 (shortly after we began operations) through 4 July 2003. Of these, three were correlated with large solar flares (including, perhaps most importantly, the first one). However, if one looks carefully at the dozen events from mid-2003 through 2004 against various space weather indexes such as F10.7 or the sunspot number, one finds that on short timescales the correlation is quite poor (excellent for just a few events) and the only overall correlation is with a 4-month running mean of the index. Thus the strong correlation between space weather and several of the events, while suggestive, does not appear to be conclusive.

Since transient events had not been observed on the ground except in the one tube that failed during testing, we took them quite seriously and looked to other missions for information. The nearest experience was from the Far Ultraviolet Spectroscopic Explorer (FUSE)[5] program at Johns Hopkins, which observed detector HV transient events regularly, including during ground test. The FUSE detectors are also MCP-based, however they operate at relatively short wavelengths compared to GALEX and thus are not contained in sealed tubes. As such, the comparisons are limited. The FUSE program opted to progressively relax the fault protection limits to try to find a balance between detector safety and operations efficiency, eventually opening the "persistence" or length of time a transient is allowed before HV shutdown, to 60 ms. GALEX opted for a different approach because of concerns that the sealed tubes would not be robust to large events that could cause gas production inside. We chose to leave our tight fault limits in place (a shutdown occurs for an event just 5 μA above the 50 μA strip current that lasts as long as 10 ms), but to modify our DPU flight software to partially automate the recovery process by downloading some diagnostic data at the time of the event and ramping the detector HV to an intermediate state where it could equilibrate after approximately 45 minutes. It is worth noting here that all GALEX flight code changes have been written for the central instrument DPU rather than for the detector FEE because the FEE code is written in assembler and is not as easily reviewable as the DPU flight software, written in C. With the partial recovery automation in place, observations would resume with just a few minutes of commanding during a regularly scheduled contact, typically about a day after each event.

We also conducted a series of experiments in the lab exposing our spare detectors to a Co60 gamma ray source. Depending on the detector, we had variable results generating overcurrent events with this method. Our damaged detector, FUV02, would overcurrent occasionally when placed in proximity to the 0.1 mCi source, however other detectors did not show the same sensitivity. Typically the gamma source would generate high pulse height events between $10 - 100$ kcps when placed close to the detector, and moving the source around produced output much like moving a flashlight around the detector. While it is interesting that there is a connection between the gamma source and lab detector overcurrents, the lack of a large number of extra background events on orbit suggests a different process at work.

For the first two months of the mission, there were similar numbers of FUV and NUV transient events, however the NUV detector suffered a very large event (saturating the 8-bit current buffer with at least 175 μA *above* the nominal 45 μA current) on 4 July 2003 that not only shut the detector down but also triggered the "FEC-without-TEC" mode that we had not observed since ground test with FUV02. This event led us to power off the detector electronics for a full month while the cause of the problem was investigated. At that time, a definitive cause was not found, but plausible options were investigated (among them many complicated timing faults, ground bounces and various oscillations), but none warranted major changes to the flight software. We did implement a DPU patch to request detector power-off when the FEC-without-TEC condition was observed. As previously noted in Section 3, the condition was eventually reproduced in the lab and found to be a benign oscillation of the pulse-height measurement circuitry, which gates all events generated by the FEE. Since the large event in 2003, the NUV detector has operated very quietly, with only a rare overcurrent event at a frequency less than 1/year, which of course begs the question of whether NUV developed a problem during launch (such as a sharp piece of debris in a sensitive location) that subsequently burned itself out in the large July overcurrent.

4.3. FUV "Blob"

The end of 2003 was punctuated by severe space weather that included 2 of the top 5 solar flares on record since 1976. On 28 October 2003, the FUV detector exhibited an entirely new anomaly that was nicknamed "the blob," which is shown in Figure 5. During a normal ground contact, controllers observed multiple count rate shutdown diagnostics in the FUV telemetry and issued commands to turn off the high voltage (overcount faults do not disable detector operation like overcurrent faults do; they result in reduced high voltage until the next target is selected). The FUV detector images revealed a large ($\sim$1 cm^2) patch of emission near one edge of the field of view generating over 30,000 cps resulting in a count rate shutdown during the HV ramp at the beginning of each eclipse. Further analysis revealed the feature had been present at a very low rate (a few to 10's of cps) for weeks previous and that the count rate jumped exponentially during one eclipse period. We also observed that the pulse height distribution of the blob events was biased very high compared to normal events that result from photons at the top MCP. It also did not take long to notice that the shape of the blob was traced by some features that had been observed first in engineering flat field images taken with out-of-band mercury pen-ray light (primarily 253.7 nm) prior to detector delivery. These flat field images were already known to display an unusual blend of features including photoemission from the edges of the grid of QE-enhancing wires. Since the electrons from the grid are accelerated through several hundred volts on their way to the front plate, they generally have higher pulse height than ordinary photocathode events. Furthermore, it had been observed that objects such as lenses placed in close proximity to the detector windows could *permanently* alter the "grid" pattern, turning straight lines into curved ones in the out-of-band images (with no effect on the in-band flat). These observations led us to the theory that the blob results from charging of the detector window, the inside of which is held at -6200 V by the grid wires while the outside floats. Thus the outside of the window is an excellent positive charge

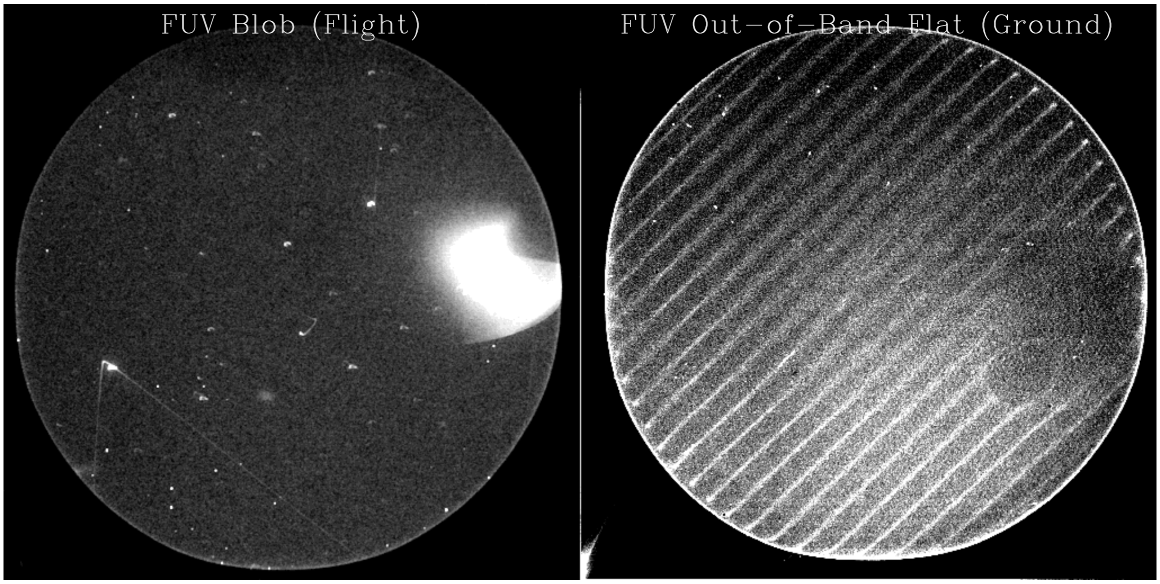

Figure 5. *Left panel:* The FUV "blob" (large feature at right in image) appeared suddenly on 28 October 2003 during an intense period of solar activity. It is characterized by a high pulse height compared to normal photon events, indicating its source is at the detector window, and it always has the same shape and detector location. The feature recurs with a period about 6 to 8 weeks, and it disappears completely after several days with the HV turned off. Similar features have been reproduced in the lab by charging the window of a spare detector. *Right panel:* Pre-launch out-of-band flat field image (representative of the window grid "electron optics") shows striking structure in the location of the blob feature, further reinforcing the window charging theory.

collector. When the outside of the window charges to 0 V potential, there is a large field across the window and our theory is that a sharp point inside the window (such as debris or a microscopic piece of delaminated grid wire) emits electrons in the presence of the field. Luckily enough, we also discovered that after approximately a week with the HV turned off the window discharges and the detector is returned to normal operation. Initially we hoped that the decline in space weather would also mark the end of the blob, however it returned after about 6 weeks and then operations continued on that schedule of 6-8 weeks on followed by one week off. It is possible the first onset of the blob was delayed by periods early in the mission when the HV was off, allowing the window to remain acceptably discharged. We have implemented trending software that is sensitive to the onset of high pulse height events, and after the first few blob occurrences we have generally been able to follow the background closely enough to be able to power down the FUV HV before a count rate shutdown. Interestingly enough, the blob never occurs in the NUV detector, and we believe that this is because the NUV detector has a cathode and thin layer of metal uniformly distributed over the inside of its window, which maintains a uniform field on the inside, even though the outside of the window is likely to be charging the same as the FUV.

After observing the blob in flight we immediately set out to try to reproduce it in the lab with one of our GALEX spare detectors. Initially we tried placing objects nearby or even in direct contact with the detector window and had some success along the lines of our early experience placing test lenses in close proximity to the detector window. A breakthrough occurred, however, when we attempted to charge the window using a Semtronics benchtop ionizer, which is a device nominally intended to reduce electrostatic charge by blowing a neutral stream of ions across the work area. In our case, we could charge the window by turning the detector on to a reduced voltage with the ionizer switched on. Then, with the ionizer switched off we would ramp the detector to the operating voltage. We quickly discovered not only that we could make blob-like features come and go in our spare detectors, *but that we could repair detectors that previously exhibited long-lasting symptoms of window charging.* For example, the features in the FUV02 detector field of view could be eliminated simply by blowing the ionizer across the window with the detector turned off! These changes would occur in seconds, which may not be surprising since the charge capacity of the window is quite small (~ 1 pF). Of our two spare FUV detectors, FUV01 appeared stable after being discharged, but FUV02 appeared to be sensitive to re-charging. This may mean that FUV02 has some type of grid/window defect that is very sensitive to small amounts of charging compared to the others, however once we understood the mechanism we continued experimenting to see if we could fix it. Initially, FUV02 was stable for periods of several hours before it had to be discharged. We then introduced a metal ring onto the exterior surface of the window at the same potential as the grid on the interior. This metal ring appeared to maintain the charge state of the window and immediately stabilized the detector, which we then proceeded to use intensively for high count rate testing over the next six weeks. FUV02 eventually failed again by overcurrent during a low rate background test. It is not clear why, and it may be that it has a potting failure independent of the window issue. Nonetheless, the pre/post ring performance change was remarkable and may be worth considering for future implementations that require a charged window. Furthermore, the ionizer test is a very simple one that could be implemented with engineering units to test their sensitivity to static charging.

While we do not understand the exact mechanism for the detector window charging in flight, we have investigated several possibilities. The most obvious of these is that low energy plasma with a density at our orbit[6] of 10^4 cm^{-3} is charging the window. The problem with this hypothesis is that with a detector window capacitance in the range of 1 pF at a potential of 6000 V, the time to charge when exposed to the plasma is only a fraction of a second. Furthermore, we have reviewed the boresight angle distribution with respect to the satellite velocity and found that there is a wide distribution of angles; if the culprit was the low energy plasma then one would expect a blob preference for times the satellite is pointed favorably to scoop up the plasma. While we can't rule out a complicated electrostatic shielding scenario that limits entry of the low energy plasma into the detector cavity, it is interesting to also consider the possible effects of the high energy protons. In this case, we have a rough measurement of their density by virtue of the detector background enhancement in flight (roughly a factor of two for the diffuse component). Given this rate and then scaling by a factor of 10 (based on laboratory measurements with a calibrated radiation source discussed in Section 4.2), we find that the density of protons that make it through the shielding (and therefore lose enough energy to be captured by the 6000 V window) is sufficient to charge the window in about 4 months, similar to the observed period. Since the energetic protons would not depend on the boresight angle of the spacecraft, this may explain why the charging cycle appears to be independent of the observing plan.

4.4. FUV Recurring FUV HV Transients and the "Flash"

Throughout 2004, operations were fairly smooth, with on-board patches handling many of the previous efficiency issues, and ground trending handling the blob on a roughly monthly basis with few-day FUV window discharge cycles. One interesting observation during this period was that it seemed that the blob and high speed overcurrents were related; that is, we would observe the blob, turn off for a week, restart without the blob, and then after returning to operations we would have a transient overcurrent event. After recovering from the transients we would see a very low level blob. This led to speculation that the transient events occurred around the window when it was discharged (thus the exterior would be at the applied window potential of -6200 V) and sitting at a relatively high potential compared to the nearby hardware, while the blob events occurred after the window exterior had grounded itself (placing a large field across the window). The transient events might cause a low level blob by partially charging the window toward ground potential.

At the end of 2004 we had an unrelated spacecraft issue that required the HV to be shut down for several weeks, but then we restarted operations normally for two weeks ending in another FUV transient overcurrent event. We attempted to restart twice over the next few days; the first restart allowed several hours of operation and the second resulted in an overcurrent during the pre-start functional test, the first ever overcurrent at below-operating voltage. Since we were clearly in new territory with FUV, we decided to stand down approximately two weeks with the idea that something might be charged in the FUV detector. We then performed functional tests with no problems and restarted operations. We observed for only one eclipse, during which we observed a unique "flash" event which we believe was a glow discharge resulting from unusually intense space weather in the form of particles observed near our altitude by the Polar Orbiting Environmental Satellite (POES). Analysis of this event shows it was *observed by the NUV detector* for about 10 ms, followed by several seconds of emission from the charged FUV detector window, but then punctuated by a count rate shutdown. This event was like the blob in that the events had high pulse height, but unlike the blob in spatial distribution. The flash appeared more like the uniform charging observed with spare detectors in the lab. After the flash event we performed a functional with near-normal results a week later, finally resuming operations at the end of January (the additional delay due to residual concerns about the space weather). After this event we had a couple of unrelated issues with the instrument and bright targets, but no more significant problems with FUV until March 2005.

4.5. The FUV Current Anomaly

The most serious instrument anomaly to date occurred on 11 March 2005, when the FUV detector suffered a new kind of overcurrent. Rather than a rapid discharge far exceeding the normal current limit (5 μA above baseline) in a few milliseconds, we observed a "slow" overcurrent that exhibited rapid onset but low enough amplitude to allow the detector to continue to operate for a large fraction of a second before finally exceeding the current limit. The high speed current trace of this event is shown in the right panel of Figure 4. While previous overcurrents did not appear to affect the detector, the symptoms of this event persisted for months. Unlike transient events, which generate counts around the periphery of the field of view, the slow overcurrent is characterized by an immediate disappearance of photon data.

After the March 2005 event, we performed a functional as usual with nominal behavior at first but ending in an overcurrent after several seconds at full voltage. Analysis revealed another slow event. Over the next weeks we attempted a variety of tests including functionals at lower voltage and a 2 day period of observation with the HV set to its lowest non-zero setting, 2500 V. In all cases, the performance was anomalous, and the most significant observation was that during the 2 day test the current appeared to be bi-modal, that is that something appeared to be switching on and off over a period of hours. This led us to theorize that we were observing some type of field emission inside the detector, perhaps due to an MCP defect that had become activated somehow, effectively shorting one of the three MCPs in the stack. Evidence mounted in this direction with two key observations:

- When the defect was at its most active, the current draw was consistent with a series drop in the resistance similar to the removal of one MCP.
- The count rate versus current curve during the anomalous event showed a precipitous decline for few-μA increases in current, which are similar in magnitude to the small increases in current observed normally as the detector plates heat up. The thermal current increase, however, which is equivalent to a parallel decrease in the plate stack resistance, is not associated with a significant change in count rate. *Thus the HV current anomaly must be a serial phenomenon.*

These realizations helped focus our attention on the MCPs, and also eliminated a host of other plausible but less recoverable possibilities, such as damaged HV insulation. We also identified strong similarities between the count rate vs current behavior of the 2005 slow overcurrents and an event that occurred early in the mission just a few months after launch (June 2003). A snapshot of the data from this early eclipse is shown in Figure 6. We had observed some odd FUV count rate behavior lasting 10s of seconds that was associated with small increases in the HV current and global decreases in count rate. This behavior was intermittent for a few minutes and then disappeared for 2 years. The similarity of the slopes of the 2003 and 2005 count rate vs current curves shows the symptoms were most likely due to the same phenomenon.

While significant progress had been made in characterizing the problem, what to do about it remained an issue. Most of the obvious options were not palatable, such as raising the current limits to allow the defect to "burn off." The most notable objection stemmed from the serial nature of the short — any attempt to raise the voltage back to nominal levels would significantly overvoltage all of the parts of the serial chain that were behaving, quite possibly spawning other problems. In order to further characterize the short, we attempted a HV cycling test, the idea being that while the GALEX software ramps voltage up slowly, decreases are rapid and might affect the anomaly long enough to definitively tell if it was the result of field emission (which might turn on and off) or something else more persistent. We were quite surprised to see the outcome of this test; a pair of slow ramps from 2500 V to 3000 V followed by rapid decrease back to 2500 V resulted in a persistent improvement in the current behavior. While we still do not understand the exact mechanism for the improvement with cycling, we observe the following:

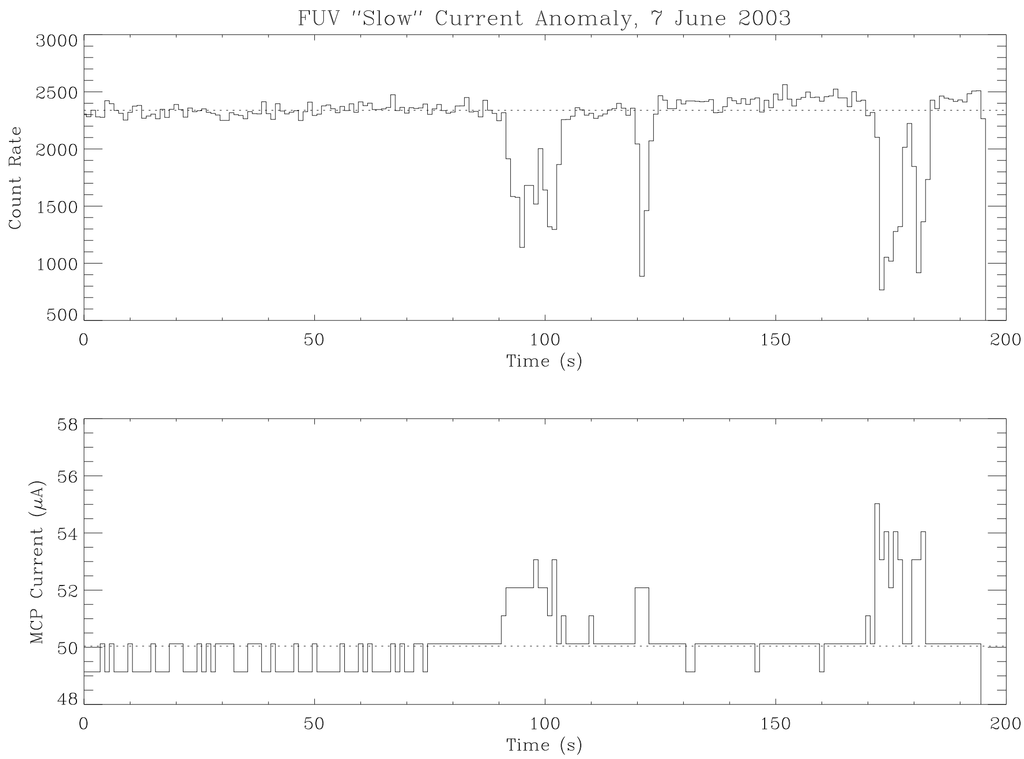

Figure 6. The anomalous FUV count rate and MCP current observed on 7 June 2003, about 5 weeks after launch. The global decreases in count rate are each correlated with few-μA increases in HV current, and the slope of the count-rate-versus-current curve is the same for this data and the major 11 March 2005 anomaly, strongly suggesting the events are the same phenomenon.

- Traditional high potting, leaving the HV on for long periods, does not improve the behavior. We think this is because the series chain has such high resistance that there is not enough current to affect the anomaly without raising the HV to the point of damaging other elements.
- The rapid decrease in voltage at shutdown, perhaps generating a capacitive current pulse, has the effect of deactivating (high-potting) the defect. Furthermore, there is evidence that the transient from HV to the minimum non-zero level (2500 V) is more effective than a cycle directly to 0 V. Since the GALEX HVPS has two outputs, one programmable and one fixed rear voltage, the transient behavior at turnoff can be complicated, even leading to field reversals for periods as long as seconds.
- On multiple cycles, if the current performance is on an improving trend it will continue to improve to nominal performance. However, if the trend degrades it will be necessary to backpedal in voltage.

Once we settled on a procedure for HV cycling, we were able to make good progress toward nominal current up to about 5000 V, still over 1000 V short of operating potential. At that point we found that the current would improve up to a point before breaking away and forcing us to repeat the process from lower voltages. After several attempts we reduced the step size to 100 V between tests and started cycling with the on-board software once per eclipse. Slowly, changing the voltage every few days, we were able to restore the detector to completely nominal performance over the course of months. Once we had reduced the voltage step size and increased the number of cycles per step (to about 50), we stopped observing overcurrents of any kind. After restoring the voltage completely by the end of July 2005, we uploaded some new DPU code to allow us to cycle the HV completely off on the day side of each orbit (NUV still operates with HV on full time but at reduced

Ball Aerospace Star Tracker Specifications	
Model	CT633
Sensor	512x512 pixel CCD
Operating range	$-30 \rightarrow +50°C$
Field of View	$18° \times 18°$
Sensitivity	$0.1 \rightarrow 4.5$ magnitudes
Tracked Stars	5
Internal catalog	2100 stars
Photometric accuracy	±0.25 magnitudes
Attitude accuracy	±6"
Roll accuracy	±45"
Tracking rate	$0.1°\text{-s}^{-1}$
Acquisition time	60 s
Update rate	5 Hz
Size	5.3 in dia x 5.5 in long
Weight	6.6 lbs

Table 1. Performance specifications for the Ball Aerospace CT633 star tracker. The tracker contains an internal reference catalog and generates a spacecraft attitude for any given pointing.

levels on the orbit day side). In addition to providing extra cycling that may stabilize the detector in the long term, this new operational mode maintains a low state of charge on the window and appears to have eliminated the "blob" problem. We spent approximately 6 weeks increasing the length of time FUV observed during each orbit, finally culminating in complete restoration of nominal operations in October 2005 (retaining the period with HV off on the day side). We also implemented an extensive white dwarf calibration program that has significantly improved our overall catalog photometry and verified that the FUV performance is unchanged from before the anomaly.

4.6. Star Tracker

After detector issues, the only other significant anomaly that has impacted observing efficiency has been a period of roughly monthly instrument safe-mode entry as a result of erroneous output from the star tracker, a Ball Aerospace (Boulder, CO) model CT633. In the GALEX ACS design, a Litton (now Northrop-Grumman, Los Angeles, CA) Space Inertial Reference Unit (SIRU), provides high speed pointing information while the Ball tracker provides an absolute reference. The output of the SIRU and the tracker are merged in a Kalman filter, where the tracker necessarily receives a high weight, since it is a much more accurate absolute reference. Normally the SIRU provides full-time data while the tracker comes in and out of operation around slews, Earth occultation, and the like. The tracker corrections to the spacecraft attitude are typically small, of order arcminutes. After about a year of operation, however, we began to observe occasional noise in the tracker output. The noise would drag the spacecraft attitude off the correct pointing, far enough (more than a degree) to trigger the ACS fault protection, which conservatively commanded the instrument into safe mode (HV off) and placed the satellite into Coarse Sun Point (CSP), which uses hardware sun sensors to maintain power-positive condition on the sun-side of the orbit. Working with the teams at Orbital and Ball Aerospace, we identified hot pixels in the star tracker image; stars would occasionally trail by these, and the tracker software would get confused about which was a star and which was a hot pixel. The tracker residuals for the mission are shown in Figure 7, revealing a large jump in outlying events starting around the fall of 2004.

We consulted with the instrument team for the Hubble Space Telescope (HST)[§] and found that although our tracker CCD is operated relatively warm ($\sim 0°C$), it is not quite warm enough to meet the normal requirements of HST hot pixel annealing and thus might be expected to have a radiation-induced hot-pixel problem similar to

[§]Randy Kimble, GSFC, personal communication. More information on the behavior of HST pixel annealing may be found at http://www.scsci.edu/hst/acs/documents/isrs/isr0209.pdf.

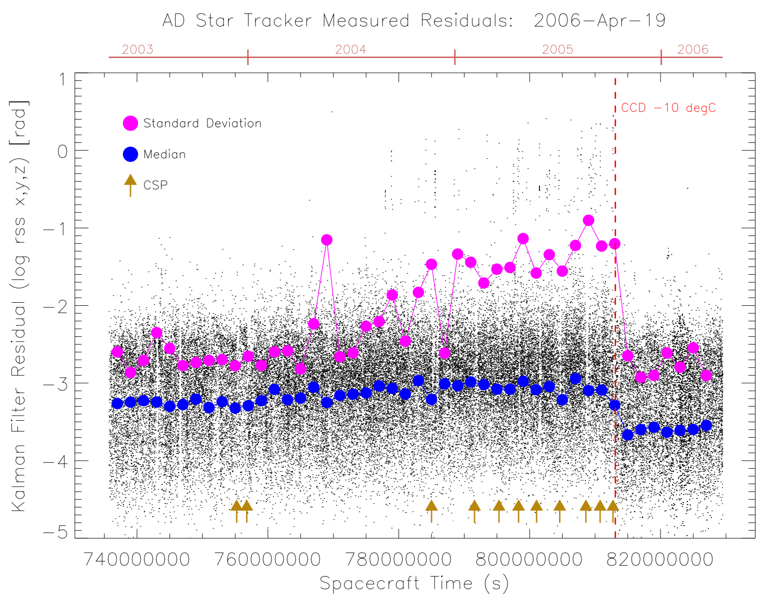

Figure 7. Tracker residuals for the GALEX mission showing the CSP events (arrows) and the improvement in noise performance after cooling the tracker CCD from 0 to -10 °C. The onset of high-residual events occurred quite rapidly about midway through 2004.

the much colder sensors on-board HST. We reduced the temperature of our tracker CCD to −10°C, with specific pixel monitoring both before and after the temperature change. Not only did the temperature change result in an immediate reduction of tracker residuals, but we have not had a CSP event since that change. The tracker now operates with the best performance of the entire mission, although there does appear to be a small upward trend since the temperature reduction was implemented. It is conceivable that hot pixels are accumulating on the sensor, but that they are a generally lower-level population due to the cooler operating temperature; if this is the case and they become problematic in the future the project plans to investigate thermally cycling the CCD in the manner shown to be effective by HST.

5. SUMMARY

5.1. Instrument Status

As of this writing, GALEX is continuing its survey of the ultraviolet sky while the project completes its second major data release, the GR2, to the Multi-Mission Archive at StSci.[¶] This release contains nearly 8000 square degrees of sky in both FUV and NUV, including a complete reprocessing of the GR1 data release. We continue to improve the calibration of the data through a white dwarf standard star observing program. After the recovery of the FUV detector to full voltage in August 2005, we conducted an extensive observing campaign for the white dwarf standard, LDS749b, which has directly benefited the recent data release. Using a grid of thousands of observations (hundreds for the FUV channel), the photometry was improved to ±0.05 magnitudes FUV and ±0.02 magnitudes NUV. Further, we have improved the absolute astrometry using a cross-match with the Sloan Digital Sky Survey catalog to a typical value of ±0.5″ with NUV-FUV relative positions good to a similar degree of precision. Improvements are possible, but mainly at the outer few arcminutes of the field, where the

[¶]MAST; http://archive.stsci.edu

distortion due to HV effects in the detector is quite large. In the GR2 release, FUV astrometry is adjusted to minimize differences with NUV. For the next round of calibration, we are considering the addition of a real-time astrometric correction to eliminate the remaining "breathing mode" in the global linearity correction for the detectors, which can be measured using on-board pulser data that is already being collected.

The post-anomaly period from October 2005 through March 2006 was the highest efficiency of the GALEX mission, achieving about 95% of the planned observations. The anomaly recurred on 30 March 2006, however the detector has been restored to nominal operations in about half the time as in 2005 by applying an accelerated version of the high potting procedure using specially-designed cycling macros uploaded to the spacecraft. Further significant improvements in recovery speed can be made if the slow current anomaly reappears, and hopefully it will continue to be an efficiency rather than performance challenge for operations. Since the detector operated completely nominally for over 6 months without any issue (or degradation) after the 2005 recovery (and for almost 2 years between the June 2003 and March 2005 events), we are optimistic for a similar or longer period of FUV observations. NUV continues to observe normally.

5.2. Lessons Learned

GALEX has been a challenge for a small team to operate, yet it continues to be a uniquely capable and successful mission. There are many lessons to be learned from the issues described in this paper, perhaps the most important being that a flexible instrument design and resourceful team have been key requirements. There are a number of specific lessons we can glean from our experience, among them:

- One must be cautious about the possibility of charging effects in space and test for them. While this is generally well known, in the case of the GALEX FUV detector it was not clear that charging the window should cause a problem; we would recommend testing for such a scenario, perhaps with a unit such as we used to charge the windows of spare detectors in the lab. The most likely result of such testing for GALEX would have been to place the FUV grid in the space between the window and front MCP, or to otherwise fix the charge state of the window.
- Programs should have sufficient funding to provide critical spare components for stress testing. This is another well-known "lesson," nonetheless a spare detector available for stress testing with both voltage and high count rates would have been very helpful considering the level of technology development that went into the large format tubes flown on GALEX.
- Along the same lines as having engineering grade equipment for stress testing would be the recommendation to have a reasonably long mission simulation ($\sim 4-6$ weeks) to help detect subtle problems such as the DPU command corruption issue. In the case of GALEX very long tests were prohibitively expensive because they would have required use of the flight instrument and a round-the-clock team to orchestrate.
- No matter how much a team plans, the unexpected is bound to arise; prepare for it by building a flexible instrument with lots of knobs. While this is mainly the case with the GALEX design, several issues have arisen that have required software patches to address. For example the detector command counter fault detection of the DPU flight software required a patch when the shutdown-causing telemetry glitches were identified. Similarly, in the ACS fault detection software, the CSP/safe-mode response to tracker noise is too conservative, but because the same response is used for numerous faults it is difficult to modify without a large effort. As a last example, the GALEX HVPS design has a minimum programmable 2500 V level (other than HV off), which has had a ripple-through effect on the DPU flight software in trying to solve the window charging problem, which requires the FUV HV to be at 0 V on the day side of each orbit.

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