In-orbit performance of UVIT over the 5 years

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Abstract. Over the last 5 years, UVIT has completed observations of more than 500 proposals with ∼ 800 unique pointings. In addition, regular planned monitoring observations have been made and from their analysis various key parameters related to in orbit performance of UVIT have been quantified. The sensitivities of the UV channels have remained steady indicating no effect of potential molecular contamination confirming the adequacy of all the protocols implemented for avoiding contamination. The quality of the PSF through the years confirms adequacy of thermal control measures. The early calibrations obtained during the Performance Verification (PV) phase have been further revised for more subtle effects. These include flat fields and detector distortions with greater precision. The operations of UVIT have also evolved through in orbit experience, e.g. tweaking of operational sequencing, protocol for recovery from bright object detection (BOD) shutdowns, parameters for BOD thresholds, etc. Finally, some effects of charged particle hits on electronics led to optimised strategy for regular resetting. The Near-UV channel was lost in one of such operations. All the above in-orbit experiences are presented here.

Keywords. Space vehicles: AstroSat—Telescopes: UVIT—Instrumentation: astronomical imaging.

1. Introduction

The Ultra-Violet Imaging Telescope (UVIT) is one of the five major scientific payloads on board the first Indian multi-wavelength astronomical satellite mission AstroSat, which was launched on September 28, 2015, with the Indian Space Research Organisation, ISRO’s PSLV-C30 rocket. UVIT consists of two identical telescopes of aperture 375 mm and field of view ∼ 28'. UVIT has high angular resolution imaging capability in the Far-UV (130–180 nm) and Near-UV (200–300 nm) wavebands using selectable narrow/medium/wide bandwidth filters as well as slit-less spectroscopic imaging. A simultaneously viewing optical band, VIS (320–550 nm) is incorporated to aid implementation of the shift and add algorithm, for getting long exposure images from short exposure frames, on the ground for avoidance of blurring due to drift in the telescope aspect. The details about various
sub-systems of UVIT and their respective qualifying tests and calibrations are described in Kumar et al. (2012a, 2012b). After an initial 6 week long in orbit out-gassing phase, gradually individual subsystems of UVIT have been tested for their functionalities and performance with the doors of the twin telescopes still closed. The first light of the entire end to end UVIT system was carried out on November 30, 2015, by imaging the Galactic open cluster NGC 188. This was followed by the nearly six month long Performance Verification (PV) phase when detailed tests, characterization and calibrations were carried out. Many details about results from the early phase of UVIT in orbit have been presented in Subramaniam et al. (2016b) and Tandon et al. (2017a, b). UVIT was thrown open (along with other payloads for X-ray astronomy) for astronomical observations planned as per peer-reviewed scientific proposals, at first under guaranteed time (GT) cycle followed by announcement of opportunity (AO) cycles. During these cycles, additional calibration proposals have also been executed at regular intervals for monitoring the health and quantifying the stability of UVIT’s performance. This article summarizes the journey of UVIT over the first five years in orbit in terms of performance and achievements including unanticipated events and recovery therefrom.

2. Performance verification phase

2.1 Tests prior to opening of UVIT doors

The earliest in orbit activities of UVIT pertained to qualification of all functions of the payload other than the optical systems prior to opening of the doors, lasting ~50 days post launch. (In these 50 days only 17 days were used for operations with UVIT, rest were used by the other 4 instruments.) These involved electrical and mechanical sub-systems — e.g. communication systems with the spacecraft, various “states” of the detector module, detector read out system, detector safety logic (Bright Object Detection, BOD), generation of high voltages, rotational movements of the filter wheel system etc. Tests were carefully planned in phases with gradually increasing complexity and with live control ensuring options of aborting in case of encountering any abnormality (required scheduling and coordinating operations only during visibility of the spacecraft above main ground station). Cosmic Ray Shower events passing through the detector system provided opportunity for checking certain functionality in the absence of UV photons from the sky. Beginning with operations for one band (among FUV/NUV/VIS) at a time, eventually simultaneous all 3 band operations were qualified. No abnormality was encountered through this phase of commissioning of UVIT’s detector and filter wheel systems prior to opening of the doors.

2.2 First light and lessons from early imaging operations

The very first imaging of the sky with UVIT was carried out on 30 November 2015 targeting the Galactic open star cluster NGC 188, whose coordinates (high declination) offered the advantage of optimal visibility through any season allowing long term follow up monitoring. Accordingly, selected stars in this cluster were used as secondary standards for photometric calibration.

One of the most critical components of UVIT is the Detector module employing a complex image intensifier system, operable in photon counting mode. Key requirements driving this choice were: (1) to keep drift in pointing to $<1''$ within an individual frame, the speed of reading out was required to be $> 10$ frames/s, (2) given that the total number of UV photons detected in 0.1 s could be as low as 10, a read out noise of $< 1$ (rms) was required. Therefore, read noise of CCD would not be acceptable. Further, a red-block filter with zero red leak would be required with a CCD, to completely block the longer wavelengths.

The image intensifier configured for each band of UVIT consists of a photo-cathode deposited on the window where primary electrons are generated by photo-electric effect by incident photons. These are then multiplied by a large factor (gain) using a Micro-Channel Plate assembly, MCP, biased to selectable high voltages. The stream of secondary electrons exiting the MCP are made to strike a phosphor acting as anode generating optical light pulses. These pulses are detected by a CMOS imager, Star250, with $512 \times 512$ pixels coupled through a fibre-optic taper. This imager is continuously read out as individual frames during imaging operation. The MCP needs carefully planned protection against exposure from bright objects since it can deliver only a limited amount of total charge in its operational life. The areas of MCP having experienced prolonged exposure to high fluxes loses its electron multiplying...
functionality leading to ineffective areas or even complete damage. In addition, the excessive load on the high voltage supplies could damage them too. Accordingly, two key safety features have been introduced: (i) a Bright Object Detect (BOD) logic has been implemented in the onboard signal processing scheme which triggers a safety shutdown of the affected band and also raises an alarm to the spacecraft for similar action in other bands; and (ii) the initial imaging of any fresh sky field or filter mandatorily begins with a very low gain gradually achieving the optimal setting (by ramping up the high voltages at a selectable rate) which allows the BOD logic sufficient time to process the incoming raw frames read out from the imager. The selectable parameters related to the triggering threshold for the BOD logic are: pixel threshold, 1-D size along faster read-out axis of the frame, and the number of consecutive frames in which the pixel threshold has been exceeded over at least one string of pixels of 1-D size. Given the long period of detector’s operations on ground during extended tests and calibrations, significant experience existed regarding choices for these parameters.

In spite of these knowledge base, an accidental BOD operation awaited the UVIT team on first light of VIS channel! It resulted from an erroneous choice of settings for the high voltages – the set corresponding to photon counting mode was configured while attempting to image in Integration mode. This oversight was corrected swiftly. Very soon another BOD trigger occurred due to a star in a field thought to be safe, indicating error in estimation of ‘signal per photon’ from the ground calibration. The observed signal in orbit was higher, needing adjustment of the trigger threshold.

Figure 1. An example of Bright Object Detect (BOD) trigger due to appearance of an unanticipated non-celestial object in UVIT’s field-of-view. One image frame in VIS band is displayed. The bright streak (near the bottom left corner) caused this BOD trigger.

Figure 2. Example of artifacts appearing in VIS band images. The horizontal stripes occur possibly due to effects of charged particle hits and they disappear after a power reset.
Tweaking of all detector related parameters to optimal values were completed within days of the first light. The selection of the band whose clock would be used as ideal Master Clock, i.e. in effect the clock for all the three bands, as well as a consistence sequence of their configuration for imaging were achieved shortly. This sequence being rather critical, its reliable implementation was achieved by embedding these details in well designed Macros for operations. The initial ramping up of high voltages was enforced for every change of filter.

Another important realization during this phase was the need for safeguarding the detector against bright stars while imaging in window mode, i.e. recording data only for part of the full field (selected size smaller than the full size of 512 × 512). This risk was mitigated by introducing a mandatory full window mode imaging preceding the imaging with a smaller window so as to ensure that BOD is triggered in case a bright object is present in the field though outside the selected window. All such details were implemented in macros for imaging operations. Eventually, this protocol was extended for even full window imaging, to bring in uniformity in operations for simplicity.

3. Experiences from long term operations of UVIT

UVIT has been in regular use after its commissioning serving scientific as well as calibration proposals. The operations involved imaging as well as slitless spectroscopy. Over the last ~5 years, more than 500 proposals have used UVIT. While most of the time UVIT has performed extremely well meeting planned design specifications, at times there have been occasional technical issues, needing urgent review followed by action. The most frequently occurring event has been the automatic shutdown of UVIT due to trigger of Bright Object Detect (BOD) logic. When any band of UVIT encounters a brighter than programmed safe limit, it autonomously parks itself in a safe mode and raises an alarm to the spacecraft bus, which in turn shuts down all the three bands of UVIT following a safe sequence of operations. From the record of which band triggered the BOD, on ground the cause for exposure to such a field is investigated. It may be noted that extreme care is taken while technically approving any sky field to be observed with UVIT, which involves consideration of all cataloged bright optical and UV objects in the target field. In most cases, either a human error or a large offset in

![Figure 3. Example of an artifact due to a stuck bit in the Master Clock. The time stamped on individual frames (frametime), are plotted against the elapsed time (tickcount). The fixed amount of jumps at each discontinuity indicates the 20th bit of the frametime to be stuck at zero.](image-url)
pointing have been identified. On a few rare occasions, brightening of a (variable) star of brightness close to the safety limit or passage of a bright non celestial object (shining satellite) is responsible for triggering the BOD. An example of the latter is displayed in Fig. 1. After each instance of BOD triggered shutdown of UVIT, a well defined recovery protocol is followed to normalize the UVIT bands after which regular operations can proceed. Typically about 3–4 incidents of BOD trigger were encountered annually. It is noteworthy that the over-current in high voltage units (described later) was never triggered. This possibly points to the quality/ruggedness of the intensifier and the high voltage generating circuits.

An anomaly noticed rather early on (within months of in orbit operations) was appearance of stripes in the raw image frames of VIS band (see Fig. 2). These were diagnosed to be effects due to charged particle hits and complete recovery could be achieved by powering OFF the VIS electronics. Since the processing pipeline on ground was agile enough to ignore such artifacts and generate final products unaffected, the mitigation action was not carried out till the situation demanded powering OFF. At a later phase, when such stripes in VIS appeared more often, along with some additional artifacts in UV bands too, a monthly schedule was drawn up to normalize (power OFF) all the 3 bands FUV, NUV and VIS.

The on-board logic was designed to handle five kinds of anticipated emergency situations in UVIT. These are described in order of increasing level of severity.

1. **TM acknowledgment error**: Initiating an imaging session starting from inactive state, involves configuring the detector following an unique sequence of commands which gradually activate relevant sub-systems ensuring complete safety. Another sequence (reverse order) is used for returning to inactive state. Receipt of any command violating the above triggers this alarm.

2. Failure of the filter wheel mechanism to reach its targeted angle within a stipulated time.

3. Threat to safety of the intensifier on detection of a bright star (BOD).

4. Threat to safety of the high voltage power supplies when current drawn exceeds the set limit.

![Diagram](image_url)

**Figure 4.** Example of multiple bits of the centroid coordinates (along Y-axis) of every photon event to be stuck to zero. The points in the plot correspond to individual photons. The systematic gaps in the values of Y-centroid indicate several successive least significant bits (corresponding to the fractional part) are affected.
(5) Transition to fail safe state on detection of high current indicating radiation induced single event latchup.

One critical point for each of these types of emergencies is the final parking state. During pre-launch deliberations, it was decided that the relatively benign ones (first 3) should land the detector electronics (for all 3 bands) to low power state and the remaining 2 severe ones to complete power OFF state through operation of mechanical relays. Being cautious during early in orbit operations, this strategy was made more conservative by demanding all 5 situations to lead to OFF state. As a result, BOD used to result in OFF state needing re-boot of the system during recovery operation.

During one of the post-BOD recovery operations (January 20, 2018), the NUV channel failed to restart. Based on ground simulations using the engineering model and after prolonged trials based on different well considered strategies (stretched RESET pulses), the NUV band could be recovered (February 16, 2018). Unfortunately, failure of the NUV channel to boot recurred after a routine monthly normalization (March 20, 2018). A very long struggle to revive the NUV channel followed. The various innovative strategies employed to recover the lost channel included: (i) different frequency of normalization trial, (ii) widening of the RESET pulse, (iii) gradual warming up of the affected electronics and trying RESET at selected higher temperatures (this involved tweaking parameters of the spacecraft’s thermal

Table 1. Chronology of issues observed in UVIT data* and their resolution.

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Date of appearance</th>
<th>Date of resolution</th>
<th>Type of issue</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16-Apr-2017</td>
<td>06-Jun-2017</td>
<td>Vertical stripes in NUV images</td>
<td>Recovered by RESET</td>
</tr>
<tr>
<td>2</td>
<td>29-Apr-2017</td>
<td>06-Jun-2017</td>
<td>Anomalous size of VIS images</td>
<td>Recovered by RESET Data made usable by developing mitigatio scheme in ground software</td>
</tr>
<tr>
<td>3</td>
<td>18-Nov-2017</td>
<td>23-Nov-2017</td>
<td>No FUV data</td>
<td>Recovered by RESET</td>
</tr>
<tr>
<td>4</td>
<td>06-Feb-2018</td>
<td>22-Feb-2018</td>
<td>Unable to turn on NUV band after a shutdown due to BOD</td>
<td>Recovery managed after exploration of many strategies to power on</td>
</tr>
<tr>
<td>5</td>
<td>30-Mar-2018</td>
<td>—</td>
<td>Unable to turn on NUV band after a shutdown</td>
<td>No recovery yet, despite repeated attempts exploring multiple strategies (periodic attempts continue)</td>
</tr>
<tr>
<td>6</td>
<td>25-Dec-2018</td>
<td>13-Jul-2019</td>
<td>Stuck 20th bit in time stamps on FUV frames</td>
<td>Eventual recovery by RESET (after adopting many alternate schemes avoiding RESET, in view of the loss of the NUV band); The data collected during this period made usable by developing mitigation scheme in ground software</td>
</tr>
<tr>
<td>7</td>
<td>05-Mar-2019</td>
<td>04-Jul-2019</td>
<td>X-centroids (FUV) with stuck bits</td>
<td>Recovered by RESET (after hesitation for use of the RESET)</td>
</tr>
<tr>
<td>8</td>
<td>03-Nov-2019</td>
<td>16-Nov-2019</td>
<td>Stuck 31st bit of Time Stamp in FUV band frames (relaying Master Clock from VIS)</td>
<td>Recovered by RESET (after exploring alternatives to RESET)</td>
</tr>
<tr>
<td>9</td>
<td>26-Nov-2019</td>
<td>13-Dec-2019</td>
<td>Stuck 31st bit of Time Stamp in FUV band frames (relaying Master Clock from VIS)</td>
<td>Recovered by RESET (with understanding of the damage, future occurrences of the issue became predictable; devised a periodic RESET plan, which works well)</td>
</tr>
</tbody>
</table>

The many instances of appearance of stripes in VIS band images are not listed here. They were always resolved through RESET. Also mitigating scheme was incorporated in the Level-2 pipeline to handle such artifacts with no loss of functionality, so that data preceding RESET also remain fully usable.
While none of the above could recover the NUV channel, the main cause of the failure was eventually understood through deeper study of technical literature. Technical understanding of this failure emerged as follows: the onboard processing of the UVIT detector data is implemented in a FPGA, whose code gets loaded from an EEPROM every time the system is powered on or undergoes RESET. The EEPROM (also the FPGA) used were not of the radiation hardened grade but of MIL spec grade, which is susceptible to damage by cosmic ray radiation. In addition, the EEPROM was of serial type which is known to compromise the reliability. As a further weakness, the code design did not provide any option for re-programming. Such devices develop weak-cells (due to radiation damage) which are also known to deteriorate further with more read-cycles.

Based on the above technical understanding of the reason for loss of NUV band, the practice of monthly normalization of VIS and FUV bands was completely discontinued. In addition, the strategy for on board handling logic post occurrence of BOD emergency state was revised. The parking state on BOD trigger was changed to low power (avoiding any booting action which involves re-loading of the code from EEPROM to FPGA). Attempts for reviving the NUV band continues to date at regular intervals.

More recently (since ~December 2018), some other types of artifacts due to radiation hits were discovered, which could be recovered. However, their recovery required power RESET. These artifacts were: (a) frozen 20th bit of VIS clock which is the selected master for all bands (see Fig. 3), (b) certain frozen bits of all X-centroids for photon events, etc. Initially, on encountering (a), plans and procedures were set up for change over of the Master Clock from VIS band to FUV band thereby avoiding issuance of any RESET (in view of the loss of NUV band). This involved re-programming all command tables corresponding to ‘imaging parameters’ for each band. The uploading of these tables to the relevant spacecraft

Figure 5. An unexplained feature (streak) observed in images in all 3 bands of UVIT for certain targets. As an example, image of the galaxy M31 in NUV band is displayed. The orientations of the streaks with reference to mountings of FUV/NUV/VIS detectors imply that they could be caused by some structure within the telescope tube.
sub-system involved certain new activities. After a
everview by ISRO experts, this course of action was not
found to be advisable. In the mean time, (b) was
encountered which forced the use of RESETs which
eventually mitigated both these issues. Most recently
(October 2020), all bits corresponding to fractional
part of the Y-centroid were stuck (see Fig. 4). All
instances of appearance of such artifacts (other than
periodic appearance of stripes in VIS image frames)
and subsequent recovery from them are presented
chronologically in Table 1.

The lone instance (over 5 years of operations) of
UVIT bands remaining in active imaging mode
beyond the mission schedule and being exposed during
one full bright (sunlit) part of the orbit, was
experienced on September 19, 2020. However, no
damage or degradation of any performance of UVIT
was noticed after this incident. The reason for this
anomaly was traced to a logic in spacecraft operations
which has been mitigated.

One non-recoverable artifact encountered (early
November 2019) was the stuck 31st bit of FUV clock
relaying Master Clock counter from VIS band (which
continued to record correct values). It is fortunate that
this bit can change state only after a few weeks and
accordingly, this defect could be by passed by an
aggressive mitigation plan. The plan involved a periodic
RESET of the VIS band electronics every \( \sim 12 \)
days.

Despite the anomalies described above, the two
bands of UVIT, viz., FUV and VIS have been serving
scientific observation plans leading to interesting
research results.

Additional effects/events, some unexpected others expected, that were experienced are summarized here.

The effects due to Cosmic Rays (CR) on the
detector system were anticipated and their handling by
the offline data processing pipeline on ground were
planned accordingly. The primary CR-energetic
charged particle – itself interacting in an imager pixel
could corrupt its value corresponding to a large signal.

On the other hand, showers of secondary charged
particles generated by interaction of primary CR in the
proximity of the detector and high electrical fields
around MCP, mimic UV photons. While in the low
gain operation of the detector (employed for VIS
band), only one pixel is affected per primary CR, a
large number of randomly located background events
are recorded in the high gain operation of the detector
used for FUV and NUV bands due to the showers.

Fortunately, each shower lasts at most a few micro-
seconds, and hence can affect only one frame.

However, the frequency of occurrence of such cosmic
ray shower is crucial. The mitigation plan in ground
software is to identify frames affected by showers
using selectable parameters (statistically determined
threshold on number of events) and flagging them for
discarding. From long term experience, on average 3.5
showers per sec are observed contributing to \( \sim 150 \)
events/s for full field operations. The impact of discarding affected frames is rather small (loss of \( \sim 10\% \)
of the observations with full field). Given the uncor-
related nature of the cosmic ray background events,
they may be ignored for fields which are UV bright.

However, for very deep observations it is important to
discard affected frames (Saha et al. 2020).

Figure 6. Effect of saturation is illustrated in the NUV
band image of a bright star in the cluster NGC 188 (size:
\( 28" \times 28" \)). The valley encircling the central peak is due to
saturation effect of photon counting mode. The radial
profile displays the local dip quantitatively.
Example of an observed artifact is a bright "streak" due to some very bright object within a few degrees of the telescope axis (though outside UVIT’s 28 arc-min field-of-view). Such streaks have been observed in VIS as well as NUV images. The orientation of the streaks in these images imply a direction fixed to the telescope tube, once the relative angle between the axes of the detectors is taken into account. Such streaks have been observed while observing the targets: M 31, PKS 1510-089 and Crab. One example is presented in Fig. 5 which is an NUV image of M 31.

Another artifact presented here relates to the effects due to saturation in photon counting mode of imaging. A deep valley encircling the central peak is observed for a bright star in the star cluster NGC 188 imaged in NUV, which is displayed in Fig. 6. The accompanying plot of the radial profile quantifies this dip.

The ground segment software system at ISRO provides absolute time information for the science data by correlating internal clocks of UVIT (one per band) with Universal Time Clock (UTC) in the Level-1 (L1) products. This utilizes simultaneous samples of spacecraft’s clock counter with those from UVIT. Accordingly, the UVIT’s Level-2 (L2) processing pipeline was designed using UTC as the primary timing reference. However, often this time correlation in L1 was found to be unreliable. Hence, it was necessary to incorporate new functionality in the L2 pipeline to by-pass UTC and use the Master clock of UVIT which ensured inter-band time synchronization.

Even in the UTC by-pass mode a provision for approximate (good to \sim 1 s) absolute time (MJD_\text{UT}) for every frame was made based on an intelligent algorithm.

4. Key performance parameters

The key parameters of performance of UVIT include the following:

1. The photometric calibration quantified by zero-point magnitude and the unit conversion factor for all the filters.

2. Effects of saturation.

3. Variation of sensitivity across the field of view (flat field).

4. Point Spread Function, PSF, and its variation over the field.

5. Dispersion, resolution and effective areas in the grating mode.

6. Astrometric calibration including distortion.

The procedure followed to arrive at these and related details have been presented in Tandon et al. (2017c, 2020). Here we summarize the results reported there.

Based on the observations carried out during the initial 18 months or so led to the first phase of calibration results (Tandon et al. 2017c). The zero-point magnitudes for all the filters in FUV and NUV band were quantified. The measured sensitivities in FUV and NUV are found to be > 80% of the expectations based on tests carried out on ground. The spatial resolutions (PSF FWHM \sim 1.3–1.5 arc-sec in FUV and \sim 1.0–1.4 arc-sec in NUV) are found to be better...
than expected. The variation of PSF across the 28’ field is small for the FUV band. For the NUV band an increase of ~10% is found in FWHM in the central part of the field compared to the edges. No detectable change in the PSFs in both UV bands have been found to date. The astrometric accuracy over the full field is found to be ~0.5 arc-sec RMS.

With passage of time (~3 years) additional regular calibration observations with UVIT were carried out. Based on these extensive additional database and improved understanding of the instrument, further refinements to the first phase calibrations were conducted. The results from these studies have been reported in Tandon et al. (2020). These improvements have led to quantification of new photometric calibrations which included subtle effects. The zero-point magnitudes, ZP, for most filters have been revised, and for some with improved precision (e.g. error on ZP for the filter N245M reduced from 0.07 to 0.005). For example, improved determination of ZP for the CaF2 filter (F148W) in the FUV band and the Silica filter (N242W) in the NUV band led to the values 18.097 ± 0.01 and 19.763 ± 0.002 respectively.

The flat fields have been significantly improved by supplementing remainders by analytic functions (third-order polynomial at the central region and linear in radius with azimuthal dependence for the outer regions). The achieved accuracy with this improved flat field correction scheme has been estimated from exposures on multiple fields of small magellanic cloud. The fractional differences in the flat-field corrected counts for sources when they fall near centre of the field and when they fall near edge of the field are ~0.06. This suggests that the errors on flat-field corrections are no more than 6%.

As a result of these improvements, the astrometric accuracy improved to 0.4 arc-sec (rms), indicating uncorrected distortion to be <0.3 arc-sec (rms). The spectral, PSF and astrometric calibrations have also been improved upon. For both the NUV and FUV bands, the FWHM of the PSF is found to be 1.4 arc-sec or better within the central 24 arc-min of the field. The new results conclude that there has been no reduction in sensitivities of FUV and NUV bands.

The result from monitoring the sensitivity of the FUV band over the entire mission including recent observations is presented in Fig. 7, which shows no detectable change in the count rate for a secondary calibrator star, WC5-5885, in the cluster NGC 188 (Subramaniam et al. 2016a). The stability of sensitivities over long duration has vindicated the care taken over the years on ground towards control of molecular contamination, viz., choice of materials, operations in clean room, cleaning protocols, pre-assembly baking, purging of the optical cavity of UVIT with pure N2 gas. In addition, the in orbit protocols followed: long in orbit wait for degassing before opening the doors as well as avoiding direct sun light falling on telescope tubes during spacecraft maneuvers also helped. The stability of the PSF is ensured by adequate on board thermal control through the mission. The temperatures of critical elements,
viz., telescope tubes and detectors (measured over ~ a week) responsible for the observed stability in sensitivity as well as PSF size are displayed in Figs. 8 and 9 respectively. The temperature of the tubes is stable within ±0.5 C, which translates to a geometrical blurring in the image by <0.1 arc-sec rms, implying a change from ~0.5 arc-sec to <0.51 arc-sec rms for the PSF. The temperature of detector (Star250 imager) is stable to within ±1 C.

5. Epilogue

UVIT has been performing quite satisfactorily over the years with most its in orbit specifications close to and a few even better than the corresponding targeted values. A large fraction of AstroSat time has been allocated to UVIT by the Time Allocation Committee based on user driven scientific proposals. The distribution on sky of the astronomical targets observed with UVIT is displayed in Fig. 10, which includes about 800 unique pointings. A large number of important astronomical results have already appeared in journals with high impact (possibly many more are in the process). All scientific payloads of AstroSat including UVIT, had a baseline design life of 5 years, which has already been achieved. While it is a pity that the NUV band was lost at the mid-point of this life, due to radiation damage of some critical electronic components, the FUV and VIS bands continue to serve the users. It is hoped that these two bands will last many years in future. Although HST allows extremely sensitive imaging in the FUV (STIS, FUV-

Figure 9. Example of typical variation of temperature of the 3 detectors (FUV, NUV, VIS) in UVIT over one week. The temperature is measured on the Camera Proximity Unit housing the image intensifier and the CMOS sensor STAR 250.

Figure 10. A plot showing distribution on sky of the astronomical targets observed by the UVIT (total ~800 unique pointings).
MAMA; 25" × 25"), UVIT currently provides the unique opportunity for wide field imaging with 28 diameter field.

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References

Subramaniam A., Tandon S. N., Hutchings J. B. et al. 2016b, SPIE, 9905, 99051F
Tandon S. N., Ghosh S. K., Hutchings J. B. et al. 2017a, CSci, 113, 583