FIREBALL : Detector, data acquisition and reduction

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ABSTRACT

The Faint Intergalactic Redshifted Emission Balloon (FIREBALL) had its first scientific flight in June 2009. The instrument combines microchannel plate detector technology with fiber-fed integral field spectroscopy on an unstable stratospheric balloon gondola platform. This unique combination poses a series of calibration and data reduction challenges that must be addressed and resolved to allow for accurate data analysis. We discuss our approach and some of the methods we are employing to accomplish this task.

Keywords: Cosmology, Integral Field Spectroscopy, FIREBALL, Data Reduction, Instrument Calibration

1. INTRODUCTION

The Faint Intergalactic Redshifted Emission Balloon (FIREBALL) successfully completed its first science observation in June, 2009. FIREBALL is a balloon borne experiment designed to observe Lyα emission from the intergalactic medium; an overview of the project can be found in Martin[1] in this volume. FIREBALL is a 1m class telescope equipped with a fiber fed UV integral field spectrograph. The integral field unit is built from 281 UV optimized fibers and covers a hexagonal field of view 2.3 arcmin across. It feeds into a R $\sim$ 5000 modified Offner design spectrograph. The details of the spectrograph design are discussed in Tuttle et al.[2] The FIREBALL detector is a legacy GALEX NUV microchannel plate (MCP) device.[3,4] The instrument exploits a narrow stratospheric balloon altitude observational window from 1950 to 2300 Å. The FIREBALL pointing system, which compensates for environmental perturbations during the flight achieved 7" RMS tracking. Mechanical and thermal instabilities have an effect on the structure and pointing of the telescope. Careful instrument calibration and significant post flight data reduction are necessary to extract the scientific signal form the collected data. This paper discusses the instrument calibration methods and how they fit into the FIREBALL data reduction pipeline.

2. DETECTOR HARDWARE AND DATA FORMATTING

2.1 Detector

The FIREBALL detector subsystem consists of a vacuum sealed, microchannel plate intensified, cross delay line readout detector head (figure 1), associated power and readout electronics (figure 2) that were designed for the GALEX satellite[5] and an interface computer that is responsible for data storage and communication with the ground and other hardware on-board the gondola. The microchannel plates multiply each photoelectron (yield of 1) by a factor of approximately 10^6. A dual-output high voltage power supply (HVPS) with one programmable ($\sim 5200V$) and one fixed ($-900V$) output powers the detector head. The resultant charge cloud lands on a delay line anode inside the tube head, where it is split and directed to four detector outputs. Measuring the timing

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Figure 1. FIREBALL NUV Detector: Legacy GALEX NUV microchannel plate detector used by the FIREBALL spectrograph.

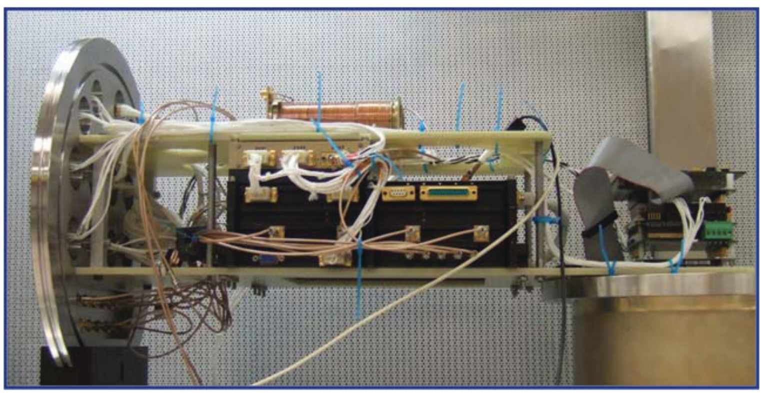

Figure 2. FIREBALL FEE and Detector PC: Left side of the image shows the FEE which does time-to-digital conversion and generates 40 bit photon data stream captured by the PC104 stack Detector PC, which is shown on the on the right. The top card in the computer stack is see the EDT data acquisition board which captures the stream from the FEE and generates a 1 Mbit/s science data stream incorporating photon, housekeeping, and pointing data.

difference at the ends of each axis determines the position of the cloud on the detector. A design resolution requirement of $\sim 50\ \mu$m coupled with 65 mm detector head results in an unique design combining a traditional current source-capacitor timing measurement (time-to-amplitude converter, or TAC) with a running coarse clock so that the TAC scale is effectively applied to a relatively small fraction of the anode for each measurement. Information for each photon incident on the detector is stored as a 64 data structure. 40 bits contain location and quality information for the collected signal, the remaining 24 bits carry timing data. Table 1 breaks down the information format. Arcing is a concern for MCP detectors and their HVPS at the typical few mbar pressures at balloon altitudes. To ameliorate this concern the FIREBALL detector is housed in the spectrograph enclosure which is kept pressurized at 0.5 atm during the flight. The interface computer and detector front end electronics (FEE) were in a separate pressurized enclosure to protect the hard disk used for data storage.

2.2 Science Telemetry

FIREBALL has three telemetry channels as shown in figure 3. These are: a 1200 baud general command uplink, a 38400 baud downlink shared by four onboard instruments, including the detector subsystem, a video downlink used by the guidance system, and a 1 Mbit/s bi-phased downlink used by the detector for science and housekeeping data. . Central to the science telemetry system is the Detector PC, which is a PC 104 stack

ID	Bits	Description
X_{AmC}	12	X-axis fine position
Y_{AmC}	12	Y-axis fine position
X_B	3	Y-axis coarse position
Y_B	3	Y-axis coarse position
X_A	5	Wiggle
Q	5	Pulse height
T	24	Time stamp

Table 1. Photon data formatting: Due to the legacy design from GALEX, FEE position data is measured by two clocks (fine and coarse) for each axis. The coarse clock is free running and the photon positions are measured asynchronously as they interact with the detector. The fine position data represents the fraction of coarse clock required to complete the timing. "Wiggle" is the actual position on each time-to-amplitude converter (TAC). Because there is non-linearity with respect to fine position measurement the Wiggle knowledge is necessary for further correction. In addition to the wiggle the pulse height (Q) of each photon is also used for correction. This is because the michrochannel plates are large and the gain varies significantly ($\sim 40\%$) over the detector head. This is due to chemical impurity over the michrochannel plates and variation in gap between the plates. Therefore, non-linear fine position correction is done by use of pulse height distribution

(ADL855PC-370C) with a data acquisition board (EDT PCI-CDa) equipped with custom bitfile loaded on one of the Xilinx FPGA, and an I/O board (ADL 104-AIO12-8). This computer ingests two input streams from the FEE, one contains 40 bit science data words, the other 32 bit housekeeping data. FIREBALL is an unstable gondola platform, pointing stabilization and accurate pointing reconstruction are crucial.[6] The FIREBALL multi-layered tracking system achieves target tracking to better than 7" (rms), furthermore, post-flight guider camera image processing recovers pointing information to better than 3" for the flight. The guider control computer notifies the detector PC when each guidance image is taken (every 33 ms) . This data is incorporated into the housekeeping stream which uses the same timing as the photon data. This way the astrometric solution is known for every photon that is observed by the detector and celestial coordinates (RA, Dec) can be assigned to it. Every count that is registered by the MCP generates a data stream from FEE that is captured by the data acquisition board. Once the data acquisition board buffer is full, an interrupt is triggered and the buffer is transferred to the relevant processes running on the Detector PC. In order to reduce the number of interrupts at Detector PC and to prevent data loss a set of 10 photons are read out at a time with 10 millisec accuracy. Each data stream are saved in separate data files on board on the hard disc.

Science telemetry consists of 256 word frame with 32 bit words. Each frame consists of 1 word start pattern, 1 word frame number, 6 word housekeeping data, 5 word guider data and rest are photon data. Guider data includes time stamp of the frame, frame number, elevation and cross-elevation value, and exposure time. The 1 Mbit/s bi-phased science telemetry goes through Greco Decom provided by Columbia Scientific Balloon Facility (CSBF) on ground. The decom generates 16 bit parallel data stream that is read into a standard desktop PC using a data acquisition board (EDT PCI 16D). The science telemetry data is sorted in software and saved on ground in separate files for each data stream. Also house keeping, photon data, and guider data are displayed in real time to monitor and validate data and operation as seen in figure 4.

3. INSTRUMENT CALIBRATION AND DATA REDUCTION

Before meaningful results can be extracted from the FIREBALL data, the location of photon events on the detector must be correlated with their location within the sky-wavelength data cube. This mapping changes during the course of the flight, predominantly from thermal effects on the instrument optics and electronics. We used a series of tools and methods to calibrate and characterize the instrument. These methods and their main goals are summarized in Table 2.

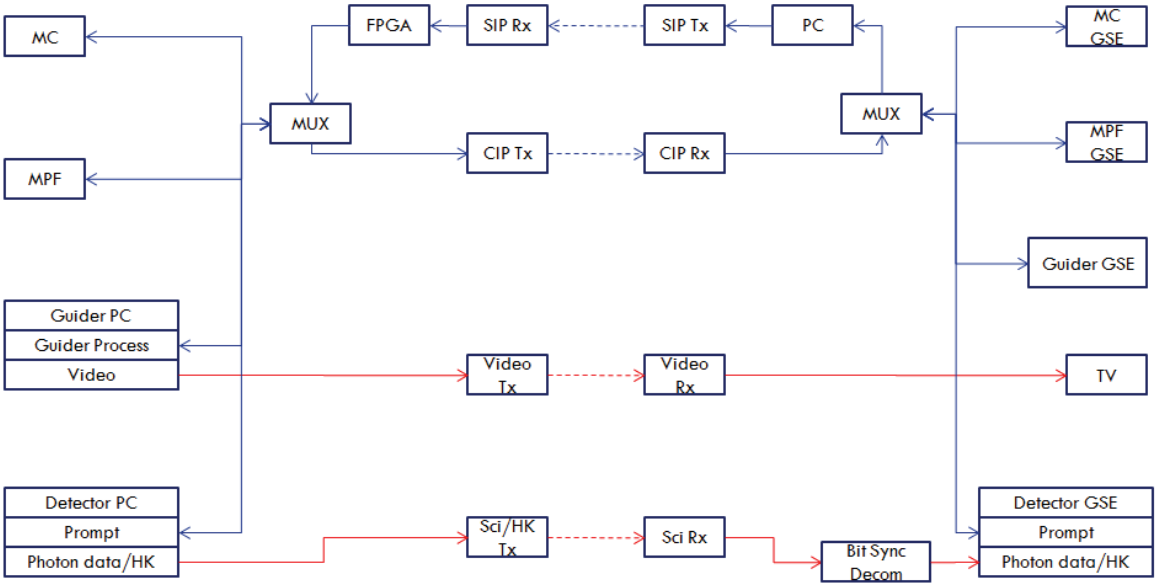

Figure 3. FIREBALL telemetry schematics: Blue is uplink/downlink shared by 4 instruments and red is video and 1 MB/s science downlink. Left half of the diagram are instruments on board on the FIREBALL gondola. Right hand side of the diagram are instruments on ground. While the dotted lines represents radio link. FIREBALL used two channels CIP[7] and SIP provided by CSBF/NASA for uplink and downlink. CSBF requires package formatting for the CIP (uplink) commands. This was done by a PC on ground and an FPGA board on the gondola.

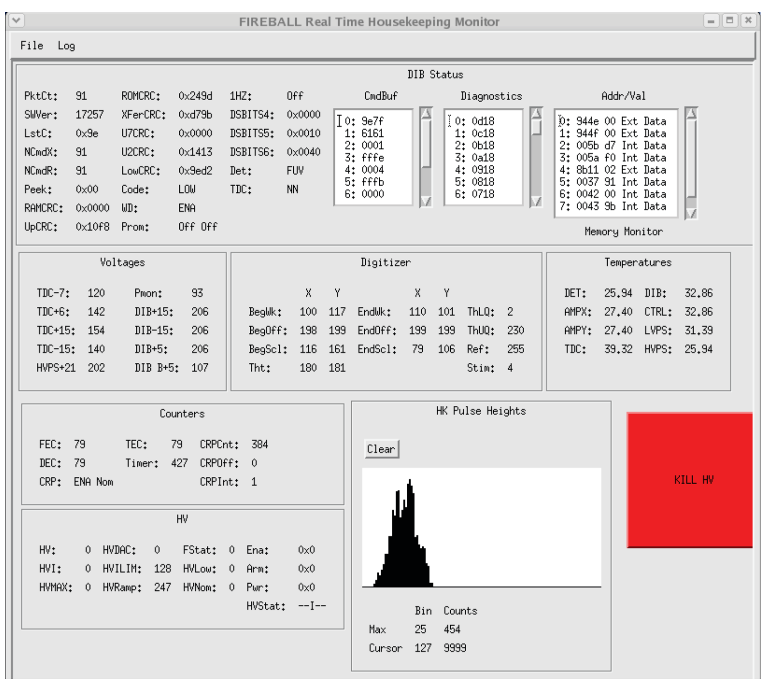

Figure 4. FIREBALL Real Time Housekeeping display is used to display count rate (left hand side 2nd from bottom box), voltages (lower left corner box), pulse height distribution (lower center box). etc. relevant to operating the detector.

Method	Purpose
Calibration bundle illuminated by PtNe arc-lamp	Mapping of the changes in wavelength and fiber location on the detector during the flight
Fiber IFU illuminated by the PtNe arc-lamp through a diffuser	Wavelength mapping for all science fibers
Fiber IFU illuminated by the deuterium lamp through a diffuser or off the inside of the gondola door	Spectral flat-fielding and locating the fiber images on the detector
Raster scan of a point source over the focal plane end of the fiber bundle	Mapping of the IFU fiber bundle in detector coordinates; locating individual fiber images on the detector
Movie of focal plane end of the IFU fiber bundle while illuminating the spectrograph slit end with a point source	Mapping of the fiber bundle slit end onto the focal plane end
Observation of calibration stars	Absolute throughput calibration
Detector dark	Subtraction of detector background from the science data
Twilight flats	Fiber flat-fielding

Table 2. A summary of the calibration data taken before and during flight. The application of this data is described in section 3

3.1 Initial Processing

Data reduction starts with converting the raw bit data generated by the detector electronics into a FITS table format that can be viewed using legacy GALEX data analysis software (DATOOL[8]) and easily be manipulated in IDL. As discussed in section 2.1, the position coordinates for individual detector events can be derived from the coarse clock and a fine clock values via the expressions:

$$\begin{aligned} X &= X_{AmC} + \alpha_x X_B \\ Y &= Y_{AmC} + \alpha_y Y_B \end{aligned} \qquad (1)$$

The two integer parameters $\alpha_{x,y}$ are in the neighborhood of 2000 and are found empirically by comparing sizes of focused spots on the detector as the values are changed. The best values found for the in-flight FIREBALL data are $\alpha_x = 2005$ and $\alpha_y = 1991$. The FIREBALL detector was mounted inside the spectrograph enclosure so as to align the detector Y axis with the dispersion direction of the spectrograph and the detector X axis parallel to the slit direction. An inspection of the data revealed a 1 degree clockwise rotation between the two sets of axes. The event coordinates were transformed to correct for this rotation. At this point four small defects on the detector that exhibit greatly increased count rates were flagged as “hot-spots” to allow for masking.

3.2 Detector Coordinate System

The FIREBALL spectrograph has 37 calibration fibers that run from the calibration light source to the spectrograph entrance slit bypassing the focal plane (see Tuttle[2]). These fibers were used periodically during and prior to the flight to illuminate the detector with a PtNe spectrum. The locations of fibers along the spatial direction of the detector and the locations of PtNe peaks along the spectral direction yield a coordinate grid. This coordinate grid is then found for all the calibration images taken. The first in-flight calibration image was chosen as the reference and all prior and subsequent spectra were transformed to match the fiber and peak locations. The coefficients of these transformations were then fitted with quadratic polynomials as a function of time and the resultant corrections were applied to the full data-set.

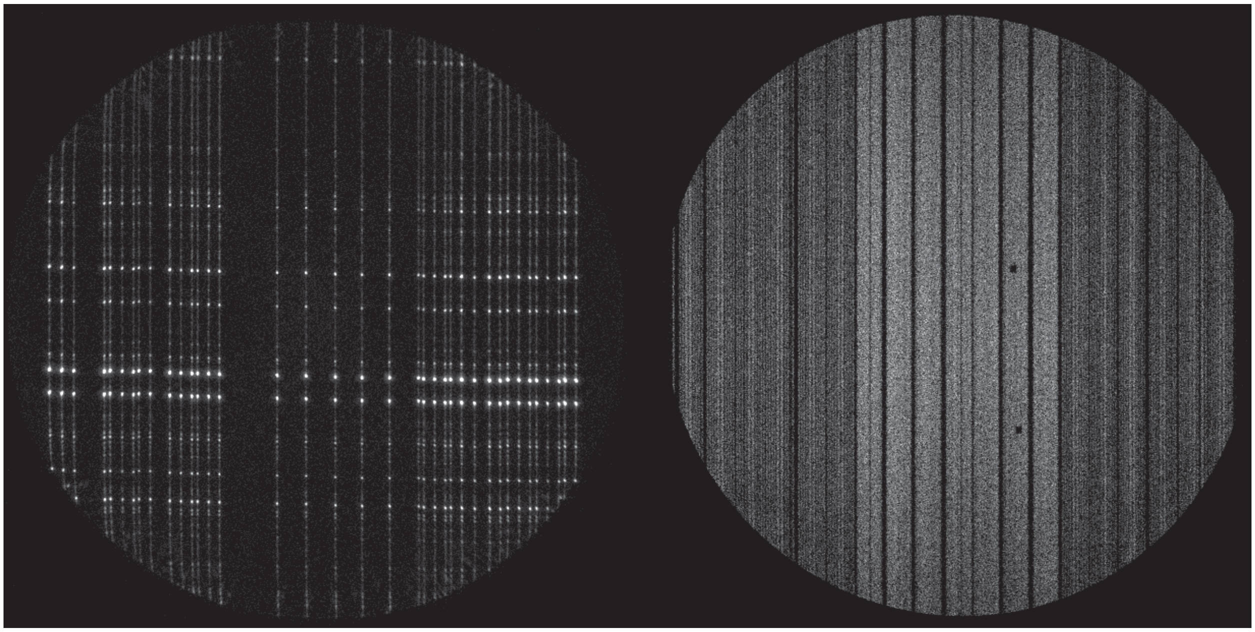

Figure 5. The left panel shows the FIREBALL detector illuminated by calibration fibers. The series of calibration images like the one pictured were used to correct for thermal changes in the electronics and the optics. The flat-field image in the right panel shows the nature of the fiber spacing within the bundle. The central regions of the spectrograph slit are more densely populated with fibers, making use of the greater wavelength coverage. The dark spots visible in the right panel are masked hot-spots.

3.3 IFU fiber locations on the detector

FIREBALL flew with 280 active science fibers. The fibers on the outer thirds of the spectrograph entrance slit were more sparsely spread than those in the center (right panel of Figure 5). Two different methods were used in establishing the location of the fiber images on the detector. The first method used full IFU fiber bundle illumination via a diffuser. The positions of the detector counts were collapsed along the wavelength direction and histogrammed. Gaussian profiles were fit to the resultant curves, deblending neighboring fibers when necessary. The second method relied on sequential illumination of fibers during a raster scan of the IFU bundle (detailed below). An inspection of the detector illumination during short time periods (1s) gave the location of each fiber on the detector. The two methods yielded results that differed by under two detector pixels in most cases (a fiber FWHM is $\sim$18 pix), notable exceptions occurring in parts of the detector where the fibers were very closely spaced.

3.4 Wavelength solution

Prior to flight the full IFU fiber bundle was illuminated with PtNe light through a diffuser. The spectrum for each of the 280 fibers was then extracted and compared with a resolution-degraded PtNe spectrum from NIST[9] from which all PtII lines were removed, as they did not appear in the spectrum of the FIREBALL lamp. Anywhere from 2 to 7 peaks were matched for the individual fiber spectra and linear, quadratic or cubic solutions were found, depending on the available number of matched peaks.

3.5 IFU – optical guider mapping

Reconstructing the on-sky positions of observed objects requires that we have a mapping between the FIREBALL guider[6] coordinates and the focal plane end of the fiber bundle. This mapping was obtained by making two measurements and combining their results. The first was a movie that was created by filming the focal plane end of the bundle while illuminating the slit end with a visible light pinhole source, picking out individual fibers. Processing the resulting image gave an accurate set of coordinates for the fibers and a sequential mapping

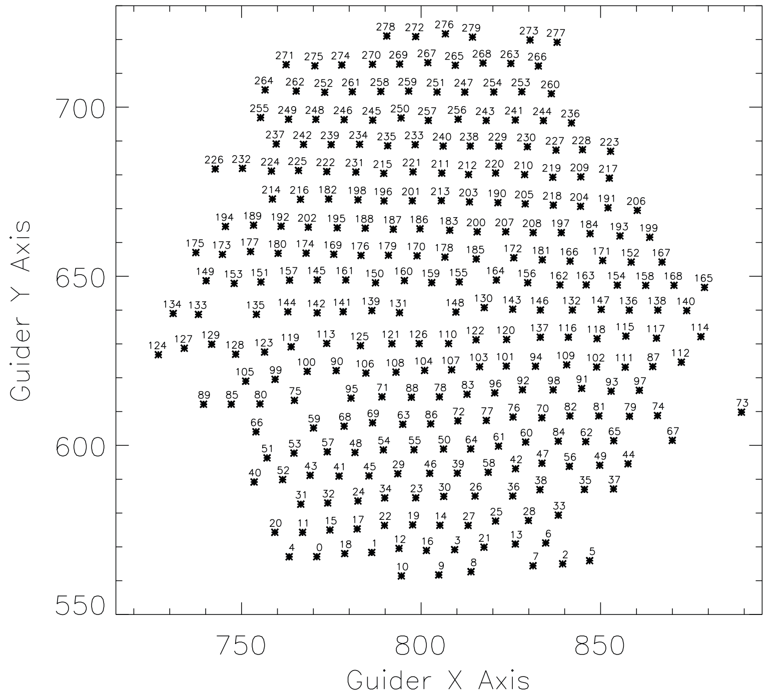

Figure 6. The layout of the FIREBALL IFU fiber bundle focal plane end. The symbols mark the fiber centers and the values above each fiber correspond to the sequential number of each fiber on the spectrograph slit end of the bundle. Some of the details of the bundle manufacture are given in Tuttle et al.[2] in these proceedings.

of these fibers from the hexagonal packing in the focal plane end to the linear array at the slit end. The second measurement was a raster scan of the bundle installed in the spectrograph. A star-simulator (an inverted telescope with a single fiber deuterium light source in its focal plane) output a collimated beam that was directed at the FIREBALL telescope. This light formed a focused spot at the FIREBALL focal plane which was moved in a snake-like raster pattern over the full fiber bundle by the FIREBALL guidance system. The recorded time-stamped spot locations on the guider CCD were correlated with the illuminated regions on the detector. This generated rough mapping of fiber locations in the guider coordinates. As the telescope and guider optics have very little field curvature, linear regression was used to convert the linear-scan coordinates to the guider frame. The resulting fiber bundle layout is shown in Figure 6.

3.6 Fiber assignment

Every detector count needs to be associated with one of the IFU fibers. The image of an individual fiber on the detector forms an ∼18 pixel FWHM gaussian when collapsed along the wavelength direction. As is visible in the right panel of Figure 5 the fibers on the sides of the spectrograph entrance slit are sparsely spaced, and so are their images on the detector (typically 30 pix apart). For photons that fall within this range fiber assignment is simple as their footprints do not overlap. The central parts of the slit, however, contain fibers whose wings on the detector do overlap (15 pix spacing). The algorithm used to mark which fiber a given detector count belongs to differs depending on the nature of the source being observed. For strong continuum sources, such as calibration stars, the observation is cut into short time slices (about 0.5 s). For each time sub-interval the coordinates of the photon count events along the slit direction of the detector are histogrammed. The histogram is fit with a linear combination of fiber gaussian profiles. This linear combination is used to generate a fiber probability distribution function (PDF) for every location along the slit. The fiber for each detector event is then randomly selected from this PDF. Faint sources do not accumulate enough counts on timescales comparable with a fiber

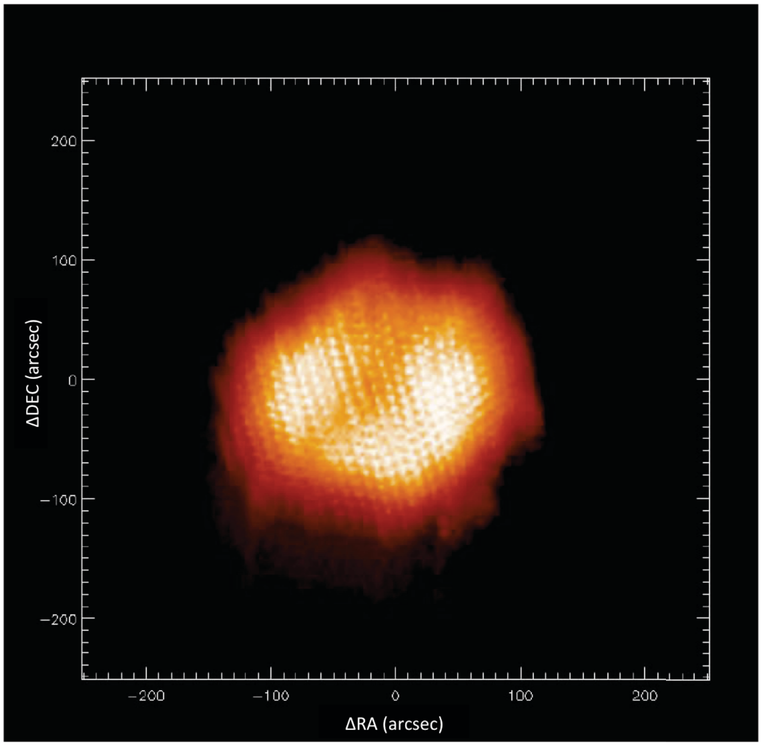

Figure 7. An exposure cube for one of the targets from the FIREBALL flight. The three-dimensional array was collapsed along the wavelength direction. The intensity in the plot is proportional to the exposure time FIREBALL spent on a particular pixel (brighter regions indicate a longer time). Histogram equalization was applied to bring out the features in the image.

crossing time during an on-sky dither. The fiber PDF is computed once, assuming all fibers contribute equally, and used for all counts during an observation.

3.7 J2000 coordinate assignment

Each detector count is associated with a frame number from the optical guider.[6] The procedures outlined above yield a fiber number and a wavelength for each count. As every fiber has been identified with a guider pixel coordinate, and an astrometric solution is known for each guider frame during an observation, J2000 coordinates can be assigned to each detector event. At the end of this step every count is tagged with an (RA, Dec, Wavelength) triplet.

3.8 Data Cube

Once the detector counts are associated with sky coordinates and wavelength a data cube (a three-dimensional histogram) is created for every observation target. The binsize used for FIREBALL is 3" $\times$ 3" $\times$ 0.25$\AA$. The intensities encoded in the data cube must be corrected for instrument response and for non-uniform coverage of the target region of the sky. The former is due to fiber-to-fiber throughput variations and different fiber wavelength ranges because of the circular detector shape. The latter is caused predominantly by the dithering that FIREBALL used to improve spatial sampling. A second three dimensional histrogram, an exposure cube, takes these into account. It is of the same size as the data cube and every voxel contains the product of the effective area and exposure time for the region of sky and wavelength range it represents. Figure 7 shows a one of the exposure cubes for the second FIREBALL flight.

4. CONCLUSION

The FIREBALL data from the first scientific flight has been reduced and data and exposure cubes have been generated. Analysis efforts are now under way to extract scientific results from the collected data.

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