Operations with the FUSE Observatory

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ABSTRACT

The *Far Ultraviolet Spectroscopic Explorer* satellite (FUSE) is a NASA *Origins* mission launched on 1999 June 24 and operated from the Johns Hopkins University Homewood campus in Baltimore, MD. FUSE consists of four aligned telescopes feeding twin far-ultraviolet spectrographs that achieve a spectral resolution of R=20,000 over the 905-1187 Å spectral region. This makes FUSE complementary to the *Hubble Space Telescope* and of broad general interest to the astronomical community. FUSE is operated as a general-purpose observatory with proposals evaluated and selected by NASA.

The FUSE mission concept evolved dramatically over time. The version of FUSE that was built and flown was born out of the "faster, better, cheaper" era, which drove not only the mission development but also plans for operations. Fixed price contracts, a commercial spacecraft, and operations in the University environment were all parts of the low cost strategy. The satellite performs most functions autonomously, with ground contacts limited typically to seven 12-minute contacts per day through a dedicated ground station. All support functions are managed by a staff of 40 scientists and engineers located at Johns Hopkins. In this configuration, we have been able to achieve close to 30% average on-target science efficiency. In short, FUSE is a successful example of the "faster, better, cheaper" philosophy.

Keywords: Ultraviolet Astronomy, Satellite Operations

1. INTRODUCTION

The *Far Ultraviolet Spectroscopic Explorer* satellite (FUSE)[1] is a NASA *Origins* mission designed to perform high resolution (R = 20,000) far ultraviolet (905 – 1187 Å) spectroscopy of a wide range of astronomical sources. The Canadian Space Agency (CSA) and French Centre National d'Etudes Spatiales (CNES) are partners with NASA in the development and operation of the mission. A graphic of FUSE on orbit is shown in Figure 1, and a photo of the satellite in a clean room at Kennedy Space Center prior to launch is shown in Figure 2.

FUSE is the long-awaited follow-on to the successful *Copernicus* mission of the mid-1970's.[2] However, where *Copernicus* could observe stars roughly in the kiloparsec region around the sun, FUSE has sufficient sensitivity to observe stars throughout our Milky Way galaxy and in the neighboring Magellanic Clouds, as well as accessing the brightest quasars and active galaxy nuclei at much greater distances. The wavelength range covered by FUSE is complementary to that of the *Hubble Space Telescope* (HST), extending spectrocopic coverage to the Lyman limit at 912 Å. The small wavelength band below 1200 Å is particularly rich in astrophysical diagnostic transitions, from the Lyman and Werner bands of molecular hydrogen to the Lyman series of H I and D I to a broad range of absorption lines arising in hot, warm, and cold components of the interstellar medium (ISM). The great versatility of FUSE has been demonstrated by observations of objects within our own solar system[3] to observations of a distant quasar, the spectrum of which was used to probe the normally invisible reaches of the intergalactic medium.[4] A full listing of FUSE scientific publications is maintained at the FUSE web site, `http://fuse.pha.jhu.edu`.

FUSE was launched by a Delta 2 rocket from Cape Canaveral Air Force Station on 1999 June 24, and is now in it's third year of science operations. The satellite is in a 765 km circular orbit inclined at 25° to the equator. Communications with the satellite are accomplished through a dedicated ground station at the University of Puerto Rico Mayaguez. A variety of operational and observational constraints limit on-target viewing times to ∼30%. Approximately 9 million seconds of observing time is scheduled per year by the operations team located

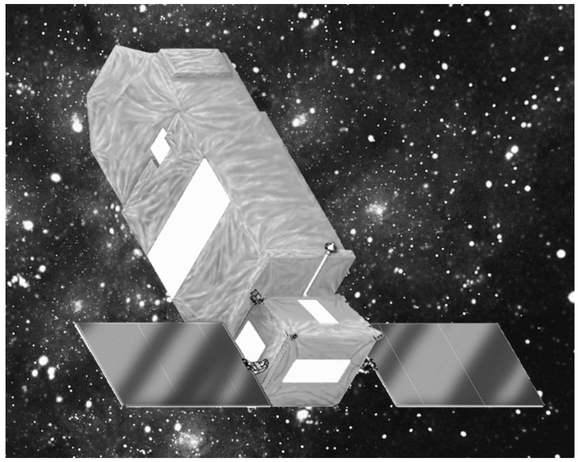

Figure 1. A graphic representation of the FUSE satellite in its orbital configuration. The small box from which the solar panels protrude is the spacecraft, while the larger structure above is the telecope assemblies and spectrograph. (Graphic courtesy of Orbital Sciences Corp.)

Figure 2. The FUSE satellite being prepared for launch in a clean room at Cape Canveral Air Force Station. FUSE is 18 feet long and weighs 3000 pounds, and was launched on a Delta 2 with three strap-on solid boosters. (Photo from June 1999 provided by NASA.)

at Johns Hopkins University in Baltimore. This team has had to adjust to a number of situations discovered during the checkout and operational phases, some of which are described below. The flexibility provided by operations within an academic setting, with scientists and engineers working closely together, has been a major reason for the success of the mission to date. In this paper, we briefly describe the history of the project, the operational environment we have adopted, and adjustments that have been made in response to on-orbit conditions. We also discuss the future of the project. Details of on-orbit operations have been provided by Sahnow et al. (2000)[5] and background and technical information is also available at the FUSE web site given above. The FUSE detector performance on-orbit is being presented at this conference.[6]

2. PROJECT HISTORY

The success of the *Copernicus* mission clearly dictated the need for a more capable follow-on mission. This was first recognized in the National Academy of Sciences Astronomy Survey Committee's decadal report in 1982 (the "Field report"), and then in April 1983 with the release of a detailed white paper by a FUSE Science Working Group convened by NASA to study the requirements of such a mission. A version of FUSE including expanded wavelength coverage to shorter and longer wavelengths was proposed to NASA in 1988 as an Explorer-class mission, and was selected for both Phase A and Phase B studies in the late 1980's and early 1990's. A FUSE-like mission also came through the next decadal review as a high priority. In mid-1994, a $256M FUSE satellite concept was under study, with the science instrument mounted on a NASA-provided Multi-Mission Modular Spacecraft. Launch was estimated for 2001. However, this was also a time of shrinking budgets for NASA, and in September 1994 it was decided that the Explorer budget could not accommodate a FUSE mission that was this expensive. FUSE as it was then conceived was cancelled.

Because FUSE had fared so strongly in the decadal reviews and had strong community support, the FUSE science team was given the opportunity to repropose a "faster, better, cheaper" mission concept. A restructured FUSE satellite maintaining the core scientific capabilities but with a final cost of $120M was submitted to NASA in January 1995 and after review was accepted for development. The dramatic cost reduction of the restructured FUSE mission arose from a number of areas: a) an aggressive, accelerated development schedule; b) fixed price contracting; c) use of commercial off-the-shelf (COTS) materials whenever possible; d) the purchase of a commercial spacecraft; e) satellite operations to be performed with a bare-bones staff within a university setting; and f) operations with a dedicated ground station. In addition, a compact redesign for the optical system, with elimination of extended wavelength coverage beyond the core spectral region (900 – 1200 Å), had been undertaken just prior to the restructuring. A schematic of the light path through the instrument is shown in Figure 3. Also, while various orbits were under consideration prior to restructuring, contained costs predicated a low-earth orbit and a commercial launch vehicle. A three-year primary period of operations was baselined, with roughly half of the available observing time belonging to the Principal Investigator (PI) science team to perform large scientific programs that had led to the selection of the FUSE mission, and half provided to the community through a NASA-run Guest Investigator (GI) program.

3. FUSE OPERATIONS

FUSE is not a large project in comparison with NASA's "Great Observatories" such as HST and the *Chandra X-ray Observatory*. Nonetheless, the FUSE project operates as a general use observatory, complete with a GI program, science timeline planning and execution, data processing, and archiving functions. The operations team is a mixture of about 40 JHU staff personnel and contractors, scientists and engineers, working closely in an academic environment. These people bring a wealth of experience from previous missions that has been a tremendous benefit to FUSE operations.

A secure Satellite Control Center (SCC), located in the Bloomberg Center for Physics and Astronomy on the Johns Hopkins University's Homewood campus in Baltimore, is at the heart of mission operations. A photo is shown in Figure 4. SCC activities are managed by a contracted Mission Operations Team (MOT) from Honeywell Technical Services Incorporated. The MOT is responsible for planning and executing all communications with the satellite, decommutating telemetry, archiving all engineering data, and Level Zero Processing of the science data stream. Communications with the satellite take place primarily through a dedicated 5 meter

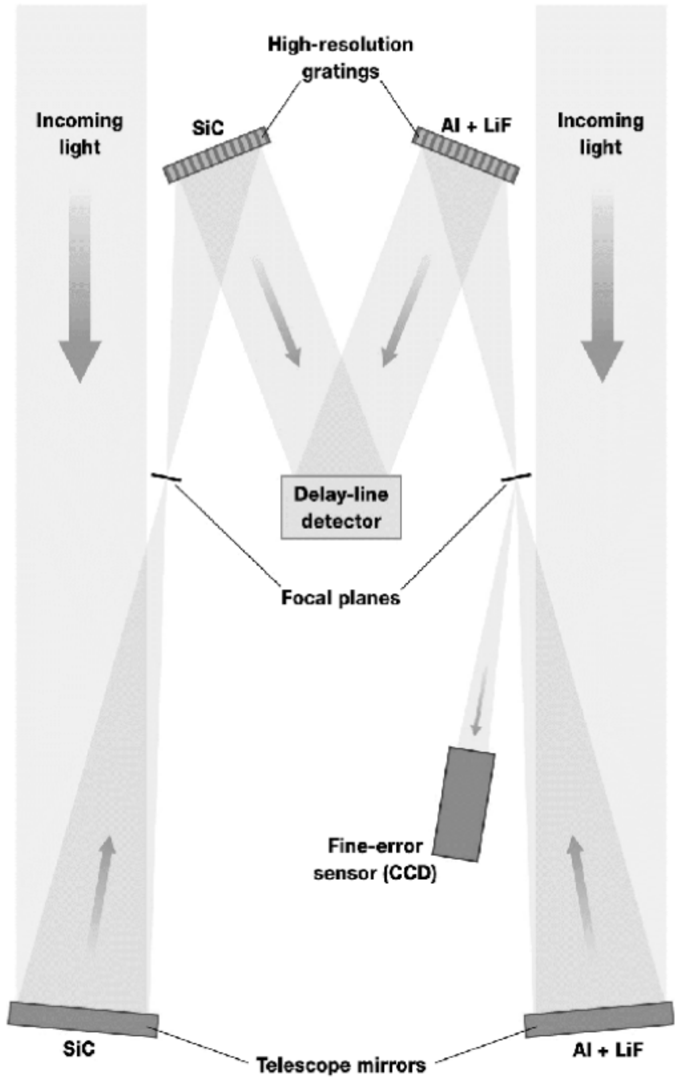

Figure 3. A schematic of the FUSE optical system showing one half of the science instrument. The telescope mirrors are coated with various materials optimized to different parts of the wavelength range covered. The mirrors focus light from a distant object through apertures at the focal plane and onto high resolution holographically ruled diffraction gratings. The dispersed FUV spectra from both channels are directed to a single detector but are offset perpendicular to the dispersion to avoid overlap. A mirrored surface at the focal plane of one mirror reflects optical light to a CCD camera utilized for field identification and guiding. A second side of the instrument duplicates what is shown here, providing redundancy and increasing the total effective area of the instrument. The multiple element optical system added complexity but greatly reduced the size and cost of the instrument for a given effective area.

Figure 4. The Satellite Control Center for FUSE is located in the Bloomberg Center for Physics and Astronomy on the Homewood campus of the Johns Hopkins University in Baltimore.

Low Earth Orbit Terminal (LEO-T) ground station antenna in Mayaguez, Puerto Rico, maintained with our partners at the University of Puerto Rico. The antenna is enclosed in a radome, as shown in Figure 5, to protect it from weather and to increase electronic element lifetimes. A control room for the LEO-T is located in the building directly below the antenna. Communications with the ground station occur via ISDN lines or over secure internet connections. Since a 1 Mb per second S-band link is used between the ground station and satellite but the ISDN line only supports a 128 Kb per second link, only selected health and safety telemetry is viewed in real time. Most data are stored at the ground station and transferred back to the SCC after a given pass is complete. With typically seven passes per day and an average of 12 minutes per pass, the satellite operates autonomously most of the time.

The flow of FUSE observatory operations is shown schematically in Figure 6. FUSE science observations begin in the form of proposals to NASA that are reviewed in a yearly peer review process. Successful proposers submit detailed target and observation planning information to JHU, where it is checked for accuracy and ingested into a master database. This information is further processed into input files used by mission planning software to schedule the desired observations.

Observations are scheduled in a two step process. A Long Range Planning (LRP) step looks at the target information and the gross visibility characteristics and lays out potential observations in weekly bins where observability is optimized based on a range of selectable parameters. A FUSE-specific version of the SPIKE software used at the Space Telescope Science Institute is used in this step. A separate program then takes these pools of potential observations and uses accurate orbital ephemeris information to create detailed orbital activity timelines called Mission Planning Schedules (MPSs). To support autonomous operations by the satellite, a table of appropriate stars surrounding each target position is generated as part of this process and delivered with a final MPS. These stars are used ultimately by the Instrument Data System computer on board for target acquisition and guiding during the observation. Any pool observations not actually scheduled in a given MPS are returned to the LRP stage for inclusion in a new LRP bin downstream. Targets with reduced scheduling opportunities are given priority in future short term scheduling activities.

Figure 5. The primary FUSE ground station is located atop a building at the University of Puerto Rico, Mayaguez (UPRM). A new antenna and protective radome, shown here in March 1999, were installed after hurricane Georges (September 1998) damaged the original antenna. (Photo: T. Ajluni, Swales Aerospace.)

MPSs are delivered through a security firewall to the MOT, where the information is processed into command loads and tables that can be utilized by the spacecraft to perform the desired activities. The flight software uses Spacecraft Command Language (SCL), a commercial product from Interface and Control Systems, Inc. SCL provides flexibility through a system of scripts and rules to not only operate the science instrument under nominal conditions but to adjust the system to handle new conditions or constraints when needed. After detailed checking of the command loads, a pass plan in generated, producing uplinkable sections that are consistent with the planned ground station passes. The relevant files for each uplink are then staged to the ground station computer for uplink at the proper time.

For a program with the complexity and budget of FUSE, it has been impossible to completely automate the above processes. Instead we have chosen to make the system work in a nearly automated fashion for "plain vanilla" operations and handle non-standard activities with a combination of automation and manual interaction. Knowledgeable humans in the loop have provided tremendous flexibility in the ground system when needed to adapt to problems on orbit, even keeping things running at times while new software was developed and tested to handle a change in a more automated fashion. Very close coordination between mission planners and the MOT has been a hallmark of the FUSE paradigm.

Data downlinked from the satellite are transferred back to the SCC after each ground station pass, where the engineering and science data are handled separately. Engineering data are decommutated and archived within the SCC computer system. Science data go through a Level Zero Process (LZP) where they are placed in a format needed for downstream processing. The LZPed data are pushed through a firewall to a dedicated cluster of computers that process and calibrate the data. Because of various complexities in the FUSE data that can compromise results, it was decided early on to add a data assessment step prior to archiving. This process has evolved from being manual to being nearly automated, with only a small number of data sets requiring human assessment. The standardized, pipeline-processed science data are delivered to the Multi-Mission Archive at Space Telescope (MAST) where they are ingested and archived. Users are sent a message electronically when

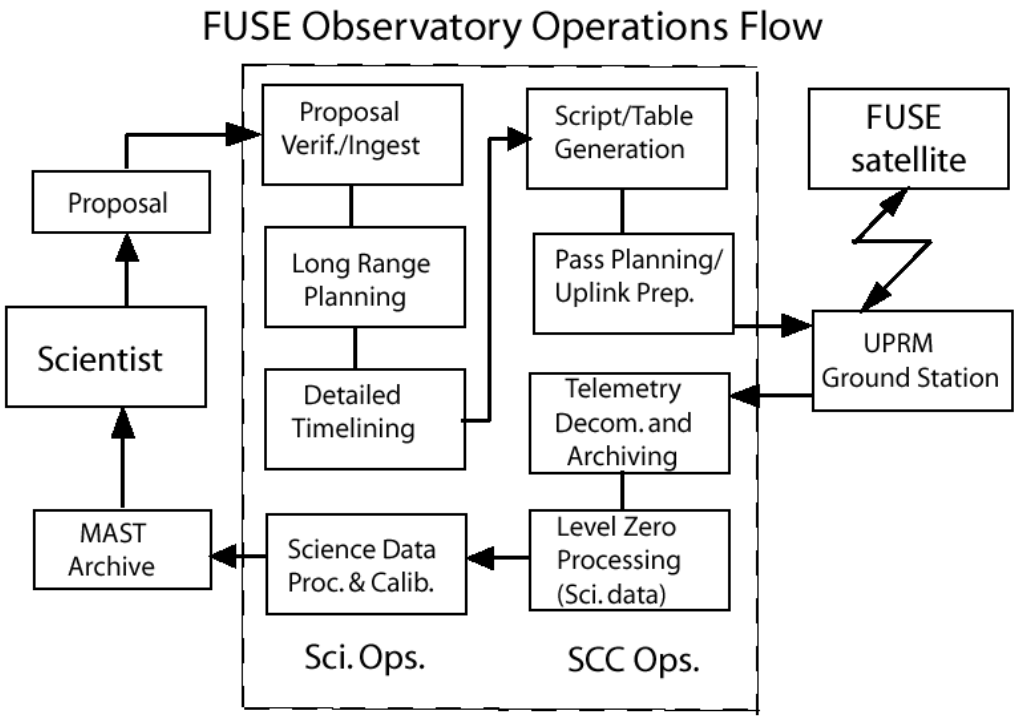

Figure 6. The flow of information from a scientific investigator (left) to the FUSE satellite (upper right) and back again is shown schematically. Operations at JHU are shown in the large box, and are roughly divided into "science operations" (left column) and "control center (SCC) operations" (right column).

data for their programs are archived, and they are expected to download the data themselves. FUSE data are proprietary to the proposer for six months after archiving, at which point the data become public domain and are accessible by others.

4. OPERATIONAL REALITIES

The FUSE operations team has had to adjust to a number of conditions on orbit that were not anticipated pre-mission. During the check-out phase, for instance, it was realized that the four separate optical channels of the science instrument were experiencing thermally-induced misalignments. On orbital timescales, misalignments were of order 5–8 arcsec and roughly repeatable with orbital phase, which could be handled in most cases by observing stellar sources in the 30 arcsec square spectrograph apertures. However, larger thermal affects were seen as a combined function of orbit pole angle, antisun angle, and hemisphere (north or south). These effects were characterized and shown to be repeatable (to first order), permitting predictive motions to be used to maintain approximate channel alignment. Subsequently, mission planners incorporated north-south hemisphere campaigns, regularized channel alignment procedures, and cluster scheduling of targets in various antisun and pole angle ranges into long range planning. This has worked well, but enforces obvious complications for targets with time constraints arising from other causes (*e.g.* phased observations of time variable sources, coordinated observations with other telescopes, etc.).

Another adjustment had to be made to account for the performance characteristics of the telescope baffles. Scattered visible light during orbital day and near the earth limb was worse than expected. Once again, the necessary changes were handled within mission planning, placing additional constraints on the timing and placement of acquisition activities, allowable magnitude ranges for usable guide stars, and when and where useful scientific data could be obtained.

By far the most dramatic problem experienced on orbit has been the loss of two out of four reaction wheels in November-December 2001. FUSE is a three-axis stabilized satellite requiring of order 1 arcsec pointing stability. Reaction wheels are used to control both major slew motions between targets and fine pointing control during observations. Four wheels (three on the main body axes plus one skew wheel) provide some redundancy, but a minimum of three wheels were required by the flight attitude control software to operate. Reaction wheels are typically very reliable. While the two wheels that failed had each shown some anomalous behavior earlier in the mission, they had both been recovered and had been operating nominally for months prior to the failures. The loss of two wheels within a span of two weeks was unexpected and left the satellite without three-axis stability and thus unable to perform pointed science observations.

The fix for this potentially mission-ending anomaly lay in another component of the attitude control system, the magnetic torquer bars (MTBs). In the nominal FUSE control system, MTBs were present only to manage satellite momentum by dumping unwanted momentum to the earth's magnetic field, allowing the reaction wheel speeds to remain in normal operating range. The new system, devised over a seven week period, placed the MTBs into the active control loop, providing a third axis of stability.[7] Again, close coordination between engineers and scientists at Orbital Sciences Corporation, Honeywell, andJohns Hopkins was crucial in effecting a quick recovery of operations. The MTBs only provide about 1/10 the impulse of a reaction wheel, however, which is not always strong enough to maintain arcsecond stability against gravity-gradient disturbances on the satellite. Initial predictions and simulations in late January 2002 indicated stable regions around each of the orbit poles (north and south) which, with orbital precession included, would allow access to about 45% of the sky for science observations.

In the ensuing months, great strides have been made in testing, understanding, and modeling this complex situation. For FUSE's 765 km circular orbit inclined 25° to the equator, the direction of the earth's magnetic field can change by up to 90° and it's magnitude can vary by a factor of two. Also, diurnal variations occur as the orientation of the orbit changes with respect to orbital effects such as the South Atlantic Anomaly. Since the magnetic field provides the muscle against which the MTBs push to provide stability, this time variability causes a significant complication to mission operations. Empirical testing and modeling have opened up effective sky coverage to greater than 75% at this writing (late-July 2002). Figure 7 shows a graphic representation of current FUSE sky coverage capabilities integrated over a one year period for the constraints as they are currently known. Future improvements are expected to get back to nearly 100% sky coverage again by mid-2003. A predictive tool is now incorporated into mission planning to schedule targets at times when stability can be maximized.

A final hurdle toward longer term mission lifetimes involves the laser-ring gyroscopes used by the attitude control system to provide drift rate information. FUSE contains six gyros, with two on each body axis. One gyro has failed (late-May 2001) and five out of the six gyros have tripped indicators that their laser intensity has dropped by a factor of two. The current flight software requires three axis gyro information for accurate slews between targets and for stable pointing.

To mitigate this potential problem, new flight software and other system parameters are being modified to permit FUSE operations with any number of gyros, including zero, in the control loop. The new software will use magnetometer data and a non-linear dynamical model of the satellite to provide rate information during slews between targets. The Fine Error Sensor (FES) CCD guide camera software and Instrument Data System software are also being revised to permit new target acquisition modes, with rate information for fine pointing being provided by the FES to the attitude control system. This system is in an advanced state of development and testing, and uplink to the satellite is expected in the October-November 2002 timeframe. A more detailed discussion of these issues is provided by Kruk et al. (this conference).[7]

5. THE FUTURE OF FUSE

The FUSE project was initially approved for a three-year primary science mission split between a Principal Investigator science team and guest observers selected by NASA. The third year of science operations, recently extended to account for the down time due to the reaction wheel problems discussed above, will be complete

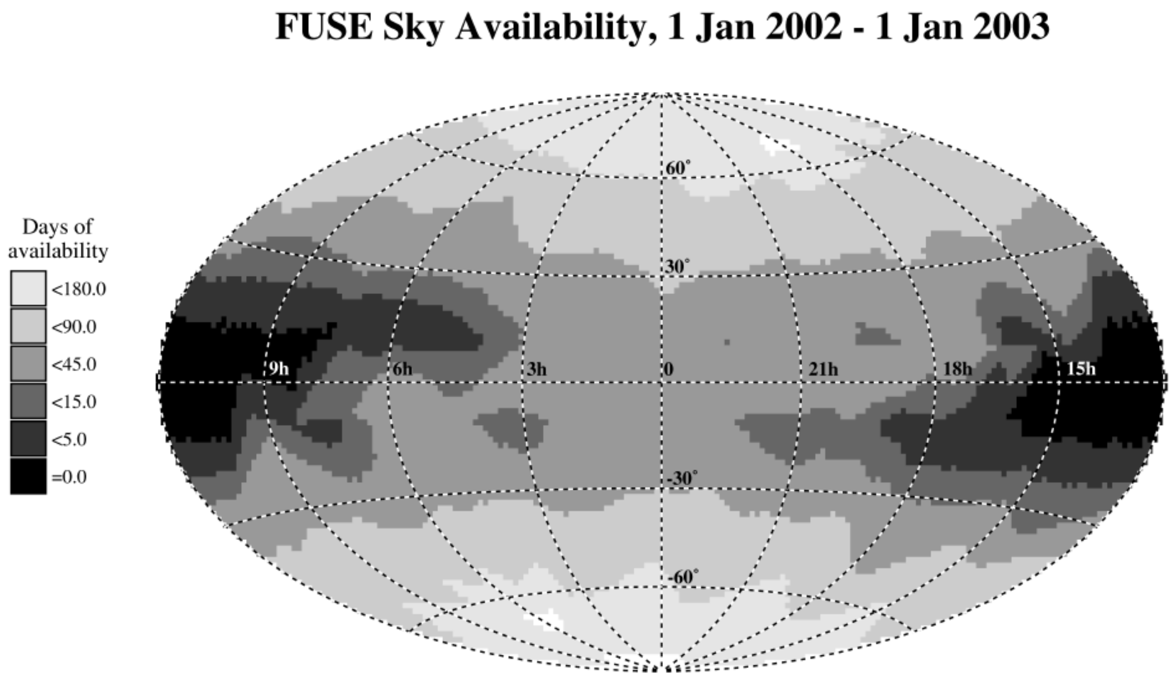

Figure 7. This all-sky map shows graphically the sky coverage available to FUSE as of late-July 2002 with the current system constraints. The scale at left shows integrated days of availability. Targets in light regions of the plot are nearly unconstrained in terms of observation scheduling, while targets in dark gray regions require careful scheduling at specific times when the MTBs can generate sufficient torque to maintain stable pointing. The black region near 12 hours Right Ascension and on the celestial equator has no times of positive torque authority and is currently unavailable for scheduling. By relaxing some scheduling constraints and investigating options such as use of partially stable orbits, we expect to regain access to the black regions by mid-2003. (Figure courtesy of Bryce Roberts, JHU.)

in March 2003. NASA recently informed the project that the 2002 NASA Senior Science Review recommended an extension of FUSE science operations through at least fiscal year 2006, and that NASA has accepted that recommendation. We take this as a strong endorsement of FUSE's scientific productivity and importance to the overall NASA mission, and look forward to at least several more years of productive science operations.

Operations in the extended FUSE mission will maintain all critical scientific capabilities of the satellite, but reduced funding levels will necessarily cause a scaling back of the expected data production rate. Staff will be scaled down as many procedures, such as ground station passes and control center operations, become automated to the extent possible. At this writing, a NASA Call for Proposals for Cycle 4 of FUSE operations is active, and we expect to support at least 7 million seconds of science data during our fourth year.

The FUSE project demonstrates that a mission born out of the "faster, better, cheaper" era can not only be successful, but can be extremely resilient and flexible in its operations. The proximity of scientists, engineers, and contractors working closely in an academic setting, along with the experienced and talented personnel involved, has been conducive to creative problem solving and quick response and implementation. It is a model that future missions should consider emulating as well.

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