DATA PIPELINE

Curvit: An open-source Python package to generate light curves from UVIT data

P. JOSEPH1,2,*, C. S. STALIN1, S. N. TANDON3 and S. K. GHOSH4

1Indian Institute of Astrophysics, Bangalore 560 034, India.
2Department of Physics, CHRIST (Deemed to be University), Bangalore 560 029, India.
3Inter-University Centre for Astronomy and Astrophysics, Pune 411 007, India.
4Tata Institute of Fundamental Research, Mumbai 400 005, India.
*Corresponding Author. E-mail: prajwelpj@gmail.com

MS received 7 November 2020; accepted 2 December 2020

Abstract. Curvit is an open-source Python package that facilitates the creation of light curves from the data collected by the Ultra-Violet Imaging Telescope (UVIT) onboard AstroSat, India’s first multi-wavelength astronomical satellite. The input to Curvit is the calibrated events list generated by the UVIT-Payload Operation Center (UVIT-POC) and made available to the principal investigators through the Indian Space Science Data Center. The features of Curvit include: (i) automatically detecting sources and generating light curves for all the detected sources and (ii) custom generation of light curve for any particular source of interest. We present here the capabilities of Curvit and demonstrate its usability on the UVIT observations of the intermediate polar FO Aqr as an example. Curvit is publicly available on GitHub at https://github.com/prajwel/curvit.

Keyword. AstroSat—UVIT—variability.

1. Introduction

The Ultra Violet Imaging Telescope (UVIT; Tandon et al. 2017a, c), consisting of two co-aligned telescopes of aperture 375 mm each, is one of the payloads onboard AstroSat. AstroSat is India’s first multi-wavelength astronomical observatory, launched by the Indian Space Research Organisation (ISRO) on 28 September 2015 (Agrawal 2006). In addition to UVIT, there are three co-aligned X-ray payloads on AstroSat enabling simultaneous observation of a celestial source over a wide range of wavelengths from hard X-rays to the Ultraviolet (UV) band. UVIT, with a field of view of 28 arcminute diameter, can perform imaging and low-resolution slit-less spectroscopy. UVIT has a large number of filters and with selectable filters or gratings, simultaneous observations in far-ultraviolet (FUV, 1300–1800 Å), near-ultraviolet (NUV, 2000–3000 Å), and visible (VIS, 3200–5500 Å) channels are possible. Of the three channels, VIS channel is used only for aspect correction, while the NUV and FUV channels are used for science observations. The detectors used in all the three channels are intensified CMOS imagers with 512 × 512 pixels. The telescope pointing can drift up to 3' over the night time of an orbit (duration can be up to a maximum of 1800 seconds) with a rate of 3''/second. This drift of the satellite is estimated, as a function of time, using observations obtained with the VIS channel. In the normal mode of operations, observations are carried out in the full window mode (default mode, 512 × 512 pixels) covering 28 diameter arcminute field resulting in a read rate of ~28.7 frames/second. It is also possible to observe a partial field (that is selectable by the principal investigators (PIs) of the observing proposals) read at a higher rate. For example, the observation of a small window (100 × 100 pixels) will provide 640 frames per second. The NUV and FUV images are generated by
combining short exposure frames with shift and add algorithm. However, for bright fields, self drift correction of NUV data with NUV and FUV data with FUV is also possible. Two modes of operation exist in UVIT: (1) photon counting mode, achievable through high electron multiplication via high voltage to the microchannel plate of the intensified imager, in the case of NUV and FUV channels, where the intensified detectors record the X and Y positions of the photons on the detectors and their arrival times and (2) integration mode, achievable through a lower electron multiplication, for VIS channel where the readout consists of image frames with a time resolution of 1 second. In the final image obtained using photon counting mode, each detector pixel is mapped to 8 × 8 sub-pixels by the centroiding of photon events with each sub-pixel having a plate scale of 0.416″ (Hutchings et al. 2007; Postma et al. 2011). Due to the availability of time-tagged events in photon counting mode in FUV and NUV channels, it is possible to probe the time variability of observed sources in UV and generate light curves similar to other branches of high energy astronomy such as X-rays and γ-rays. UVIT has been performing as per specifications. More details and related calibration can be found in (Tandon et al. 2017b) and (Tandon et al. 2020).

The UVIT Payload Operation Center (POC) at the Indian Institute of Astrophysics (IIA) runs the UVIT Level-2 pipeline (UL2P; Ghosh et al. 2021, this volume) on the Level-1 (L1) data, containing both spacecraft and observational data in FITS format, to produce science ready Level-2 (L2) data products. A description of UVIT data reduction is given in (Postma & Leahy 2017) as well as Ghosh et al. (2021). The UVIT-POC processed L1 and L2 data are made available to the PIs of the observations through the ISRO Indian Space Science Data Center (ISSDC). The L2 data contains: (i) orbit-wise calibrated events list after corrections for the drift of the spacecraft, flat field, and distortion, (ii) orbit-wise science ready images in detector coordinate and world coordinate systems and (iii) combined images that belong to a single pointing, wherein observations in a particular filter carried out over many orbits in a particular pointing are combined. L2 data from ISSDC are science ready products, and the PIs can directly carry out their photometric, spectroscopic or imaging analysis. Alternatively, PIs willing to do a custom analysis of their observations can also do so, using UL2P, along with the CALDB (that contains the calibration data files) and the CATALOG (that contains the catalogues for astrometry) downloadable from ISSDC1, UVIT-POC2 or the AstroSat Science Support cell3.

Time variable phenomenon can be studied naturally using the "photon counting mode" of operation for the UV bands of image acquisition by UVIT. In principle, in the full window mode observations with UVIT, one can study time-varying phenomenon with a time resolution as low as 66 milliseconds in both the UV bands. Even higher time resolution is possible with smaller window observations (for example, ~3 milliseconds in 100 × 100 pixels window). Studies of such high-resolution events will open up a new avenue of research in UV Astronomy, and for such studies, software tools are required to generate the light curves directly from the events list. The motivation is therefore to develop a software tool, that has the ability to create light curves from the events list. Here we present Curvit, an open-source Python package designed to create light curves from UVIT L2 events list. Curvit makes use of the functionalities available in other open-source Python packages such as Astropy (Astropy Collaboration et al. 2013, 2018), NumPy (Harris et al. 2020), Matplotlib (Hunter 2007), Photutils (Bradley et al. 2020, and Scipy (Virtanen et al. 2020). The availability of this tool to the PIs of UVIT will also avert the cumbersome task of first creating images of small time-bins and then doing the photometry of the target to generate light curves. gPhoton is a similar tool to create UV light curves from GALEX data (Million et al. 2016). Section 2 contains a short summary of the L2 products at ISSDC. In Sections 3 and 4, we describe the functionalities and working of the tool. In the final section, we demonstrate the usefulness of the tool by generating the light curve of intermediate polar FO Aquarii (FO Aqr), observed under the guaranteed time and now open for public after the lock-in-period.

2. UVIT data products at ISSDC

The UVIT data is available at ISSDC AstroBrowse website4. Both L1 and L2 data of UVIT are available as compressed files at the archive. L2 products are organised into two categories: individual datasets (single orbit for a filter and window; see Table 1), and combined datasets over all the orbits (for a single filter

---

1http://www.issdc.gov.in/.
2http://uvit.iiap.res.in/.
3http://astrosat-ssc.iucaa.in/.
4https://astrobrowse.issdc.gov.in/astro_archive/archive/Home.jsp.
and window; see Table 2). The UVIT filters are given in Table 3.

3. Curvit workflow

Curvit\(^5\) is an open-source Python package to produce light curves from UVIT data. The events list from the official UVIT L2 pipeline (version 6.3 onwards) is required as an input to the package. Curvit has two functions for light curve creation: makecurves and curve. Both the functions accept a single events list at a time which the user has to provide. We describe below each of these functions and its usage on the observation of the intermediate polar FO Aqr.

\(^5\)https://github.com/prajwel/curvit.

3.1 Function makecurves

The makecurves function of Curvit automatically detects sources from the events list and create light curves for all of them. The user will have a control on the number of sources detected automatically through the use of the detection threshold parameter. Two source detection methods are available; daofind and kdtree. The user can select the preferred source detection method using the detection_method parameter (the default value is daofind).

The daofind method detects sources in the following manner. It first creates a 4800 × 4800 sub-pixel\(^2\) image from the events list and a circular mask is applied to select the central ~24 arcminute region. Sources are then detected using the daofind algorithm (Stetson 1987). Mean and standard deviation values of

---

Table 1. Details of the data products sent to ISSDC for each orbit of observation done in a particular window-size and filter.

| Product                                      | Description                  | RAS VIS\(^\star\) | RAS NUV\(^\star\) | Total |
|----------------------------------------------|------------------------------|-------------------|-------------------|-------|
| Sky image (instrument coordinates)          | 4800 × 4800 sub-pixel\(^2\) FITS image | 1 1 1 1 1 4       |                   |       |
| Sky image (astronomical coordinates)        | 4800 × 4800 sub-pixel\(^2\) FITS image | 1 1 1 1 1 4       |                   |       |
| Exposure map (astronomical coordinates)     | 4800 × 4800 sub-pixel\(^2\) FITS image | 1 1 1 1 1 4       |                   |       |
| Error map (astronomical coordinates)        | 4800 × 4800 sub-pixel\(^2\) FITS image | 1 1 1 1 1 4       |                   |       |
| Photon events list                          | FITS binary table            | 1 1 1 1 1 4       |                   |       |
| RAS file                                    | FITS binary table            | 1 1 1 1 2         |                   |       |

\(^\star\)The above file structure corresponds to the ideal case when VIS, NUV, and FUV are configured by the PI. In the event of VIS not being configured, the files generated using the relative aspect series (RAS) obtained from VIS data will be missing. Similar is the case for NUV.

Table 2. Details of the combined data products sent to ISSDC. The observations carried out over the entire pointing are combined filter wise.

| Product                                      | Description                  | RAS VIS | RAS NUV | Total |
|----------------------------------------------|------------------------------|---------|---------|-------|
| Sky Image-A\(^\star\) (Astronomical coordinates) | 4800 × 4800 sub-pixel\(^2\) FITS image | 1 1 1 1 1 4       |         |       |
| Sky Image-B\(^\star\) (Astronomical coordinates) | 4800 × 4800 sub-pixel\(^2\) FITS image | 1 1 1 1 1 4       |         |       |
| Exposure map\(^\star\) (Astronomical coordinates) | 4800 × 4800 sub-pixel\(^2\) FITS image | 1 1 1 1 1 4       |         |       |
| Error map\(^\star\) (Astronomical coordinates) | 4800 × 4800 sub-pixel\(^2\) FITS image | 1 1 1 1 1 4       |         |       |

\(^\star\)Sky image-A: The astrometric accuracy of this image is limited to the accuracy of knowledge of the spacecraft aspect, which is typically around 2–3 arcmin.

\(^\star\)Sky image-B: This is the final image generated after astrometry which may or may not be successful. When the astrometry is successful, the accuracy in aspect is typically 3 arcsec. When the astrometry is not successful, this image is a copy of sky image-A. The information about astrometry being successful or unsuccessful is available in the header of the FITS images.

\(^\star\)They correspond to the coordinate system of sky image-B.
the background, required by *daofind*, are estimated by *Curvit* itself and the user can control the number of sources detected using the *threshold* parameter. Pixels in the image that have the events greater than the threshold times the standard deviation of the background will be detected.

The *kdtree* method works as follows. A source is characterised by a cloud of events around its centroid. Therefore, to detect sources, the events are projected onto a two-dimensional Cartesian grid (with one grid cell being of 1 sub-pixel\(^2\) size), and the grid cells are sorted based on the number of events falling in each cell. Since a single source can occupy multiple grid cells, a nearest neighbour search using *kdtree* algorithm is performed to remove grid cells belonging to the same source (Maneewongvatana & Mount 1999). This method may not work properly on crowded fields. But in non-crowded fields, the method can detect all the sources present in the events list. However, the user may limit the number of sources to be detected using the parameter *how many*. Also, the aperture radius that is used to count the source events (through *radius*) and the size of the time bin to generate the light curves (using the parameter *bwidth*) can be controlled by the user.

The function *makecurves* generates light curves for each detected sources that depend on the threshold set by the user in terms of decreasing order of brightness. The operation of the function is summarised in Fig. 1.

### 3.2 Function curve

The function *curve* is similar to *makecurves*, with the exception that it generates light curve for a single user-defined source (through *xp* and *yp* parameters).

### 4. Light curve creation

From the events list FITS table, the columns Fx, Fy, MJD\_L2 and EFFECTIVE\_NUM\_PHOTONS (hereafter ENP) are used by *Curvit* (see Table 4). However, the events list FITS table has more columns than the ones given in Table 4. Each row of the table characterises a single event defined by X and Y Cartesian coordinate positions (Fx and Fy) with an associated time value (MJD\_L2). For the L2 data available from ISSDC, MJD\_L2 provides only an approximate absolute time, good to \(\sim 1\) second. The time values in MJD\_L2 column increment as the frame number (as denoted in the FrameCounts column of events list) changes. Therefore, MJD\_L2 column can be considered as a proxy for FrameCounts column. ENP column stores the counts/second contribution from that specific event (row of the table) after including instrumental correction like flat-field across the detector (Ghosh et al. 2021, in preparation). In the methods mentioned below, each event is weighted as per the corresponding ENP value.

For a given source coordinate position, it is possible to define an aperture of some radius in the detector coordinate system \((x, y)\) and select only those events (rows of the table) which fall inside the aperture. Thus, a subset table can be created from the original table. Here, the term original table is used to refer to the input events list table. The subset table will have only those events of the original table, that is assumed to be solely coming from the source. We will refer to the time values (equivalent to frame numbers) in the

### Table 3. The UVIT filters in VIS, NUV and FUV channels.

| Filter ID | Old filter name | New filter name | Filter ID | Old filter name | New filter name | Filter ID | Old filter name | New filter name |
|-----------|----------------|----------------|-----------|----------------|----------------|-----------|----------------|----------------|
| F1        | VIS3           | V461W          | F1        | Silica - 1     | N242W          | F1        | CaF2 - 1       | F148W          |
| F2        | VIS2           | V391M          | F2        | NUVB15         | N219M          | F2        | BaF2           | F154W          |
| F3        | VIS1           | V347M          | F3        | NUVB13         | N245M          | F3        | Sapphire       | F169M          |
| F4        | ND1            | V435ND         | F4        | Grating        |                | F4        | Grating - 1    |                |
| F5        | BK7            | V420W          | F5        | NUVB4          | N263M          | F5        | Silica         | F172M          |
|           |                |                | F6        | NUVN2          | N279N          | F6        | Grating - 2    |                |
|           |                |                | F7        | Silica - 2     | N242Wa         | F7        | CaF2 - 2       | F148Wa         |
subset table as subset-time. Also, a separate array of unique time values is created from the original table. We will call this array as original-time.

Using the resultant two arrays of time (subset-time and original-time), two separate histograms are created. The number of bins (same for both histograms) to be used is determined from the user-provided bin width (see Appendix A). For subset-time, the histogram can be interpreted as the number of events per bin coming from the source. Whereas histogram of original-time should ideally give a constant value per bin. For example, if bin width is set to 1 second, one should always get \( \sim 28.7 \) frames per second at all the bins for 512 \( \times \) 512 mode. However, if some frames are missing (for example, due to large telescope drift or missing data), this will be reflected as reduced values in the original-time histogram. Therefore correction for missing frames is carried out using the original-time histogram (see Appendix B for a detailed explanation).

By taking the ratio of two histograms, counts per frame (CPF) array is obtained. CPF array is then multiplied by frame-rate (\( \sim 28.7 \) for 512 \( \times \) 512 mode; the user may specify the frame-rate using the framecount_per_sec parameter) to obtain the counts per seconds (CPS) array. Finally, the CPS array is plotted against time as the light curve. The user is advised to look for variability in sources within the central 20 arcminute region to reduce telescope drift effects.

Figure 1. Flowchart for the function makecurves in Curvit.
4.1 Background, aperture, and saturation corrections

Estimation of background CPS can be obtained by manually specifying a background region \((x_{bg} \text{ and } y_{bg})\) and aperture size \((sky\_radius)\). It is also possible in Curvit to automatically determine background count-rate. To do this, a two-dimensional (2D) histogram of events with \(16 \times 16\) sub-pixel\(^2\) bin size is created. A mask is applied on the 2D histogram to select only the central \(\sim 24\) arcminute region. As opposed to a source, a background region will not have the crowding of events around some centroid and have a comparatively low number of events in a 2D histogram bin containing it. Also, the values of histogram bins containing background regions are assumed to be normally distributed. Therefore, the bins with sources are removed using sigma clipping of the 2D histogram values and locations of background histogram bins are randomly selected to estimate the mean sigma clipped background count-rate using an aperture size of \(sky\_radius\).

The end-user has also the option to apply aperture and saturation corrections using \(aperture\_correction\) and \(saturation\_correction\) parameters. Depending on the size of the radius used, the measured CPF will change. This difference is represented as a table of encircled energy at radii from 1.5–95 sub-pixels for both UV channels in (Tandon et al. 2020). Cubic
interpolation was used to create a continuous function mapping radius to encircled energy in the stipulated range. From the encircled energy, aperture-corrected CPF can be represented as follows:

\[
\text{Aperture-corrected CPF} = \frac{\text{Measured CPF}}{\text{Encircled energy} \times 100}
\]

Thus, aperture correction is applied to CPF values in each bin.

If the average photon rate per frame is not \( \ll 1 \), the effects of saturation will make the measured CPF different from the real CPF by a value of RCORR. As long as the measured CPF is \(< 0.6\), RCORR can be estimated as below (Tandon et al. 2017b):

\[
\text{ICPF5} = - \ln(1 - \text{measured CPF}),
\]

\[
\text{ICORR} = \text{ICPF5} - \text{measured CPF},
\]

\[
\text{RCORR} = \text{ICORR} \times (0.89 - (0.30 \times \text{ICORR}^2)),
\]

\[
\text{Real CPF} = \text{Measured CPF} + \text{RCORR}.
\]

Following the method above, saturation correction is applied to CPF values in each bin.

4.2 Zero event frames and centroid parity errors

When the total count-rate for the observed region is small, then there will be many frames with no events; as the total count-rate go down, the fraction of zero event frames go up. This can be modelled using Poisson statistics (Tandon et al. 2017b).

\[
F_{0\text{total}} = \exp(-X_{\text{total}}),
\]

where \( X_{\text{total}} \) is the CPF for the whole field of view and \( F_{0\text{total}} \) is the fraction of frames with no events (see Fig. 3). For \( X_{\text{total}} \) values above 4.6, the \( F_{0\text{total}} \) is less than 1% and \( F_{0\text{total}} \) is less than 5% for \( X_{\text{total}} \) values above 3. Since original-time histogram is used to account for the missing frames, CPF values for the source will be overestimated depending on \( X_{\text{total}} \) value.

Additionally, a small fraction of the events (less than 0.01%) can be lost due to centroid parity errors. Since both zero event frames and centroid parity errors are randomly distributed, any light curves with periodicity and/or high count-rate can be taken to be having true variability.

Table 4. Sample events list that show only the columns used by Curvit.

| Frame counts | Fx   | Fy   | ENP  | MJD_L2          |
|--------------|------|------|------|-----------------|
| 3            | 2461.9 | 2918.0 | 28.5  | 213453019.048   |
| 3            | 3139.5 | 3651.2 | 25.6  | 213453019.048   |
| 4            | 875.9  | 2924.2 | 23.8  | 213453019.084   |
| 4            | 1444.0 | 3605.5 | 23.7  | 213453019.084   |
| 5            | 3355.4 | 1229.8 | 25.6  | 213453019.120   |
| 5            | 3216.9 | 1497.7 | 26.3  | 213453019.120   |
| 5            | 2798.5 | 3836.8 | 25.7  | 213453019.120   |
| 6            | 3113.4 | 2230.7 | 27.5  | 213453019.156   |
| 6            | 4367.8 | 2483.6 | 20.7  | 213453019.156   |

Figure 3. Fraction of frames with no events as a function of total counts per frame.

Figure 4. The sources that are detected within the central 24 arcminute region (dashed circle) by makecurves.
5. Test on sample data

We took the publicly available L2 data (UL2P version 6.3) of FO Aqr (observation ID: G06_084T01_9000000710) from the ISSDC AstroBrowse website. As an example, the Curvit software was run on L2 events lists that correspond to observations with the FUV filter F148W to create light curves. Using makecurves function with the detection threshold value of 4, six sources were automatically detected and Curvit generated light curves for all of them (Fig. 5).

They are labelled as (a) to (f) in Fig. 4. An aperture radius of 6 sub-pixels (2.5 arcseconds) and time bin of 50 seconds was used. The observed variance ($\Sigma^2$) of each of the light curves in Fig. 5 is due to contributions from intrinsic source variability and measurement uncertainty. In the event of the source being non-variable, the contribution of source variability to the observed variance is zero. Therefore variance becomes equal to the average value of squared errors ($\sigma^2$) of the light curve points. For each light curve, we calculated the variance and the mean of squared errors in the points.

Figure 5. Light curves generated by the makecurves function in Curvit.
and the ratio $R = \frac{\Sigma^2}{\sigma^2}$. For non-variable sources, this ratio $R$ will be close to unity, and a source is considered variable if $R$ is much larger than unity. The values of $R$ calculated for the light curves of all the sources is given in Table 5.

We also calculated the normalised excess variance, $F_{\text{var}}$, for the light curves to test the significance of their variations following (Rani et al. 2019). For variable sources, $F_{\text{var}}$ will have a real and positive value (see Table 5). It is evident from Table 5 that only for the source (a), namely FO Aqr, (i) the ratio $R$ is much larger than unity and (ii) $F_{\text{var}}$ is much larger than the error in $F_{\text{var}}$. These indicate that the larger variance of the source (a) is due to the intrinsic variability of the source. Though sources (c) and (d) have real and positive $F_{\text{var}}$ values, and $R$ greater than unity, for (c) the error in $F_{\text{var}}$ is much larger than $F_{\text{var}}$ itself and for (d) $F_{\text{var}}$ is not that significant considering its error. Thus from the light curves of sources (a) to (f), statistical tests confirm that only source (a) is variable. We note that the light curves of the sources presented here pertain to one orbit of data and such an analysis of one orbit data can only pick out short-period variables and will miss out long-period variables. Therefore, for sources where the period of variability is much longer than the one orbit data presented here, it is advisable to generate light curves for the complete observation (that can spread over many orbits), which might amount to carrying out photometry on each orbit wise images and then check for the presence of variability.

6. Conclusion

The UVIT-POC at IIA processes the L1 data for UVIT received from ISSDC, generates science ready L2 products and transfers both the corrected L1 and L2 products to ISSDC for archival and dissemination to the PIs. Among the various files sent to ISSDC is the calibrated orbit-wise photon events list. The Curvit software tool presented here is a standalone package in Python that can generate light curves from the events list. This overcomes the cumbersome task of first creating images at any time resolution from the events list and then doing photometry on the images to generate the light curves of any desired object in the observed field. The Curvit package has the capability to (1) generate light curves for all the sources in the observed field detected above a threshold for any time binning given by the user and (2) generate light curve for any particular source at any time binning desired by the user. We have also shown an example light curve of a target FO Aqr observed by UVIT. Curvit is publicly available on GitHub at https://github.com/prajwel/curvit.

Acknowledgements

This publication uses the data from the AstroSat mission of the Indian Space Research Organisation (ISRO), archived at the Indian Space Science Data Centre (ISSDC). This publication uses UVIT data processed by the payload operations centre at IIA. The UVIT is built in collaboration between IIA, IUCAA, TIFR, ISRO and CSA.

Appendices

Appendix A. To estimate the number of bins

To calculate the number of bins, the very first and last values of the original-time array is taken to estimate the width of the time array. Then, the time array width is divided by the bin width, and integer part of the resultant value is taken as the number of bins.

$$\text{Number of bins} = \frac{\text{original time width}}{\text{bin width}}. \quad (A1)$$

Appendix B. Missing frame correction

Assume that an ideal non-variable source has a flux of 0.1 CPF (or $\sim 2.87$ CPS for $512 \times 512$ mode). If the bin width were set to 1 second, then the subset-time histogram would be as follows:

$$[2.87, 2.87, 2.87, 2.87, 2.87, 2.87, \ldots].$$

However, if some of the frames vis-a-vis rows are missing from events list FITS table, we might get an array as given below:

$$[2.87, 2.53, 1.01, 2.84, 1.94, 2.87, \ldots].$$

Table 5. Variability measure of detected sources.

| Source | $\Sigma^2/\sigma^2$ | $F_{\text{var}}$ | $F_{\text{var}}$ error |
|--------|---------------------|-----------------|------------------------|
| a      | 11.87               | 0.14            | 0.02                   |
| b      | 0.88                | –               | –                      |
| c      | 1.01                | 0.04            | 0.58                   |
| d      | 1.39                | 0.38            | 0.16                   |
| e      | 0.35                | –               | –                      |
| f      | 0.61                | –               | –                      |
A false variability can be inferred from the above array. To overcome this, the original-time histogram is used. The missing frames will be reflected as a reduced number of events per bin in original-time histogram. For the case above, the original-time histogram would be as follows:

\[28.7, 25.3, 10.1, 28.4, 19.4, 28.7, \ldots].\]

By taking the ratio of two histograms, the real light curve in CPF is obtained as follows:

\[0.1, 0.1, 0.1, 0.1, 0.1, 0.1, \ldots].\]

CPF is then converted to CPS by multiplying with the frame-rate (\(\sim 28.7\) for \(512 \times 512\) mode).

References

Agrawal P. 2006, A broad spectral band Indian Astronomy satellite ‘Astrosat’, Advances in Space Research, 38, 2989, Spectra and Timing of Compact X-ray Binaries
Astropy Collaboration: Robitaille T. P., Tollerud E. J. et al. 2013, Astropy: A community Python package for astronomy, A&A, 558, A33
Astropy Collaboration: Price-Whelan A. M., SipHocz B. M. et al. 2018, The Astropy Project: Building an Open-science Project and Status of the v2.0 Core Package, Astron. J., 156, 123
Bradley L., Sipőcz B., Robitaille T. et al. 2020, astropy/photutils: 1.0.1, https://doi.org/10.5281/zenodo.4049061
Harris C. R., Millman K. J., van der Walt S. J. et al. 2020, Nature, 585, 357362
Hunter J. D. 2007, Matplotlib: A 2D graphics environment, Computing in Science & Engineering, 9, 90
Hutchings J. B., Postma J., Asquin D., Leahy D. 2007, PASP, 119, 1152
Maneewongvatana S., Mount D. M. 1999, in Center for Geometric Computing 4th Annual Workshop on Computational Geometry, vol. 2, 1–8
Million C., Fleming S. W., Shiao B., Seibert M., Loyd P., Tucker M., Smith M., Thompson R., White R. L. 2016, Astrophys. J., 833, 292
Postma J., Hutchings J. B., Leahy D. 2011, PASP, 123, 833
Postma J. E., Leahy D. 2017, PASP, 129, 115002
Rani P., Stalin C., Goswami, K. D. 2019, MNRAS, 484, 5113
Stetson P. B. 1987, PASP, 99, 191
Tandon S., Stalin C., Subramaniam A., Ghosh S., Hutchings, J. 2017a, Curr. Sci., 113, 583
Tandon S. N., Subramaniam A., Girish V. et al. 2017b, Astron. J., 154, 128
Tandon S. N., Hutchings J. B., Ghosh S. K. et al. 2017c, J. Astrophys. Astron., 38, 28
Tandon S. N., Postma J., Joseph P. et al. 2020, Astron. J., 159, 158
Virtanen P., Gommers R., Oliphant T. E. et al. 2020, Nature Methods, 17, 261