# UVOT Bright Source Safing System

Barry Hancock [1], Hajime Kawakami [2]
[1] Mullard Space Science Laboratory University College London Holmbury St Mary Dorking Surrey UK RH5 6NT
[2] Currently at Meisei Electronics, Department of Space Instruments and Technologies Japan

## ABSTRACT

The Swift mission requires that the Swift UV optical telescope (UVOT) have the autonomous functionality to protect itself against the potentially damaging effects of observing bright sources. This capability had to be added to an existing heritage camera design, which was used for the Optical Monitor telescope (OM) on ESA's XMM-Newton spacecraft. The solution used a two part mechanism employing data from a catalogue of known bright sources, and a real-time system for monitoring the raw pixel data from the camera and automatically reducing the detector gain when a signal above a programmed threshold is seen. This discussion will describe the resulting Field Programmable Gate Array (FPGA) based implementation that sits alongside the heritage camera and processing electronics and can be programmed and monitored by the UVOT instrument controller.

## 1. INTRODUCTION

The UVOT is a UV optical telescope based on the design of the Optical Monitor (OM) flown on the European Space Agency X-ray Multi Mirror (XMM) - Newton Mission. The detectors used are microchannel plate (MCP) intensified charge coupled devices. These detectors are photon-counting devices capable of detecting single photons. The benefit of this sensitivity to very low-level light sources has the disadvantage that the detector may be damaged or degraded by prolonged exposure to bright sources.

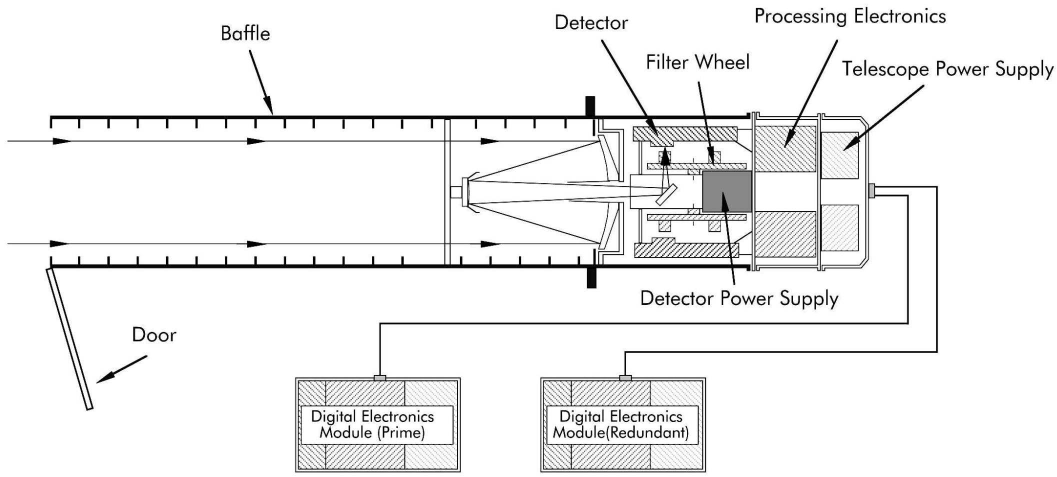


**Figure 1: UVOT instrument diagram**

The UVOT instrument architecture is fundamentally the same as that of OM, with many subsystems unchanged from the original design. The Digital Electronics Module (DEM) unit containing the Data Processing Unit (DPU) and the Instrument Control Unit (ICU) are new systems to Swift, however, although the ICU has some electronic and software heritage from the OM. The UVOT has two complete processing chains with electronic redundancy up to and including the beam steering mirror mechanism. Two filter wheels are included; one for each detector, and each includes 7 filters, 2 grisms and an image magnifier. The UVOT detectors operate in the wavelength range 170 to 600 nm. The photosensitive surface is an S20 photo-cathode at the front of the detector with an active area of $19mm^2$. The detector format is 256 x 256 pixels with each pixel approximately 9.6 $\mu m^2$.

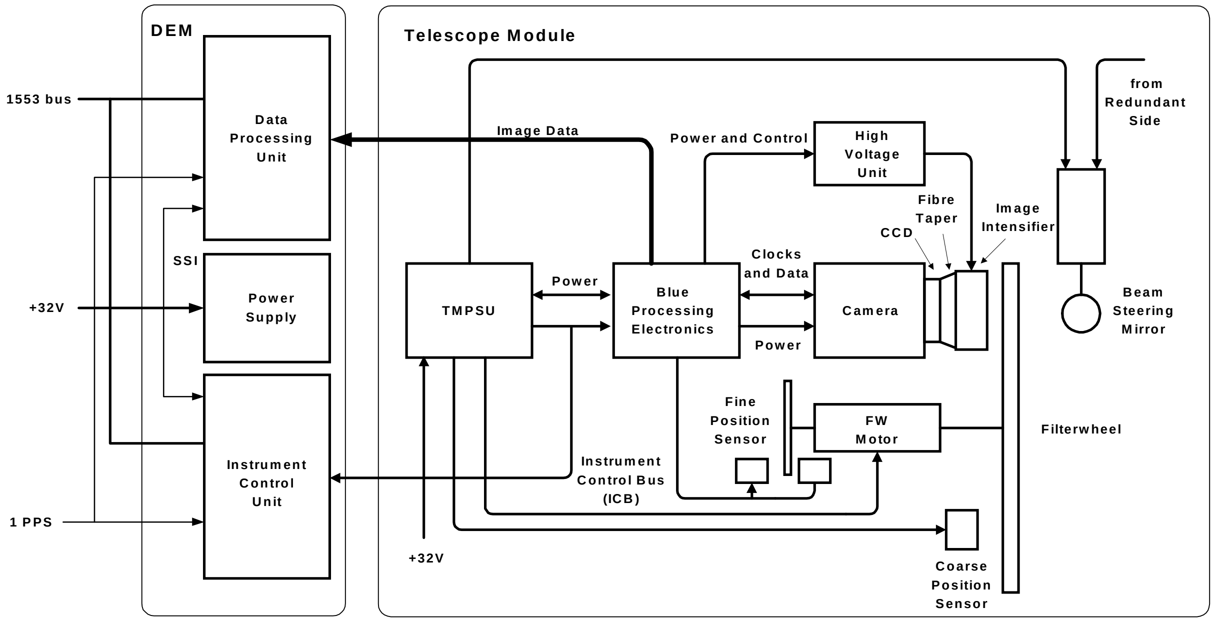


**Figure 2: UVOT electronic architecture**

The diagram in figure 2 shows the major subsystems of the UVOT Telescope module and the Digital Electronics Module. An image is projected onto the image intensifier of the channel selected by the beam steering mirror and a shower of photons is registered by the CCD. The frames are clocked into the processing electronics at high speed. Events are validated and centroided to increase position resolution. Event data are buffered and synchronously passed to the DPU for subsequent data processing and transmission to the ground. The ICU controls and monitors the instrument observations.

**Blue Processing Electronics (BPE) Functional Summary**

- CCD Readout: 10MHz pixel rate, 11ms frame rate
- Dark current subtraction using covered reference pixels
- Image centroiding: 256 x 256 up to 2048 x 2048 pixels
- Event validation table driven window control
- FIFO data buffer on Data Capture Interface to DPU
- Instrument Control Bus interface to ICU including: table load and dump utility, HV unit control, flood LED control, filter wheel position sensing and thermistor conditioning

A more detailed description of the function of the UVOT instrument may be found in reference 1.

## 1.1 THE UVOT REQUIREMENT FOR INSTRUMENT AUTONOMOUS SAFETY

The autonomous nature of the Swift mission and the sensitivity of the UVOT detector system, require that the UVOT instrument protect itself with little or no ground intervention. The UVOT must function by observing planned targets or automatically observing GRBs for periods of up to 72 hours without any ground interaction. It must also protect itself from a number of risks: bright stars, the Sun, Earth, Moon and other bright sources that may appear in the detector field of view.

If exposed to bright sources the UVOT detectors may be temporarily or permanently degraded. The main effects are:

- Fluorescence / phosphorescence: This is a temporal effect. If a 5.6mag A0 star illuminates the detector through the white filter for one minute, then its phosphorescence remains above detection limits (0.008 counts $s^{-1}$) for 16 hours. More information is given in reference 4.
- MCP gain loss and photocathode damage: This results in permanent performance degradation, due to a localized gain loss in the MCP and a loss in sensitivity of the S20 photocathode due to ion feedback from MCP pores.

In order to mitigate the risks identified above a number of potential solutions were identified:

- The spacecraft systems could provide some protection against certain risks; messages are sent to the UVOT about spacecraft position allowing the ICU to monitor pointing constraints. The spacecraft also manages instrument pointing constraints for the Earth, Sun, Moon and if necessary can power off the UVOT.
- On-board software in the ICU could also provide a safety monitoring function
- A hardware based system in the telescope module could be implemented to provide protection at the camera output level.

The spacecraft can offer some degree of protection by managing the UVOT's pointing constraints. The ICU can provide independent pointing constraint monitoring and offer extra protection against prolonged observation of star fields with known sources brighter than a given magnitude limit. On their own, however, none of the potential solutions cover all risks.

## 1.2 UVOT OPERATIONAL SAFETY STRATEGY

After careful consideration the following strategy was developed that utilizes all the potential solutions identified above.

- The spacecraft to monitor the position of Sun, Moon and the Earth and the health of the spacecraft Attitude Control System (ACS) and to send a go to safe message or power down instruction to the UVOT telescope module in the event that the constraints are violated.
- A star catalogue to reside in the ICU – with over 200,000 entries classed by magnitude, colour index and sky position. The data will be used to generate a theoretical count rate for each filter and the count rate will then be used to decide how long, if at all, it is safe to observe in each pointing direction.
- An independent pointing monitor function – the ICU will monitor the spacecraft position message and safe the instrument if any constraints are violated.
- The ICU independently to calculate the position of Sun, Moon and the bright planets.
- A hardware based detector safety circuit to monitor the output of the camera and safe the detector with an appropriate detector safing action.

A more detailed explanation of the ICU safety operations is described in reference 2.

# 2. UVOT SAFETY CIRCUIT

## 2.1 UVOT SAFETY CIRCUIT GOALS

The UVOT safety circuit should protect the detector against unexpected bright sources. This function must operate independently of the ICU but be under its overall control. A fast response time of less than one second is required to prevent damage to the detector system. The safety circuit must be flexible enough to cope with changing circumstances and must have the facility to be disabled. The safety circuit needs to be insensitive to the effects of penetrating radiation in the CCD and detector.

## 2.2 UVOT DETECTOR CHARACTERISTICS

During testing of the UVOT image tubes it was observed that in conditions of high event rates when the overall system would, in normal operation be showing significant coincidence losses, there was a broadening of the event profile. This was originally thought to be due to a mix of the system Point Spread Function (PSF) and saturation of the image tube. It was, however, later found to be predominantly an effect of the image tube.

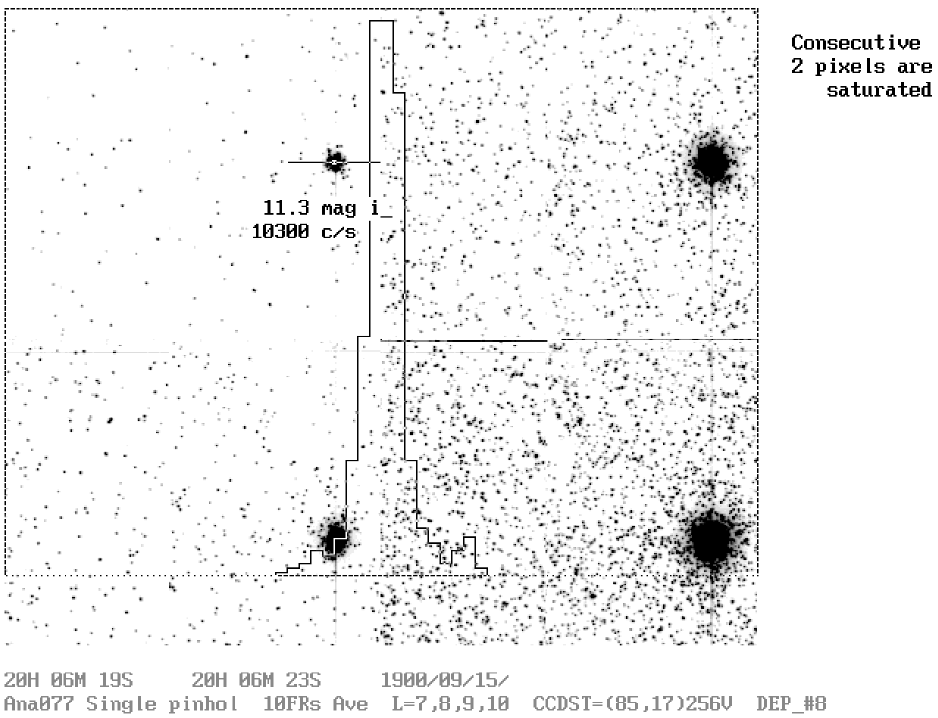


**Figure 3: Detector profile for an 11th magnitude star in the white filter**

The Full Width Half Maximum (FWHM) of a single event profile at the phosphor screen is about 70µm (about 1 CCD pixel), with an extended wing at very low levels < 1 LSB in the CCD camera. At the other extreme when the event rate is much higher, i.e. 100 000 events per second, the faint wing reaches saturation. Figures 3 and 4 show the effect of bright stars (simulated by a pin hole image) on the UVOT detector CCD camera output. It was considered that this repeatable characteristic provided a good indication of source brightness. Consequently, a system to measure the maximum width of a star profile provides a robust indication of source brightness for the bright source safety circuit.

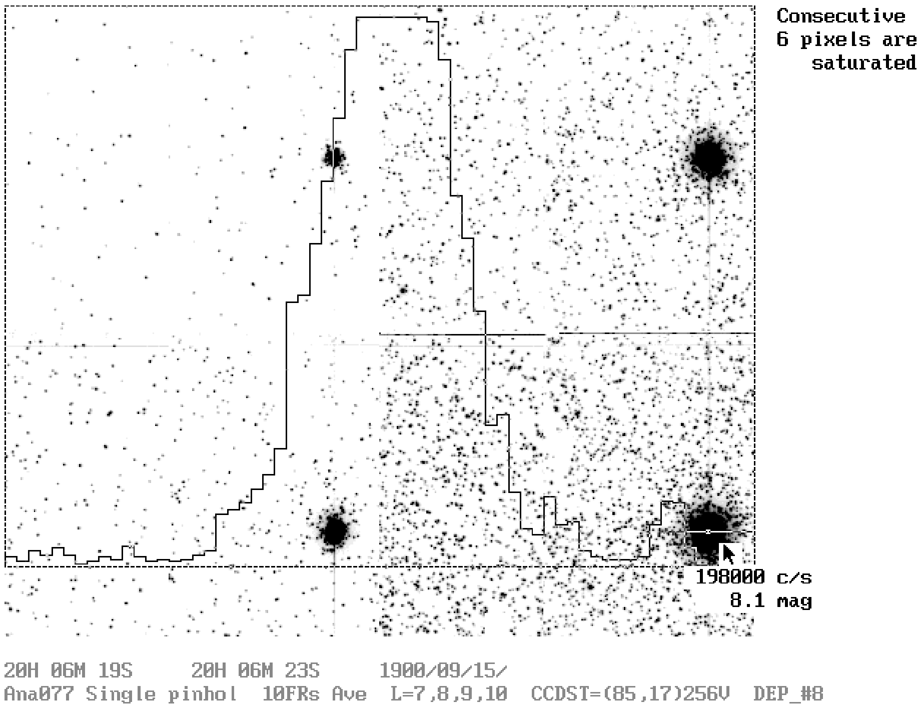


**Figure 4: Detector profile for an 8th magnitude star in the white filter**

### 2.3 DETECTOR SAFING OPTIONS

Three options were identified to place the detector into a safe state.

- Move the filter wheel to its blocked position: The filter wheel can only be moved under ICU software control and may take up to 20 seconds to reach the blocked position under worst-case conditions.
- Lower or remove the image tube microchannel plate bias voltages: A reduction in high voltages would decrease system gain dramatically. However, restrictions on the voltages ramp rates make automatic control difficult. Under normal circumstances the ICU software controls the ramp rates for these rails.
- Set the detector cathode voltage to 0V: This action reduces the overall detector gain by ~10 000 (K0 star) and is controlled by a single control line. Although under software control it could be simply modified for automatic control.

All three options above are utilized for UVOT bright source protection. When tripped the safety circuit automatically power down the cathode voltage of the detector, thereby significantly reducing detector gain. The ICU will then monitor the safety circuit status and when it is tripped will take extra safety actions: the MCP bias voltages will be ramped down to 0V, and the filter wheel will be moved to the blocked position.

## 3. SAFETY CIRCUIT DESIGN

### 3.1 BASIC DESIGN CONSIDERATIONS

A system was designed that connects between the camera and the BPE and scans the raw video data for a predetermined number of consecutive pixels above a preset amplitude threshold. To ensure immunity to the effects of penetrating radiation these consecutive pixels must be present for multiple consecutive frames. It was also necessary to ensure that only valid pixels from the camera were analyzed. This was achieved by synchronizing the pixel analysis to the frame sync (IRUN) signal issued at the start of each frame. The horizontal row readout clock (HRUN) signal was used to gate valid pixels from each CCD row. Data from the CCD frame transfer period is also ignored. This is achieved by ignoring the first HRUN period for each frame.

Because connector pins onto the BPE motherboard were limited in number, not all the raw CCD video signal lines could be analyzed. Only the five most significant bits are used. This reduces the resolution of pixel amplitude that can be set.

When the trigger conditions are met, the safety circuit latches a control signal routed to the cathode voltage control circuitry and reports the alert signal in the safety circuit status register. For test purposes the cathode voltage control circuit may be disabled, while still reporting the alert in the control register. The flow diagram in Figure 4b shows the basic operational principles of the safety circuit. It demonstrates the potential logical flow for each valid raw pixel read out from the camera. A typical operation configuration sequence is shown in Figure 4a.

The safety circuit needs to have a command interface with the ICU. This was implemented using two spare address lines on the internal BPE Instrument Control Bus. The lack of available address lines required that all the command and status functions be compressed into two 16-bit words.

The FPGA was implemented using synchronous design techniques and designed in accordance with the NASA FPGA design guidelines shown in reference 3. The FPGA circuit design was subject to a NASA peer review in March 2001.

### 3.3 SAFETY CIRCUIT BPE INTERFACE

The safety circuit connects to the data and control signals between the camera and the blue processing electronics and monitors the raw pixel flow using frame signals to determine valid video pixels. Figure 5 shows a block diagram of the safety circuit connection to the BPE and camera.

### 3.4 CONTROL INTERFACE

Two read/write lines were available from the ICB interface, so all the safety circuit functionality was accommodated with two 16-bit words. Some output register multiplexing was required to accommodate the required control and status functions. Table 1 contains a detailed breakdown of the input and output registers.

**Control Signal Summary**

**System enable** This function enables the safety circuit. When asserted the command is internally synchronized to the next IRUN signal, allowing the system to start in a predictable manner.

**Alert flag** This read register signal indicates when the safety circuit has fired. The cathode safe signal is asserted if the alert enable bit is set.

**Alert reset** This function resets the cathode safe signal register to its power-up default state “off” (allowing control of the cathode voltage) and returns the alert flag to zero. The safety circuit is also reset to its power up default state. It should be noted that safety circuit settings are not affected by this signal and that the previous state will be maintained until it is reconfigured or reset by power cycling.

**Alert enable** This function enables the cathode voltage control register. The alert flag is not affected by this control. This allows for on orbit calibration of the system without turning the cathode voltage off whenever the alert flag is set.

**Input threshold preset** This read/write register allows the pixel threshold to be set. Only the most significant 5 bits are used.

**Consecutive pixel preset** This read/write register sets the number of consecutive pixels that must be greater than the input threshold to trigger the frame counter.

**Consecutive frame preset** This read/write register sets the number of consecutive frames that are required to be above both the input and consecutive pixel thresholds to cause a safing action.

1. Set-up safety circuit pixel threshold
2. Set-up consecutive pixel and frame counts
3. Set system enable and alert enable bits
4. Read the alert flag bit at regular intervals
5. If the alert flag is set the cathode has been set to 0V automatically by the safety circuit. The ICU will set the cathode control to 0V, power down the other HV rails and reset the alert

**Figure 4a: Typical operational sequence**

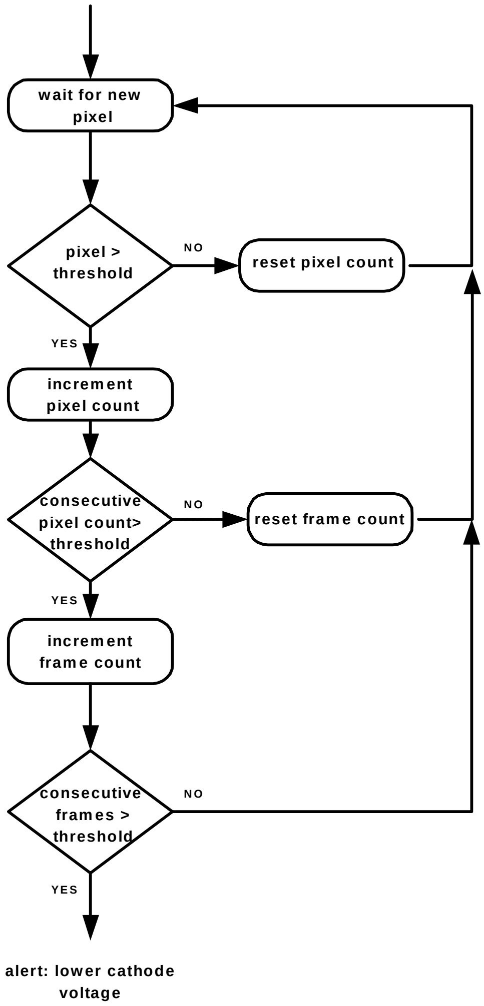


**Figure 4b: Safety circuit flow diagram**

### 3.5 IMPLEMENTATION

As the pre-existing design of the telescope was physically very compact, little space was available for the introduction of a new unit. It was decided to put this new function into the Blue Processing Electronics. The BPE contains all the control signals and power needed to implement the required functionality. One of the BPE boards required modification due to the lack of availability of memory devices and this involved a new printed circuit board design. Therefore it was convenient to add the safety circuit to this board. To enable the new function to fit within the existing envelope an FPGA was chosen to implement the design. The safety circuit design fitted comfortably within an FPGA. The Actel 54SX16 was chosen as radiation tolerant parts were readily available. The FPGA was mounted on a daughter board attached to the new board. The daughter board scheme was chosen to decouple the BPE build and test programme from the safety circuit development activities. See Figure 6 for a photograph of the UVOT flight BPE with safety circuit daughter board.

| Signal Type | Function | Bits/Signals | Comments |
|---|---|---|---|
| Command registers | Input threshold preset | 5 bits | 5 most significant bits |
| | Consecutive pixel preset | 7 bits | |
| | Consecutive frame preset | 5 bits | |
| | Alert reset | 1 bit | |
| | System enable | 1 bit | |
| | Alert enable | 1 bit | |
| | | | |
| Input signals | Frame sync | 1 | IRUN signal |
| | Horizontal read out control | 1 | HRUN signal |
| | Clock | 1 | System clock |
| | Power up reset | 1 | BPE system reset |
| | | | |
| Status registers | Input threshold preset | 5 bits | 5 most significant bits |
| | Consecutive pixel preset | 7 bits | |
| | Consecutive frame preset | 5 bits | |
| | System reset | 1 bit | |
| | Alert reset | 1 bit | |
| | Alert flag output | 1 bit | |
| | System enable | 1 bit | |
| | Alert enable | 1 bit | |
| | | | |
| Output signals | Cathode safe signal | 1 channel | Control line to high voltage unit |

**Table 1: Safety circuit register assignments**

## 4. SIMULATION AND TESTING

The FPGA was designed using schematic entry and simulation was performed using the tools provided with the Viewlogic Workview Office package. Two design iterations were made before reaching the final flight design. A 20% timing margin was demonstrated by simulation when the system clock was increased from 10 to 12 MHz. The hardware test program consisted of a number of phases using the test set up shown in Figure 7.  This included a Blue Processing Electronics channel with the safety circuit, the data capture computer to store and display the processed data from the BPE, and a frame grabber to record and display raw data frames from the camera output. An ICB simulator was used to configure the BPE and the safety circuit and to monitor the status of the safety circuit during various tests. Initial tests were carried out with a camera and lens and variable slit source mounted on an optical bench. The safety circuit was tested against a range of input conditions, using horizontal, vertical and angled slits of varying widths. Later tests were carried out with a full detector configuration including image intensifiers and variable point sources. A range of tests was carried out with a range of simulated source intensities in different positions in the detector frame. In this case the position of the point source was moved using an Aerotech linear x-y stage. Other tests included simulated star fields and grids of sources. The safety circuit performed as expected in all the tests.

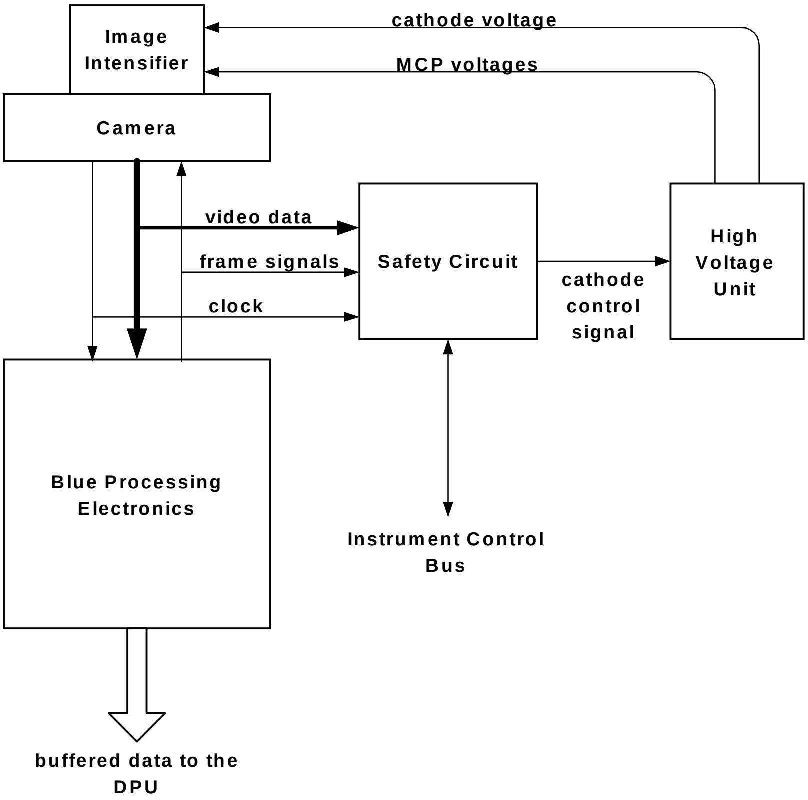


**Figure 5: Safety circuit connections to the BPE and camera**

## 5. ON-ORBIT CALIBRATION AND NORMAL OPERATIONS

### 5.1 ON-ORBIT CALIBRATION

Before the UVOT safety circuit can be used operationally in space, it will be necessary to verify the predicted setup parameters. Currently, it is planned to configure the safety circuit to trip on A0 stars with a magnitude brighter than 8. After launch and during the UVOT TM checkout phase, there will be a period of Pre-Planned Target observations that will automatically observe a number of known sources in a predetermined region of the sky. During ground contacts, procedures will be run to change the safety circuit parameters until a trigger setting is determined for each class of star. By disabling the alert enable function it is possible to monitor the alert flag for action without the cathode voltage being set to 0V. Once these parameters are obtained the final flight safety circuit on-board scripts can be uploaded if required. For a detailed description see reference 2.

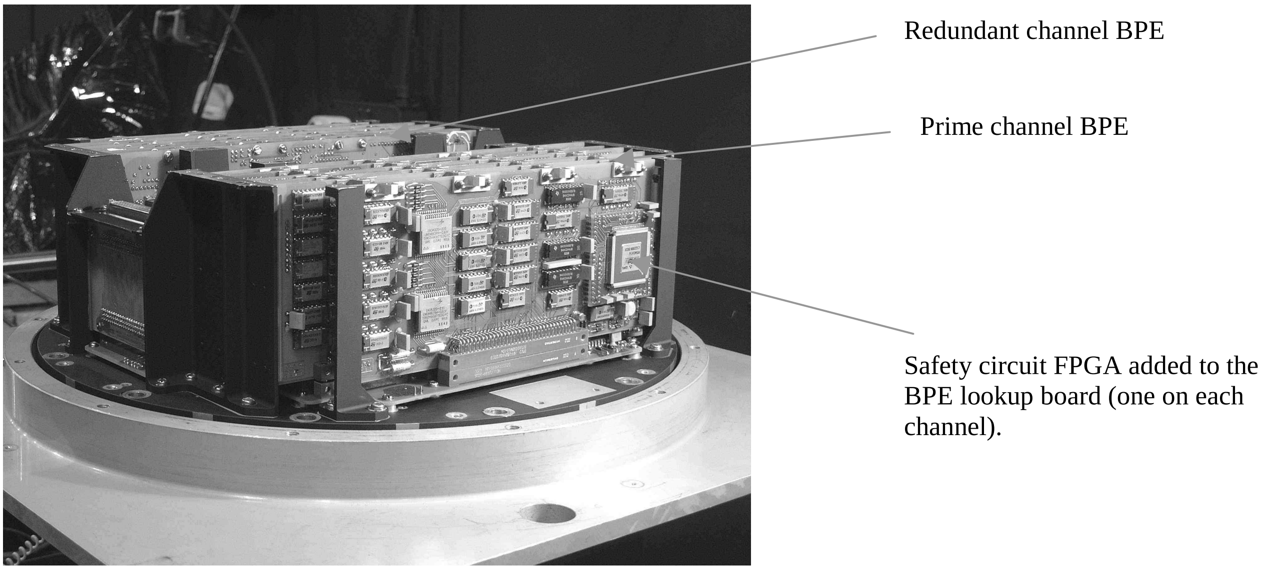


**Figure 6: Photograph of the flight BPE with safety circuit**

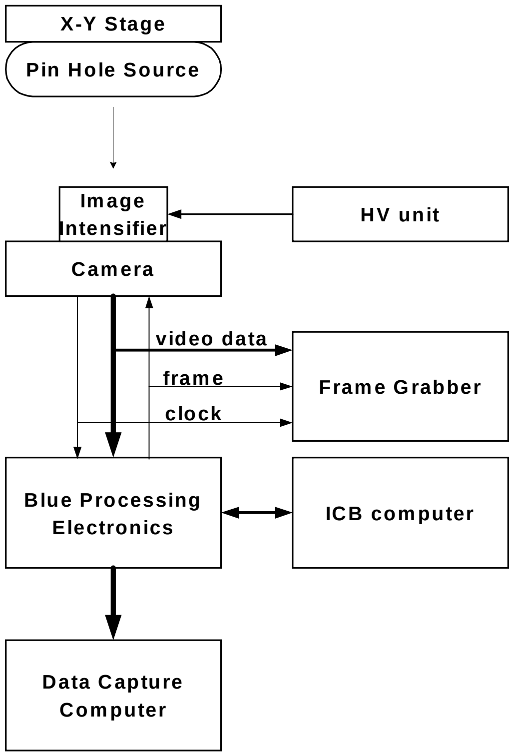


**Figure 7: Safety circuit test configuration**

### 5.2 ON-ORBIT OPERATIONS

After successful calibration, the safety circuit will be automatically configured by the ICU autonomous control system. If necessary, alternative settings may be implemented for different exposure sequences. If the safety circuit should trigger, the detector cathode voltage supply will be automatically commanded by the safety circuit to 0V. At this point the safety circuit alert flag will also be set. This will cause a limit violation within the ICU resulting in the UVOT being automatically commanded into a safe mode. The ICU will automatically ramp down the detector MCP supplies and the filter wheel will be set to the blocked position. The UVOT will then wait for ground intervention and reconfiguration.

## CONCLUSION

The SWIFT mission places a challenging set of autonomous safety requirements on the UVOT instrument. We expect the bright source safing circuit to complement the other protection mechanisms present within the UVOT and after in-flight calibration, to offer a high degree of protection against detector degradation or damage.  Even though limited by the compact telescope design and existing electrical architecture of the XMM-Newton OM it has been demonstrated that a comprehensive and robust system is possible without major changes to the original telescope design.

## REFERENCES


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