Performance of the UVIT Level-2 pipeline

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Abstract. Performance of the Level-2 pipeline, which translates the UVIT data created by the ISRO's ground segment processing systems (Level-1) into astronomer ready scientific data products, is described. This pipeline has evolved significantly from experiences during the in orbit mission. With time, the detector modules of UVIT developed certain defects which led to occasional corruption of imaging and timing data. This article will describe the improvements and mitigation plans incorporated in the pipeline and report its efficacy and quantify the performance.

Keywords. Telescopes: UVIT—instrumentation: pipeline.

1. Introduction

The Ultra-Violet Imaging Telescope (UVIT) on board AstroSat carries out simultaneous imaging of the sky in three bands, viz., Far-UV (FUV: 130–180 nm), Near-UV (NUV: 200–300 nm) and visible (VIS: 320–550 nm). Using a selectable filter for each band, radiation in limited ranges of wavelength are allowed to reach the respective detectors. Gratings for UV bands also allow low spectral resolution slit-less spectroscopy. The detector for each of the 3 bands consist of an image intensifier assembly consisting of a photo-cathode deposited on the window which proximity focuses photo-electrons onto a pair of Micro-Channel Plate assemblies biased to suitable high voltages to multiply them. These secondary electrons are further accelerated by electric field to hit a phosphor (acting as anode) to generate corresponding optical light pulses. This light is coupled through a de magnifying fibre-optic taper onto a CMOS imager (512 × 512 pixels) which covers the entire circular active area of the detector. The full field of view of UVIT is 28 arc-min (diameter) for each band and it is read at a rate ~28.7 frames/s, but a centrally positioned square window of selectable size allows for imaging in smaller fields (smallest: 5.5′ × 5.5′ corresponding to 100 × 100 pixels) with proportionately faster sampling in photon counting mode imaging operation of the UV detectors. The Far-UV and Near-UV bands are operated in photon-counting mode, with a high gain of the Micro-Channel Plate assembly, while the VIS band is operated in an integration mode, with a low gain of the Micro-Channel Plate assembly and a much slower image read out rate which aid determination of drift of the spacecraft with high accuracy. Each band is configured for sky observations by effecting several user selectable parameters, the major ones being filter/grating and window size (coupled image frame rate). Further details about UVIT can be found elsewhere (Kumar et al. 2012a; Tandon et al. 2017a, b).
The data originating from UVIT (detector modules/electronics, filter drive units) as well as the spacecraft systems (time, aspect, etc) are sorted in time and collated on ground by various processing stages at the centres of ISRO (ISTRAC, URSC, ISSDC). The resulting data products, called Level-1 (L1), are provided to Payload Operation Centre, POC, for UVIT (at IIA, Bangalore). At POC further processing are carried out using the UVIT’s Level-2 pipeline along with some auxiliary programs, which result in final astronomer ready L2 products for dissemination and archiving. The most significant role of the Level-2 pipeline is to first extract spacecraft drift parameters with time (from stars detected in sky images in VIS) and apply corresponding corrections, along with various systematic effects inherent within UVIT, to combine the series of short exposure UV data into integrated sky images.

The development of the UVIT’s Level-2 pipeline, hereafter “pipeline” was initiated well before the launch of AstroSat/UVIT, but significant changes of strategy/algorithms/coding were needed to be carried out after real L1 data corresponding to in orbit operations became available. This article chronicles the evolution of the pipeline over the initial years after the launch of September 2015. The performance of the pipeline in terms of achieved angular resolution (characteristics of Point Spread Function) and efficiency with which input L1 data could be translated into L2 products have been quantified.

2. Functionalities of the pipeline

Typical observation of any astronomical target is organized as a sequence of exposures in selected Filter-Window size configurations of Far-UV and Near-UV bands as per scientific requirements of the observer. The VIS band is configured with largest window (512 × 512; covering the full 28 arc-min sky field) and a ‘safe’ filter such that the brightest star in the field would not cross the nominal safety threshold set to trigger the on-board autonomous Bright Object Detect, BOD, logic of the detector. Identical detector safety concerns are also addressed while selecting acceptable filters for the UV bands. The UVIT can observe only during the dark part of any orbit due to large background from scattered solar and earth radiation in the bright part. This allows a maximum of ∼2000 second uninterrupted exposure at one instance (this could become even shorter in practice, due to passage of spacecraft through South Atlantic Anomaly, SAA, or constraints like minimum Sun angle, etc). Hence, observation needing longer total integration time is spread over multiple orbits. Each uninterrupted imaging operation with a fixed Filter-Window configuration is called an “Episode”. The dark part of one orbit can also accommodate more than one Episode (e.g. shorter exposures with different Filter/Window). Generally, observations of a specific target are scheduled in successive orbits sandwiched between two spacecraft slews—one for pointing to the target and the next away from it (typically pointing to another target) called a “Pointing”. Accordingly, UVIT observations from each Pointing would generally contain multiple Episodes. The complete Level-1 data from a particular Pointing are finally combined by the ISRO ground station software systems into a single “Merged L1” data bundle. Initially, ISRO promptly provides Level-1 data from individual orbit dumps (say, “Orbit L1”). While Merged L1 would mandatorily hold data from multi-Episode observations for each band of UVIT, the Orbit L1 would most often hold single Episode per band. The L1 data bundle for UVIT consists of Science (Imaging) data from all 3 detectors and Auxiliary (Aux) data containing inputs regarding UVIT Filters and various information from Spacecraft Systems, e.g. time calibration, attitude of satellite reference axes, position in orbit, gyro sensors’ output and house keeping information.

The pipeline has been designed to automatically handle an entire input L1 data bundle at a time and carry out a series of tasks sequentially to generate all output products from its single run. It uses the UVIT’s Calibration Database (CALDB) and the user selected various parameters and switches through a Parameter Interface Library (PIL).

As mentioned in the introduction, the detectors for all 3 bands of UVIT are constructed identical intensified CMOS-imaging systems, which can be operated either with a high gain effecting Photon Counting mode (PC) or at a low gain effectively functioning in Integration mode (INT). The detectors for Far-UV and Near-UV bands are operated in PC mode and frames are read out at a high speed (∼28.7 fps for full field; max ∼ 640 fps for smallest field) while for VIS band INT mode is used at a low frame rate (∼1 fps). Successive frames from the CMOS imager are read out continuously during active imaging (Kumar et al. 2012b; Tandon et al. 2017c, 2020). The on-board processing of these frames depends on the mode. For INT mode, pixel values for the image within the selected Window constitute the detector data. On the
other hand, for PC mode, for each frame the part within the selected Window is processed to identify photon events from the light distribution and compute their centroid coordinates along 2 axes of the detector. The details of individual detected photon events constitute the imaging data for PC mode. In view of the above mentioned differences in the data emanating from the detector operated in INT/PC modes, the processing schemes employed in the pipeline are separately dedicated for each mode.

The key functionality of the pipeline is to translate UVIT measurements to astronomer ready sky images by recovering absolute aspect and the angular resolution in presence of various systematic effects and random perturbations of the spacecraft pointing. While the many processes involved to achieve it are rather complex, they are divided into two main themes:

(a) Extraction of the drift and disturbances to the optical axes of UVIT/spacecraft reference axes, and use these to combine the frames using shift and add algorithm.

(b) Generation of sky images of intensity and corresponding exposure arrays and uncertainty arrays, by applying all applicable corrections for instrumental effects, e.g. flat-field corrections and corrections for distortion as quantified in the calibration database.

Exposure arrays are required because exposure over the field varies due to drift of the pointing, and uncertainty arrays are required because the actual number of photons depends on flat field corrections in addition to the exposure and the intensity. Each of these have been implemented as stand alone processing chain handling UVIT single band data from one Episode of observation, named Relative Aspect (RA) and Level-2 imaging (L2) respectively. Given that two very different modes of operation of UVIT, viz., INT and PC, each chain gets further diversified into two, making in total four chains. The relevant chains are operated on individual Episode data sequentially since the L2 chain needs results from RA chain run for corresponding time range. Most common instance of processing of data from a specific Episode, involves execution of the RA chain on VIS band data to extract drift series followed by two separate executions of the L2 chain on NUV and FUV band data using the corresponding drift series. In the rare situation of absence of VIS data for the particular Episode, drift series is extracted using the NUV data. This sequence completes processing for one NUV data. This sequence completes processing for one Episode generating a complete set of resulting products. The most important ones are: UV sky images of intensity, exposure and statistical uncertainty arrays (4800 × 4800; pixel ~ 0.4 arc-sec) in both the detector as well as equatorial coordinate systems (along with astrometric corrections when successful), final corrected UV event table with details for timing studies.

As stated earlier, in general, the total exposure for a target with a specific Filter-Window configuration for an UV band would constitute multiple Episodes. Hence, additional processing are involved in combining the results from individual Episodes. The “combining” operation of multiple Episodes involves determination of relative shifts and rotations between UV images from individual Episodes and applying these corrections to align and then stacking. This is carried out in the following steps: identification of a ‘master’ Episode (with largest exposure); tabulation of stars and their centroid coordinates detected in the UV intensity image from each Episode; correlation of stars between ‘master’ and every other Episodes and determine shifts and rotations relative to the ‘master’; application of shifts and rotations to products of all non-master Episodes aligning them with the ‘master’ Episode; accumulation of corresponding products from all Episodes generating the final “combined” products. One important detail regarding generation of combined UV intensity image—the offsets for each Episode are applied to the centroids of individual photons first and finally gridding them on to a common array, thereby retaining the precision/angular resolution achieved in individual Episodes, even in the most general case for offset including a rotation in addition to shifts along the two axes. On the other hand, all shift and rotation operations for exposure and uncertainty arrays are performed on the array elements (following first sub-division to 9600 × 9600 then shift and rotation operations on sub pixels, re-gridding followed by binning back to 4800 × 4800 to minimize the loss of precision due to finite pixel size). The success of this scheme for combining critically depends on availability of bright enough UV stars in the field. Accordingly, the success rate for the FUV band is lower than that for the NUV band. The astrometric refinements are carried out on the combined multi-Episode UV images also. All the usual L2 products (except events list) are generated for the multi-Episode cases.

3. Evolution of the pipeline during early in orbit operations of UVIT

The development of the pipeline had begun well before the AstroSat/UVIT launch when the instrument details were frozen after engineering model was
realized successfully. The architectural and structural detail of the pipeline were finalized early on. Given the similarities of certain processes used in multiple chains, these were developed as modules. The chains called several such modules in appropriate sequences supplemented by unique processes dedicated for the chain. Once the laboratory data from UVIT detectors became available, many functionalities of the modules could be tested and validated. However, the real inputs for the pipeline, the L1 data bundles, became available only after UVIT was turned on in orbit. For the first time concurrent data originating from the spacecraft sub systems along with UVIT could enable testing of modules dependent on such interconnected dataset. Initially there were some surprises leading to discovery of minor oversights in the pipeline realization. This resulted in many additional features to be incorporated. Here we briefly describe a few of them.

It may be recalled that the data from the UVIT Filter drive units are collected directly by the spacecraft sub-system appearing in the Aux data in L1 as opposed to UVIT detector data from UVIT electronics as Science data stream. The L1 product introduces the Filter information in to detector data using time correlation between Aux and Science data. However, it was noticed that the reported identity of the Filter was incorrect at times. Since no credible reason could be attributed to this anomaly, UVIT POC devised a scheme to correct for this and generating a L1' data bundle, which was sent to ISSDC for archiving and dissemination.

As time progressed, the UVIT detector electronics was found vulnerable to charged particle hits (Single Event Effects/Latchups). This manifested as peculiar anomalies in the Science data stream rendering many logics of the pipeline to fail. A few examples are described here. The raw images of VIS band showed bright (pixel with higher ADU counts) stripes along one axis of the CMOS imager, which affected the success of star finding algorithm. Since the affected pixels appeared in a pattern and also constituted a negligible fraction, appropriate logic was developed and incorporated in the pipeline to address them without any loss of functionality (introducing a new block named “Artifact Handler”). As time progressed,

Figure 1. Example of stripes (along horizontal axis) in Quick Look image generated from VIS band images from one Episode. Such artifacts are handled successfully by the pipeline while extracting the drifts. A few curved tracks correspond to detected stars and their movement due to spacecraft drift during the observation Episode.
the number of such stripes increased (see Fig. 1.), which required further tweaking of the fix. Later, the positions of the stripes too started jumping around, which required completely new kind of logic to by pass them. Still, the RA_INT chain could successfully extract the drift series without any degradation of accuracy. Since mid-2017, no new kind of artifacts have been observed in the VIS band images and the current Artifact Handler continues to mitigate such effects successfully.

At times the Science data from successive Episodes for the NUV band showed extremely unusual patches rendering these dataset to be completely unusable (see Fig. 2). Fortunately, a power RESET could recover the NUV band from these artifacts.

The L1 dataset was expected to correlate UVIT’s internal clocks (one per band) to well calibrated Universal Time Clock (UTC) based on periodic simultaneous time sampling by the spacecraft. Hence, the pipeline was originally designed using UTC as the primary reference for time. However, often this time correlation was found to be unreliable. Accordingly an additional functionality was introduced in the pipeline which allows use of UVIT’s Master Clock for timing (UVIT is configured selecting an unique band, VIS, as Master for all the 3 bands ensuring inter-band time synchronization). This timing scheme has since been used successfully. Even, while by passing the UTC for primary processes in the pipeline, a parallel scheme has been introduced to provide approximate (good to \( \sim 1 \) s) absolute time (MJD_UT) for every frame, by identifying selected patches of time where UTC correlates well with the UVIT Master Clock. This allows timing studies using the pipeline product providing photon event table with all details including MJD_UT, even in UTC by passed mode.

In the L1 Science data for UV bands operated in PC mode, various anomalies were noticed. For example: jumps (spike) in Frame Number or Frame Time, completely discontinuous Frame Number and Frame Time inserted within normal good data sequence; data from a particular frame repeated elsewhere in the data from the same Episode; abrupt discontinuity in Frame Number which violated monotonicity. These artifacts were discovered gradually during early in orbit phase. Appropriate remedial logic were designed and incorporated within the DataIngest block of the pipeline.

### 4. Performance of the pipeline

The pipeline is routinely operated at the UVIT Pay-load Operation Centre (POC) at the Indian Institute of Astrophysics, Bangalore. The L1 data are regularly received by the POC from ISSDC/ISRO. The POC sends L1’ data (modified) and L2 product bundles.
back to ISSDC for dissemination to the Proposers and archiving. An installer for the pipeline, Calibration Database and relevant instructions are publicly available from the sites: https://uvit.iiap.res.in/Downloads; http://astrosat-ssc.iucaa.in/?q=uvitData; https://www.tifr.res.in/~uvit/.

Though the pipeline has undergone major evolution during the initial year or so, it has since stabilized and has been performing satisfactorily. The data for the early phase are also being re-processed using the last stable version at the POC.

The astrometric accuracy achieved over the central 24' diameter of the field is better than 0.3'' (rms), but it is not so good for larger diameters and the errors could be up to 0.8'' for parts of the outer annular region with radius between 12' and 14'. The photometric error, as determined from multiple observations of SMC fields, is found to be <6% (rms) (Tandon et al. 2020).

Two key parameters to quantify the success of the pipeline are: (a) size of the PSF and (b) the amount of L1 data incorporated in the final L2 sky products. The former checks not only the quality of drift tracking but also application of all corrections for systematic effects. Accordingly, the POC has devised a quality factor which grades the intensity image products from the FWHM size of the core of the PSF as well as the fraction of intensity in the pedestal, for a few point like sources spread across the field. The best value of the quality factor is ‘10’ gradually reducing with degradation to lower values. Figure 3 shows the distribution of the quality factor for a large sample of pipeline products. The quality report for every data set is always included in the standard L2 product bundle.

For a sizable fraction of the observations in both NUV and FUV bands, a score of 9 or above has been achieved. This implies the FWHM of the PSF to be < 1.8 arc-sec and the pedestal <20%.

The second aspect relates to the “yield” of the pipeline. The sum of exposure time of frames contributing to the final sky images (T_L2) is compared with the corresponding frames available in the L1 data set (T_L1), as a fraction, yield = (T_L2/T_L1). The distribution of yield among a large sample of datasets is presented in Fig. 4.

5. Future plans

The UVIT’s Level-2 pipeline has been performing quite satisfactorily as evidenced in the earlier section. However, at times some issues have hampered the generation of Merged L1 data sets. Since the L1 datasets corresponding to individual dump orbits are available, a scheme to stitch them in to pseudo merged L1 data has been developed at the POC. It has been planned to generate the missing merged L1 data using this scheme. Another plan for future augmentation of the pipeline is to utilize optical stars detected in VIS frames in the logic for combining multi-Episode data (instead of UV stars used currently). This would also help improving the success rate of astrometry block.

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