Saturation Correction for Extended Sources observed with UVIT

S N Tandon, IUCAA   September 18, 2022;

Introduction:

Ultraviolet Imaging Telescope (UVIT) Is the ultraviolet eye of multi-wavelength astronomy satellite ASTROSAT, launched in the year 2015. UVIT is primarily an imaging instrument, consisting of two co-aligned Cassegrain telescopes each of diameter ~ 375 mm and an f/12 focus, with a field of view of ~ 28′, for observing simultaneously in NUV (200 nm – 300 nm) and FUV (130 nm – 180 nm) with a spatial resolution < 1.5″. One of the two telescope observes in FUV, while the other observes in NUV and visible band. In each of the two ultraviolet ranges a narrow range can be selected through a set of filters mounted on a wheel kept close to the focal plane. The filter wheels also carry gratings for slitless low resolution (80-100) spectroscopy. Simultaneous observations are also made in visible range for keeping track of any drift in pointing of the satellite. A drawing of mechanical configuration of the instrument is shown in Fig. 1. More details of design and operation of the instrument can be found in Tandon et al (2017B).

Fig. 1: Mechanical configuration of UVIT. Internal view of one of the twin telescope Is shown. Each of the telescopes is a Cassegrain system with a primary mirror of diameter ~ 375 and the focal ratio of 1/12. A baffle is used in front to control the off-axis light, and a door is used for isolation to minimise contamination. The door is opened about six weeks after

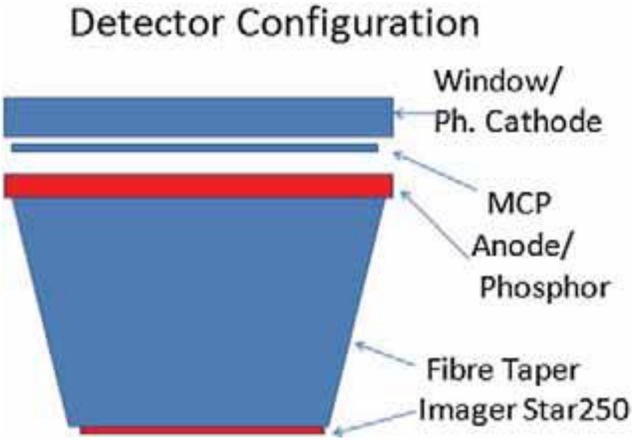
reaching in the orbit. The door is also used as sun-shield. The filters and gratings are placed about 40 mm in front of the detectors. One of the two telescopes observes in FUV while the other observes in NUV and VIS through division of the light by a dichroic mirror.

The UV observations are made in photon counting mode, and in each individual reading element only one photon can be detected and if more than one photons occur in any element those are counted as one, and this in effect leads to saturation. There are two kinds of popular photon counting imaging detectors. In one of these each detected photon, after being amplified to a pulse of ~ a million electrons, is read-out and located by a grid of electrodes, e.g. detectors of Galex, and if more than one photons are detected within time-resolution of the read-out these are read out as one. In the other each detected photon deposits a pulse of light on a solid state imager, and the imager is read periodically to locate the detected photons. The latter method is employed in UVIT. The individual pulses occupy ~ 3X3 pixels of the imager, and if more pulses are caused by other photons within these pixels only one photon is counted. For the point sources, a prescription has been given in Tandon et al (2017) to calculate correction for such a saturation. The process required for correcting saturation in an extended source would be more complex. Here, we describe an approximate procedure to correct for mild saturation in extended sources. In the following we first describe some details of detecting photons in UVIT and the process of saturation, next a simple procedure for estimating the saturation is presented, and in the end the limitations of the presented process are discussed.

Detection of Photons

The detectors in UVIT use MCP for multiplication of the photo-electron generated by the photo-cathode to generate an electron pulse (~ a million electrons), conversion of the electron-pulse in a light pulse (several million photons) on a fluorescent screen, and imaging of the light pulse by a CMOS-imager through a fibre-taper for reduction of size by a factor ~3. The photo-cathode has a diameter of ~ 39 mm and the CMOS-imager has 512X512 pixels of 0.025 mm X0.025 mm. The plate scale on the imager is ~ 3.3" per pixel. A sketch of the detector is shown in Fig. 2.

Fig. 2: Detector module



The footprint of the light pulse is roughly Gaussian with a FWHM of ~ 0.09 mm on the fluorescent screen and is reduced to a FWHM of ~ 0.03 mm by the fibre-taper. Thus the footprint is almost fully contained within 3X3 pixels of the imager. In the most common mode of operation full CMOS-frames are read every ~ 34 ms; for a faster readout rate, and partial frames smaller windows around the field centre can be read to reduce photon number per frame, e.g. for a partial frame window size of 100X100 pixels a rate of ~ 600 frames per second can be obtained. *For minimising any confusion, before going further we clarify that by "photon" we always mean a photon falling on the detector and by "photon-event" we mean a photon detected by a detector*. Photon events are found by looking for pixels which have a signal above a threshold and are brighter than all the neighbouring pixels or the brightest in a 3X3 window. The position of each event is defined by centroid of the signal distribution in 3X3 pixels surrounding these pixels. If two or more photons fall within a window of 3X3 pixels, these would be counted as a single photon located in the pixel having the largest signal. Let us consider a patch of 3X3 pixels which have average photon number per frame as "C_{-1-1}, C_{0-1}, C_{1-1}, C_{-10}, C_{00}, $C_{1,0}$, C_{-11}, C_{01}, C_{11}"where "C_{00}" refers to the central pixel.

Fig. 3 Pixels' counts

$C_{-1\,1}$	$C_{-0\,1}$	C_{11}
$C_{1\,0}$	$C_{-0\,0}$	$C_{0\,1}$
$C_{-1\,-1}$	$C_{-0\,-1}$	$C_{1\,-1}$

For a given average number per frame, the probability for occurrence of "0", "1", "2" or more photons can be estimated from Poisson distribution. Given the logic of detecting photon-events, as explained earlier, in any frame only one photon-event is counted in these 9 pixels even if more than one photon falls on these. Here we work with a simplified model, which ignores the large random variation in the total signal of photon-events. It can be described as follows:

If one photon falls on each of any "n" pixels, one photon-event is assigned to one of these "n" pixels in a random fashion. Similarly, if "N" photons fall on each of "n" pixels, one photon is assigned to one of the "n" pixels in a random fashion. However, if "N" photons fall on any pixel and the number of photons falling on any of the other eight pixels is <N, the pixel with "N" photons is assigned one photon-event.

Poisson statistics can be invoked to list probability for different distributions of the number of photons falling on the pixels. Let us consider a simple case where the average number is uniform over the pixels and is << 1 /frame per pixel such that we can ignore the small fraction of those frames which get two or more photons in more than one of the nine pixels. The probabilities for different distributions of photon numbers are listed below:

Photon Number		Probability	Effective Photon-events in the central pixel
Central pixel	Other pixels		
0	0	exp(-9x)	none
1	0 in all	exp(-9x)*x	one
1	1 in 1 pixel	8*exp(-9x)*x^2	one/two
1	1 in 2 pixels	28*exp(-9x)*x^3	one/three
1	1 in 3 pixels	56*exp(-9x)*x^4	one/four
1	1 in 4 pixels	70*exp(-9x)*x^5	one/five
1	1 in 5 pixels	56*exp(-9x)*x^6	one/six
1	1 in 6 pixels	28*exp(-9x)*x^7	one/seven
1	1 in 7 pixels	8*exp(-9x)*x^8	one/eight
1	1 in 8 pixels	exp(-9x)*x^9	one/nine
=>2	either 0 or 1	(1-exp(-x)*(1 + x))	one

Here, “x” is the average count per pixel per frame, first number in the expression of the third column is the number of different combinations within the eight pixels. Further, as explained earlier, if a photon falls in each of “m” pixels, one photon-event to assigned to one of the “m” pixels in a random fashion. The last row is based on the assumption that only one of the nine pixels can have =>2 photons in any frame.

Correction for Saturation

Here we illustrate the calculation for a case of uniform intensity of 0.1 photons per pixel per frame. Following the simplified procedure described above, estimate of the rate of photon-events in the central pixel is shown in Table 1.

Table 1: The first two columns give actual number of photons in the frame for the central pixel and the other eight pixels, the third column gives the probability of such an occurrence, the fourth column gives the effective photon counts on the central pixel per frame for frames with such occurrence, and the last column gives contribution of such frames to average counts per frame in the central pixel.

Photon Number Central pixel	 Other pixels	Probability	Effective Photon-events in the central pixel	Contribution per observed frame
0	0	0.40657	none	0
1	0 in all	0.04066	one	0.04066
1	1 in 1 pixel	0.03253	one/two	0.01627
1	1 in 2 pixels	0.01138	one/three	0.00379
1	1 in 3 pixels	0.00228	one/four	0.00057
1	1 in 4 pixels	0.00028	one/five	0.00006
1	1 in 5 pixels	0.00002	one/six	0
1	1 in 6 pixels	0	one/seven	0
1	1 in 7 pixels	0	one/eight	0
1	1 in 8 pixels	0	one/nine	0
=>2	either 0 or 1	0.00468	one	0.00468

Summation of last column of all the rows gives the average observed photon-events as 0.06603, i.e. the actual rate of 0.1 per pixel per frame for the photon flux the observed rate of photon events is only 0.06603. Following a similar procedure we can estimate the observed rate of photon-events for different rate of photons. The results are shown in Table 2.

Table 2: First column gives the actual counts of photons, second column gives counts for observed photon-events, and third column gives the ratio of the counts of photons to the counts of the observed photon-events.

0.1	0.06603	1.5146
0.09	0.06174	1.4577
0.08	0.05706	1.4019
0.07	0.05196	1.3473
0.06	0.04637	1.2938
0.05	0.04027	1.2416
0.04	0.03359	1.1907
0.03	0.02629	1.1410
0.02	0.01830	1.0927
0.01	0.00956	1.0457

For calculation of the correction the starting point would be the observed counts. If we assume that the observed counts are the actual counts the calculated correction would be an underestimate. Let us take example of real rate of 0.07 which would be observed as a rate of ~ 0.052. An estimate of the correction factor for 0.052 would give a value ~ 1.24, i.e. the actual rate would be inferred as ~ 0.052 *1.24 ~ 0.064. Thus, for the real rates up to 0.07 the first order estimate of the correction gives a result within 10% of the correct value. If we estimate the correction factor with the inferred corrected rate of ~ 0.064, we shall get a value ~ 1.3 and applying it to the original observed rate of ~ 0.052 we get the corrected rate as ~ 0.068. If we do the same exercise for real rate of 0.1, we shall get the corrected rate (with the two step process described above) as ~ 0.095. We infer that for nearly uniform intensities up to 0.1 photon per pixel per frame, the above procedure gives acceptable correction for saturation.

Conclusion

A simple procedure for estimation of the saturation correction in UVIT images for extended sources has been presented. It has been shown that for nearly uniform intensity the process works well for rates < 0.1 photon per pixel per frame (each pixel is ~ 3.3" across).

A similar process can be used for the spectral images of point sources. As most of the energy in PSF is contained within 3X3 pixels, a simplified 1-D version of the procedure can be used, after collapsing the image on a single row along the dispersion axis, in which only the two neighbouring pixels would contribute to the saturation in any pixel.

References: …

Tandon, S. N., Subramaniam, Annapurni, Girish, V. et al, 2017, The Astronomical Journal, 154, p 128

Tandon, S. N., Hutchings, J. B., Ghosh, S. K., et al. 2017B, JApA, 38, 28

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