Large Area X-ray Proportional Counter (LAXPC)

Calibration and Data Reduction

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I thank all members of LAXPC and ISRO team for support and guidance.

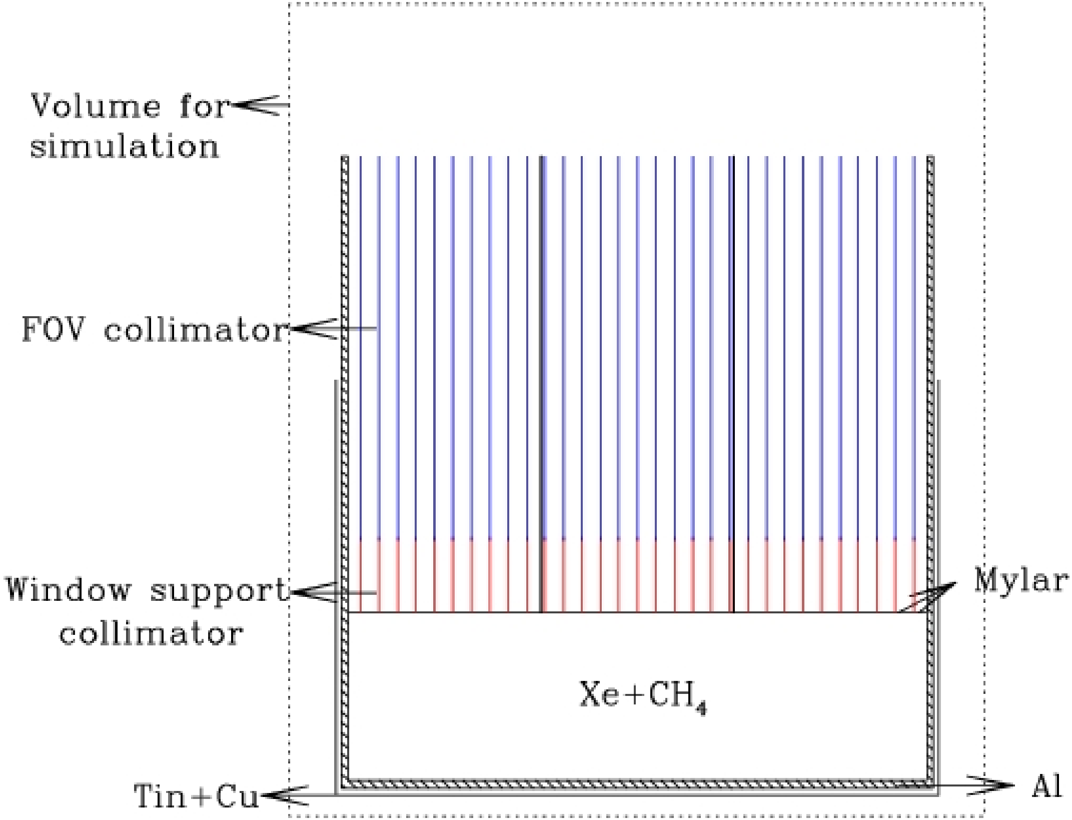
LAXPC website: http://www.tifr.res.in/~astrosat_laxpc

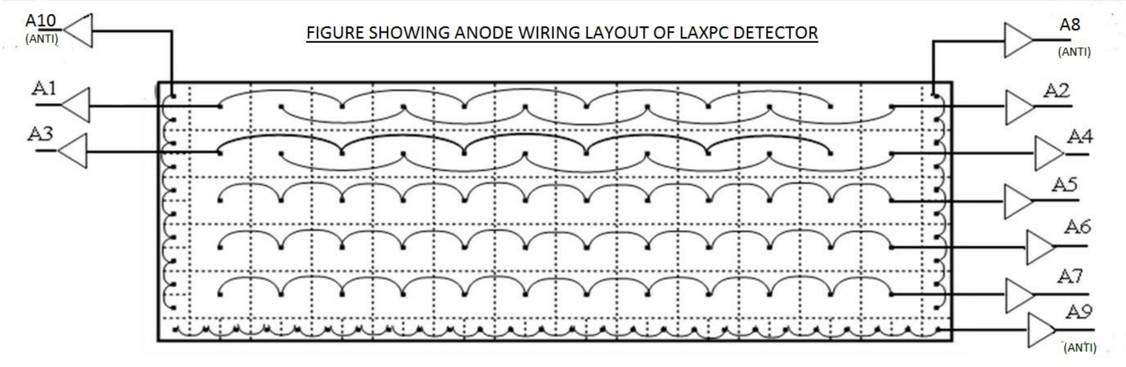
- LAXPC payload consists of 3 large area X-ray proportional counters

- Detector size: $100 \times 39 \times 16.5$ cm filled with a mixture of Xenon (90%) and Methane (10%) at a pressure of 2 atmospheres.

- Top of the detector is covered by a $50\ \mu$m thick Mylar window

- Above the Mylar window there is a window support collimator of height 7.5 cm and the field of view collimator of height 37 cm. These collimators have mesh with a pitch of 7 mm.


Volume for
simulation
FOV collimator
Window support
collimator
Mylar
$Xe+CH_4$
Tin+Cu
Al



Main Anodes : A1–A7 in 5 layers

Veto Anodes : A8, A9, A10 on 3 sides

No Veto Anodes on two small sides (39×16.5 cm)

Mylar and collimator on the top side

- GEANT4 simulations of the detector were performed for estimating the background and field of view as well as to calculate the response matrix for the detectors.

- Each simulation had 10^6–10^7 photons with fixed energy.

- Initial Photon trajectory is normal to detector top (except for FOV and background)

- Uniformly distributed over detector area.

- For background simulation the flux is assumed to be uniform and isotropic.

To reject background events the following logic is implemented which is consistent with the processing electronics:

- Any event that is recorded in veto-anodes (A8–A10)
- Any event that deposits more than an upper limit (80 keV) in any anode
- Any event that is recorded in more than 2 main anodes (A1–A7)
- If an event is recorded in two main anodes, then it is accepted only if at least one of the energy is in K-threshold for Xe (30 ± 4.5 keV). If the event is accepted the energies in two anodes are added and it is recorded as an event of combined energy. Such events are referred to as double events.

Detector Calibration using Radioactive Sources

- Three radioactive sources Fe^{55} (5.9 keV), Cd^{109} (22 keV), Am^{241} (59.6 keV with Xe K-escape peaks at 29.8 keV and 26 keV) were used for calibration.

- Rejection and K-escape logic as used in PE is applied in simulations also and total energy in each anode is converted to channel No.

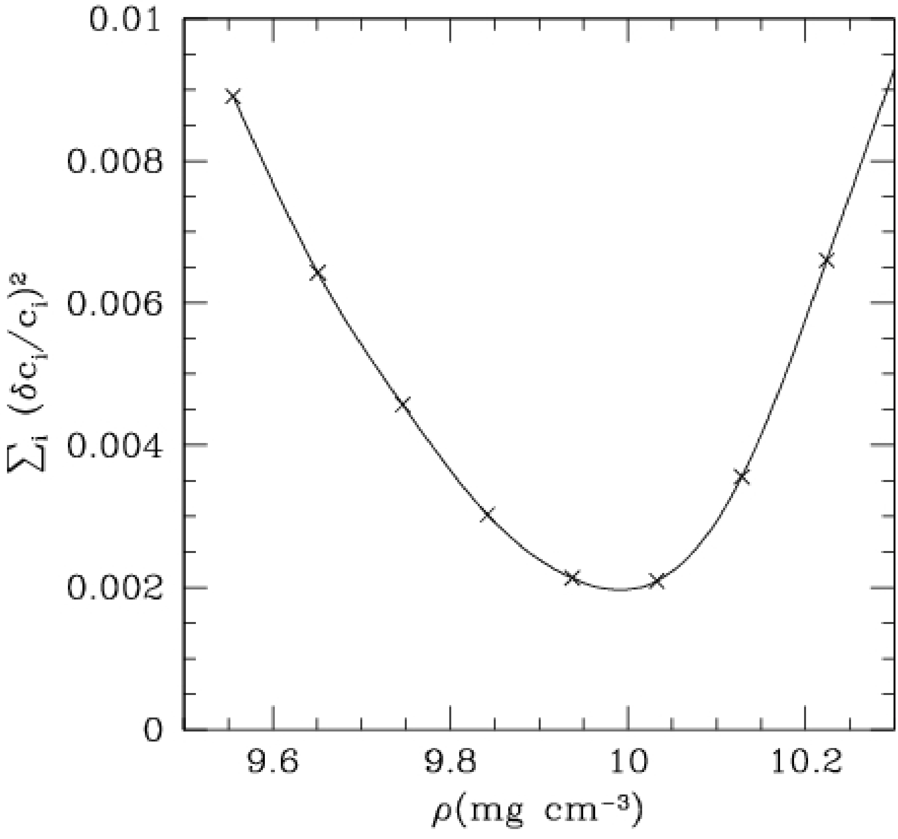
$$n_c = e_0 + e_1 E_p (1 + e_2 E_p)$$

- The simulated spectrum is compared with observed spectrum after subtracting the background. For normalisation the simulated spectrum is multiplied by a constant to match the total counts under one peak.

- To adjust the density of gas the square of relative difference in total counts for each anode layer for Cd^{109} is minimised

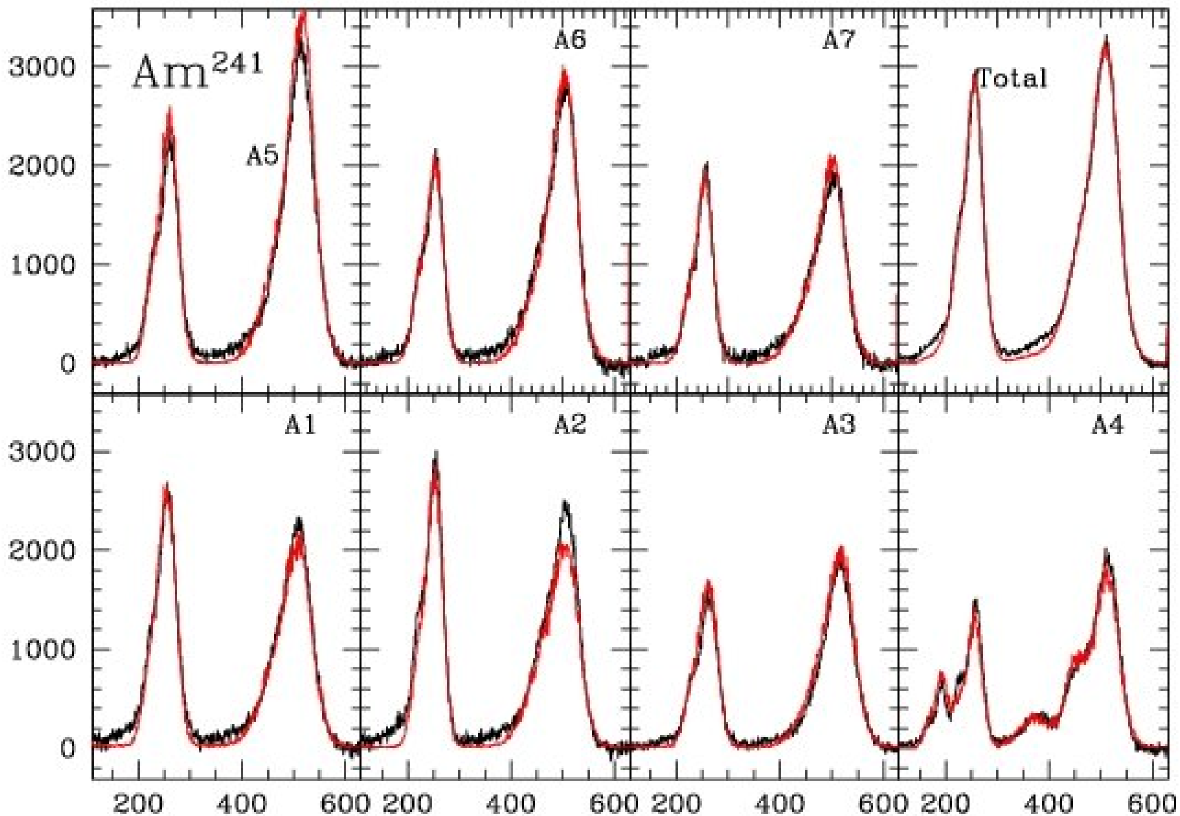
$$\sum_{i=1}^{5}\left(\frac{O_i - S_i}{O_i}\right)^2$$

This corrects for difference in temperature or pressure

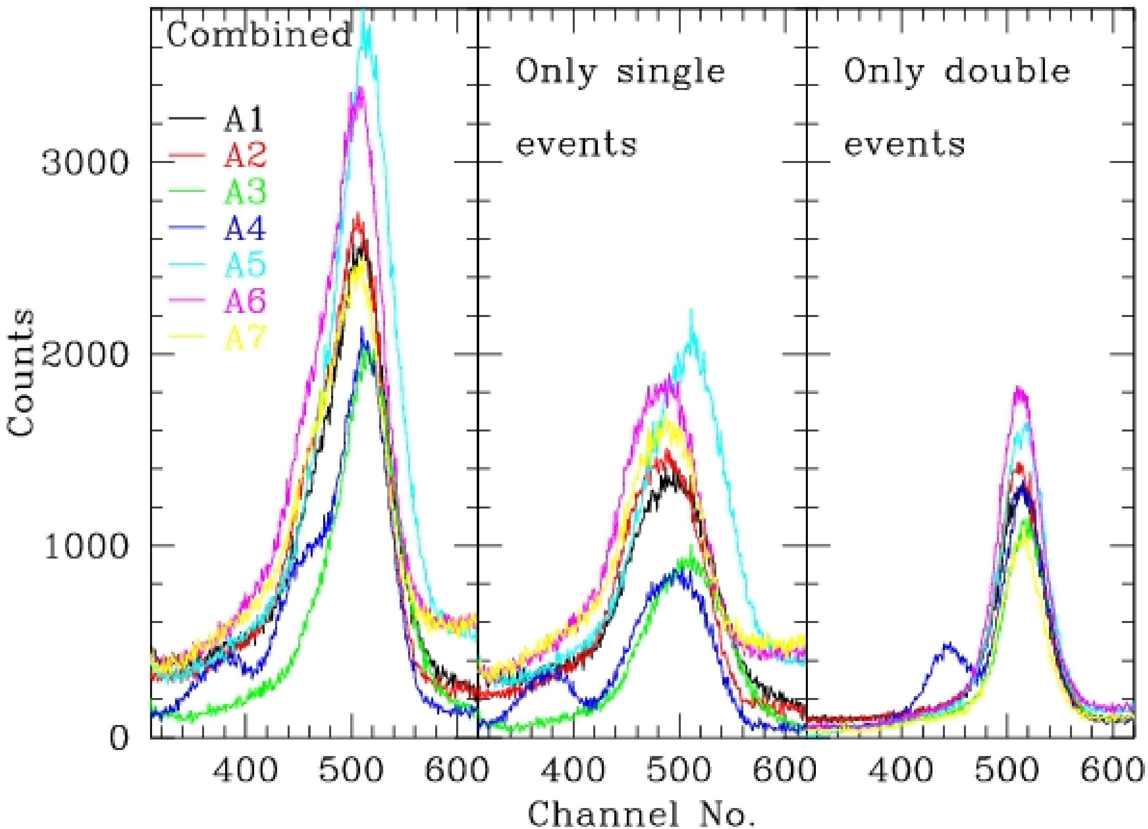


0.01
0.008
0.006
0.004
0.002
0
9.6
9.8
10
10.2
ρ(mg cm^{-3})
$\sum_i (\delta c_i/c_i)^2$

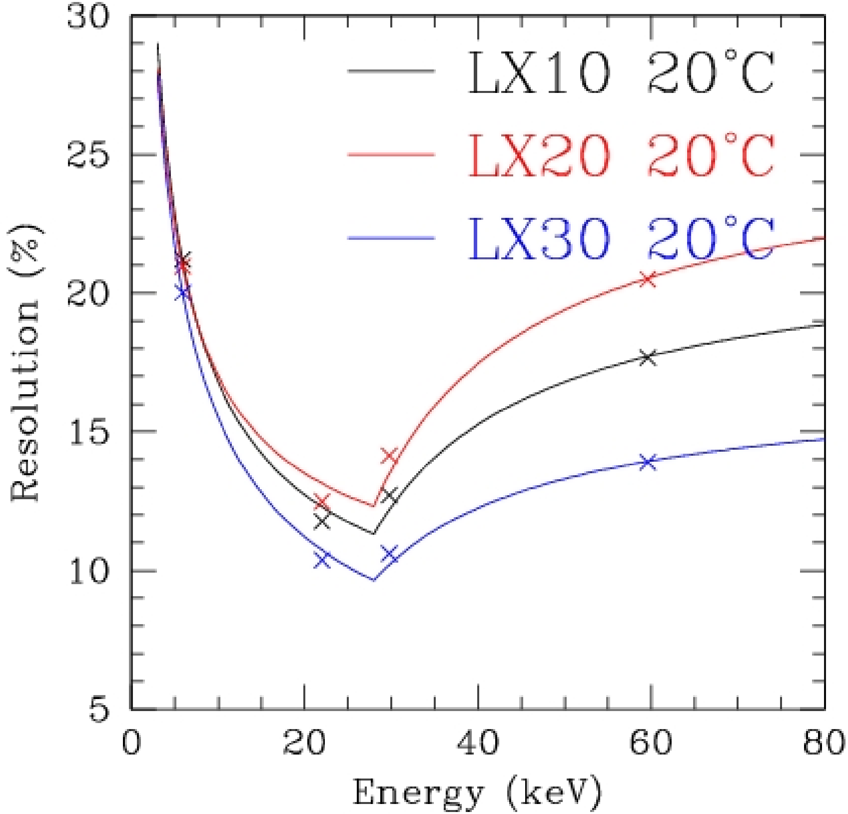
- The density at 20° C is found to be 10.0 mg cm^{-3} for LX10, 10.7 mg cm^{-3} for LX20 and 11.5 mg cm^{-3} for LX30.
- The resolution as a function of energy is determined by fitting a linear spline with 3 knots to $\sigma^2(E^{-1})$
- To calculate detector response for other energies we need $\sigma(E,T), n_c(E,T)$

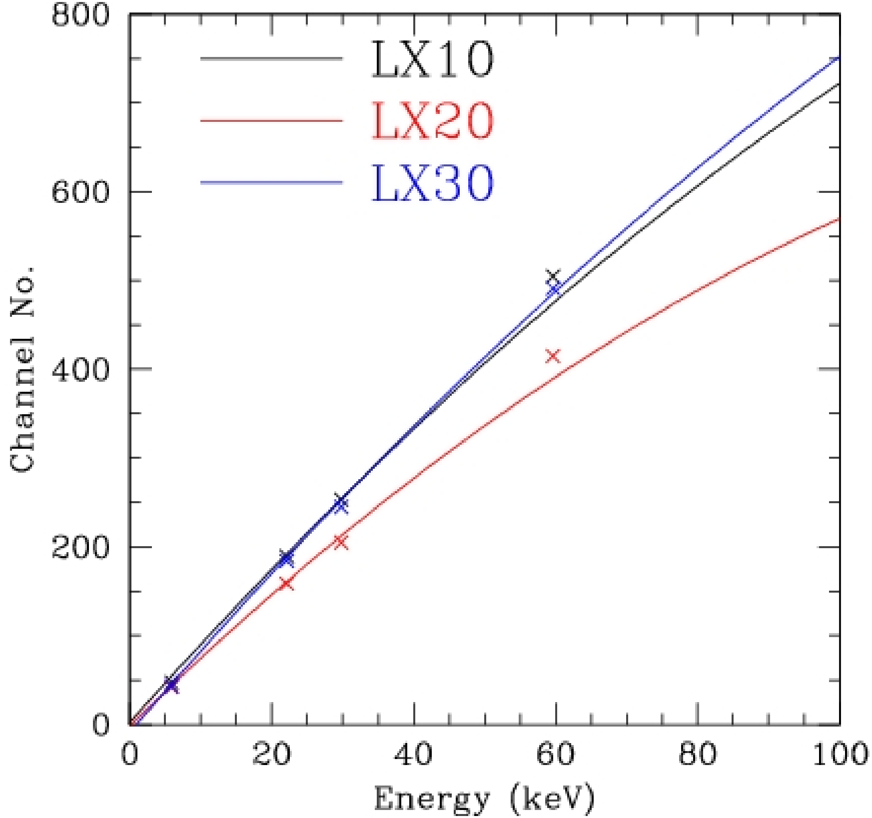


Am^{241}
A5
A6
A7
Total
A1
A2
A3
A4
0
1000
2000
3000
200
400
600

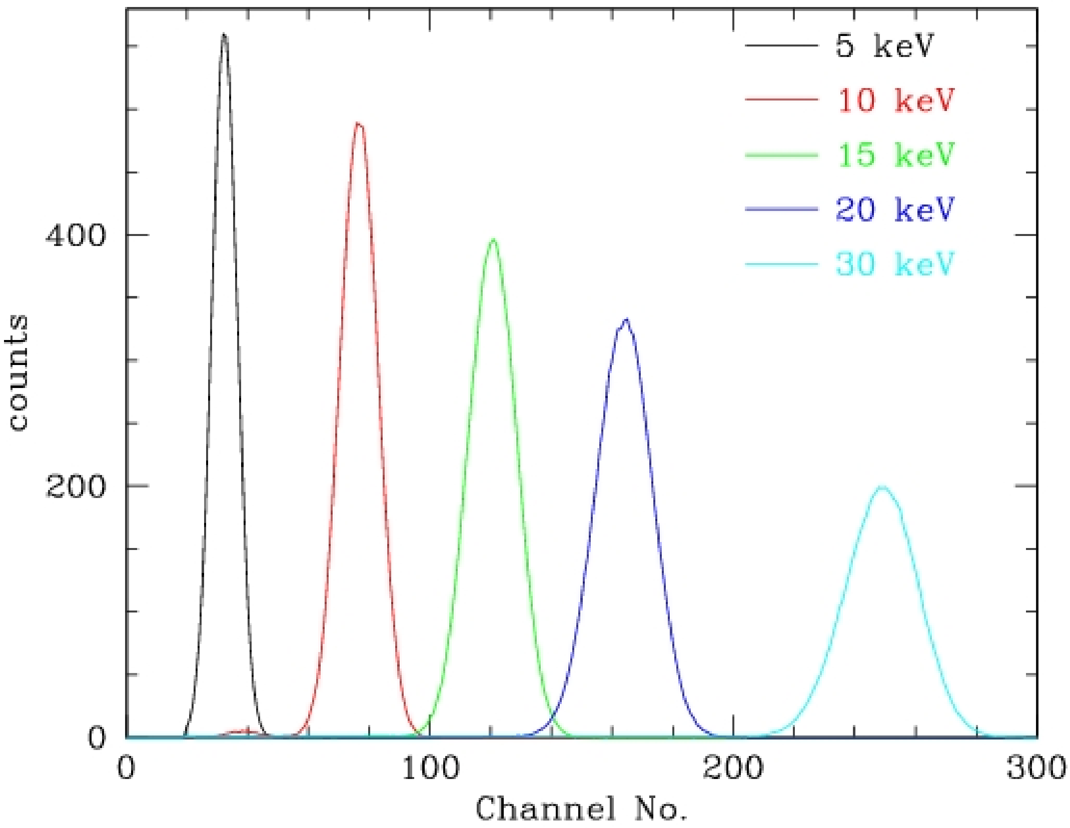


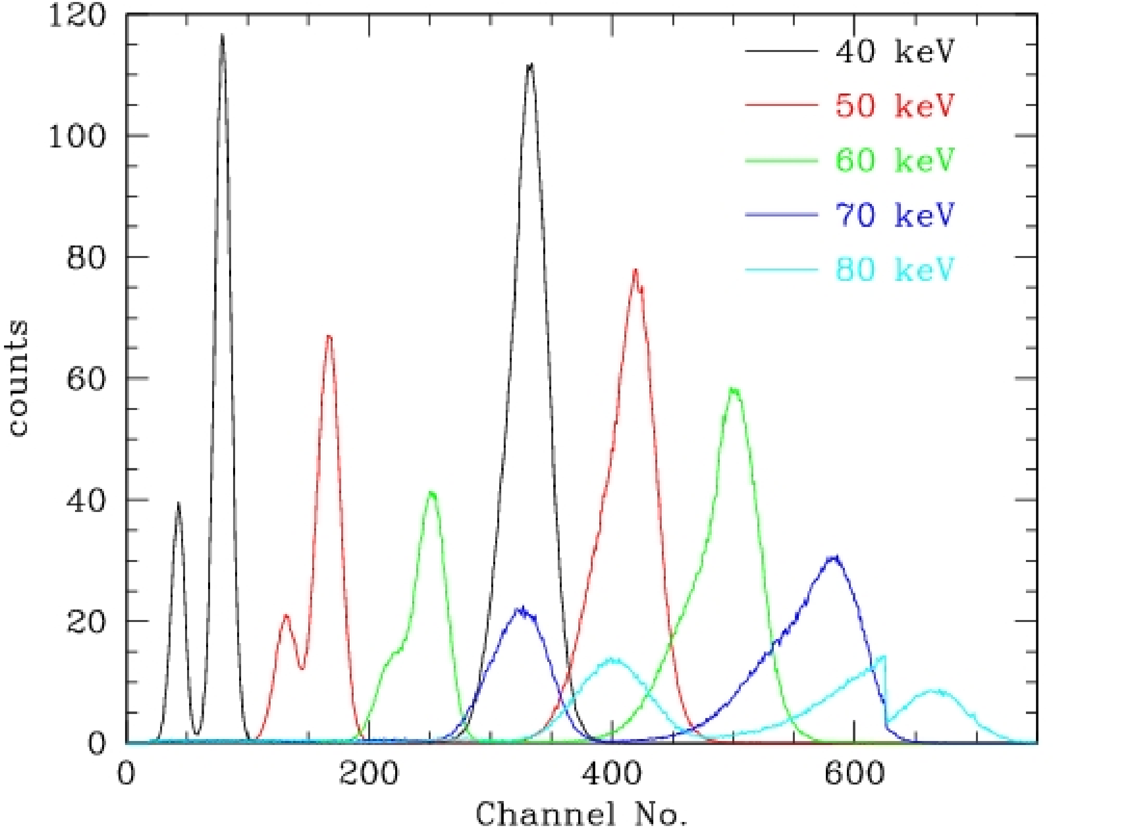
Combined
Only single events
Only double events
A1
A2
A3
A4
A5
A6
A7
Counts
0
1000
2000
3000
400
500
600
Channel No.


LX10 20°C
LX20 20°C
LX30 20°C
Resolution (%)
Energy (keV)
5
10
15
20
25
30
0
20
40
60
80



LX10
LX20
LX30
Channel No.
Energy (keV)
0
200
400
600
800
0
20
40
60
80
100

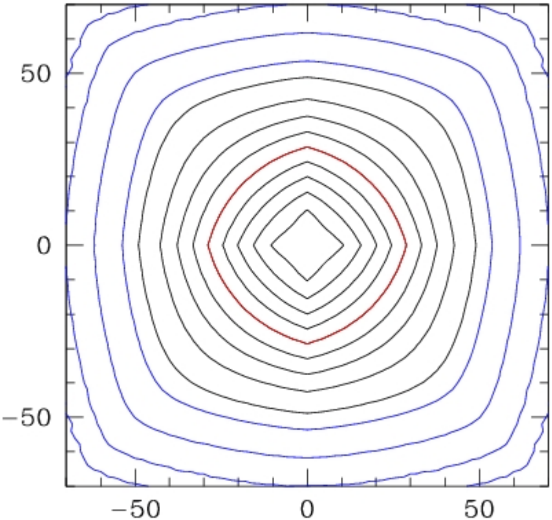

5 keV
10 keV
15 keV
20 keV
30 keV
counts
400
200
0
0
100
200
300
Channel No.

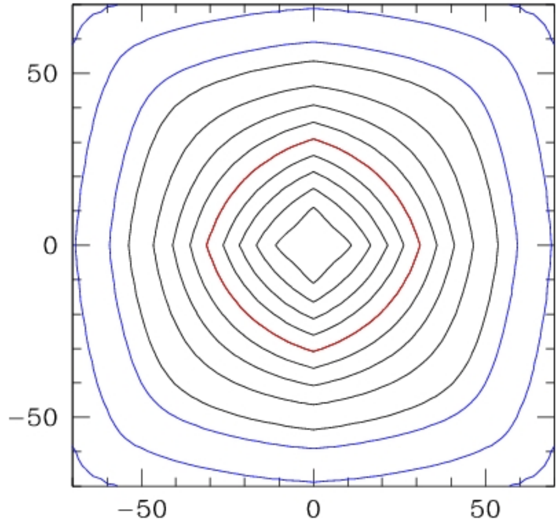


counts
Channel No.
40 keV
50 keV
60 keV
70 keV
80 keV
0
20
40
60
80
100
120
0
200
400
600

- AstroSat orbital period is about 97.4 min
- Data are dumped when AstroSat is over the ground station near Bengaluru. This does not happen during every orbit, but data for multiple orbit is stored on board and is dumped when link is available.
- HV of all LAXPC detectors is turned off during SAA passage of about 30 minutes. At all other times the detectors are always on and recording data.
- In addition depending on the source position the source may be behind the Earth for some time, which gives a typical duty cycle of 45%.

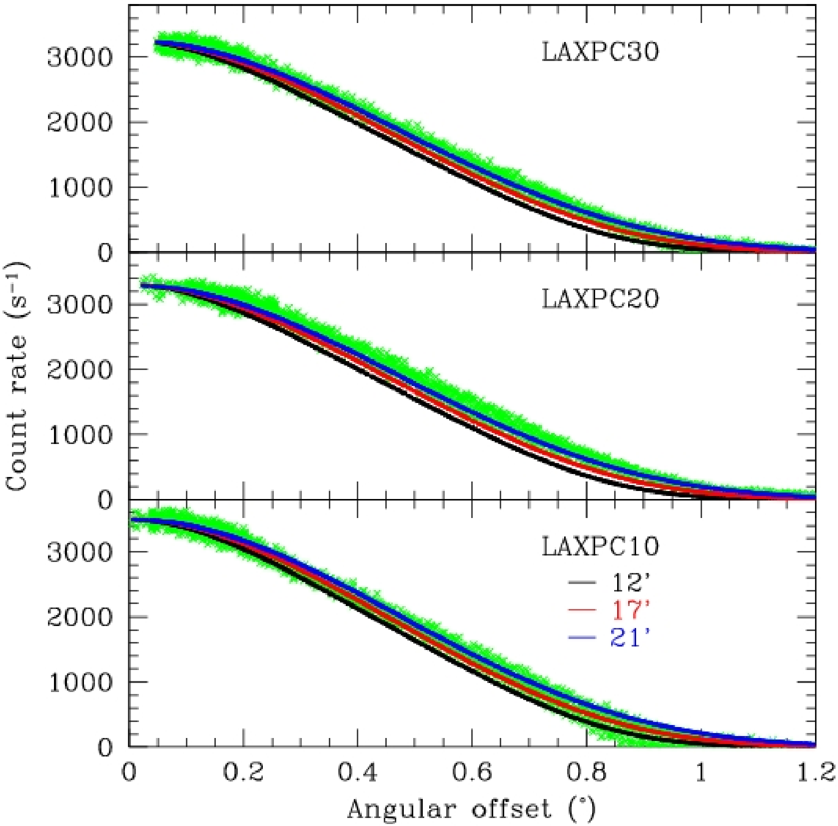
Calibration of the Field of View





15 keV: FWHM $= 55' = 0.92^\circ$ 50 keV: FWHM $= 63' = 1.05^\circ$

FOV is determined by scan across the Crab source.



LAXPC30
LAXPC20
LAXPC10
12'
17'
21'
Count rate (s⁻¹)
Angular offset (°)
0
1000
2000
3000
0
0.2
0.4
0.6
0.8
1
1.2

- LAXPC offset from scan on 3 February 2016

	RA (°)	DEC (°)	Offset (°)
LX10	83.78	22.01	0.15
LX20	83.63	22.08	0.07
LX30	83.74	22.03	0.11
Mean	83.72	22.04	0.09
Crab	83.63	22.01	

- Satellite pointing depends on the primary payload for observations. Hence, the relative normalisation of 3 detectors should be kept free.

Background Model

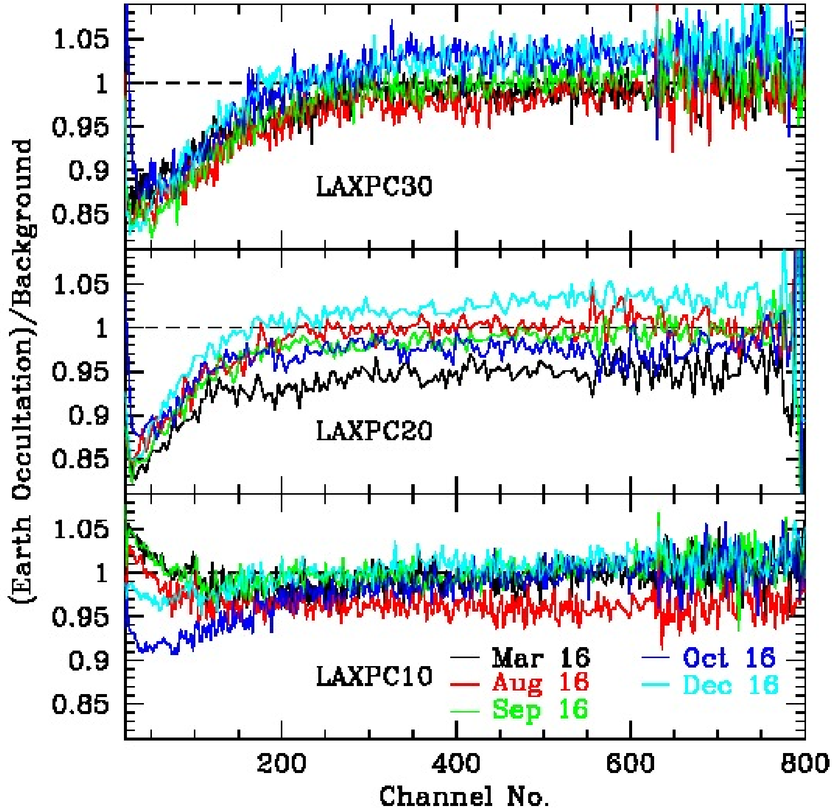
- Different models have been tried

1. Using ULD (Upper Level Discrimination) counts (sensitive to gain shift and temporal variations)

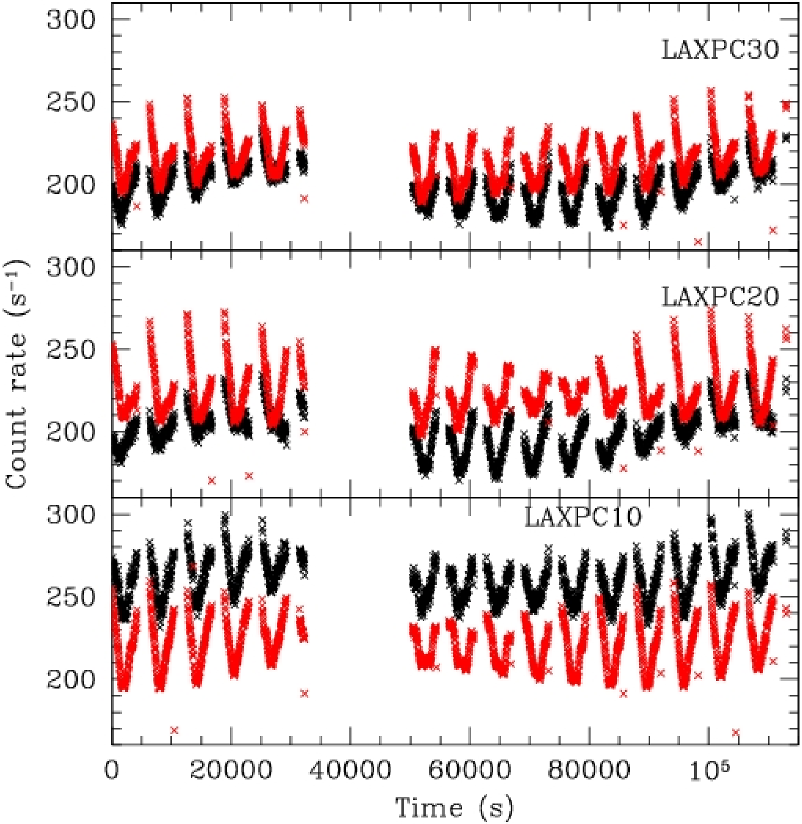
2. Fitting background count rate as a function of latitude and longitude (sensitive to temporal variation)

3. For faint sources, instead of ULD we can use counts at high energy to scale the background (R. Misra et al. 2021) (sensitive to temporal variation and gain shift)

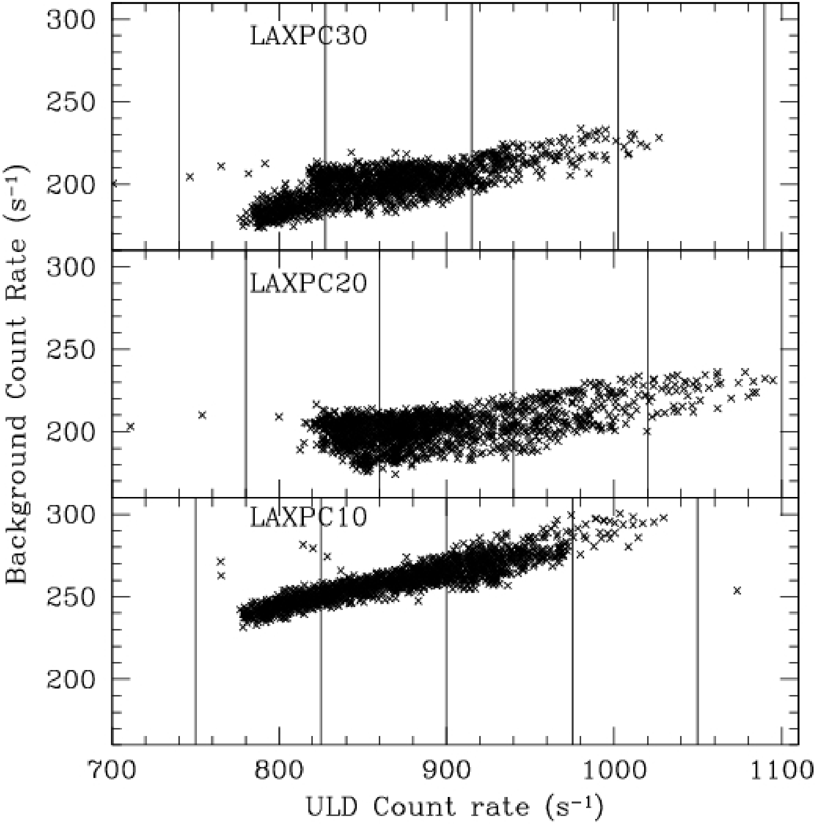
4. Observation during Earth Occultation (affected by Earth albedo/shadow)

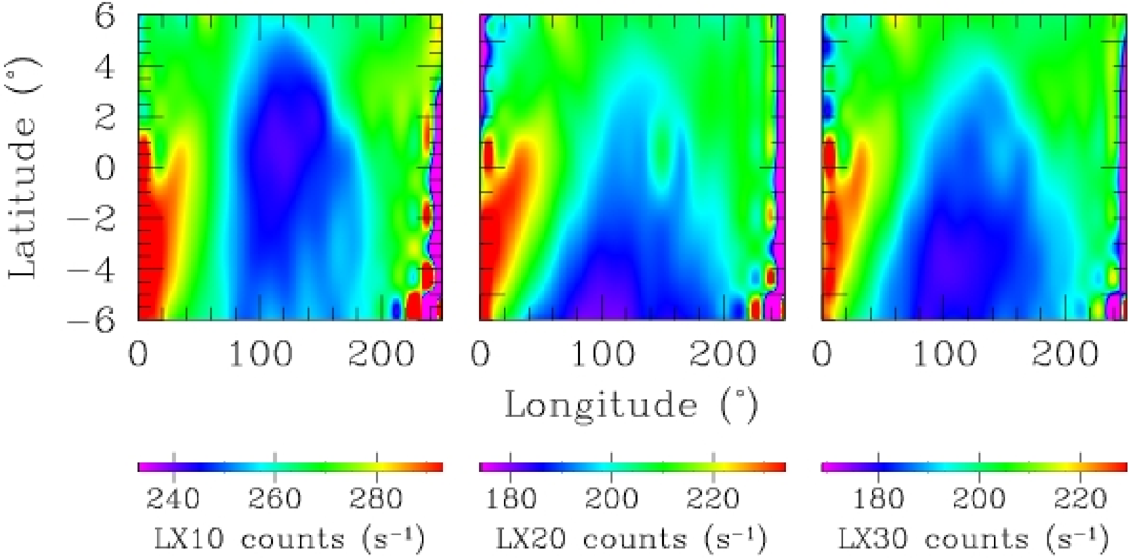


(Earth Occultation)/Background
LAXPC30
LAXPC20
LAXPC10
Mar 16
Aug 16
Sep 16
Oct 16
Dec 16
1.05
1
0.95
0.9
0.85
200
400
600
800
Channel No.



LAXPC30
LAXPC20
LAXPC10
Count rate (s⁻¹)
Time (s)
0
20000
40000
60000
80000
10⁵
200
250
300


LAXPC30
LAXPC20
LAXPC10
Background Count Rate (s⁻¹)
ULD Count rate (s⁻¹)
300
250
200
700
800
900
1000
1100

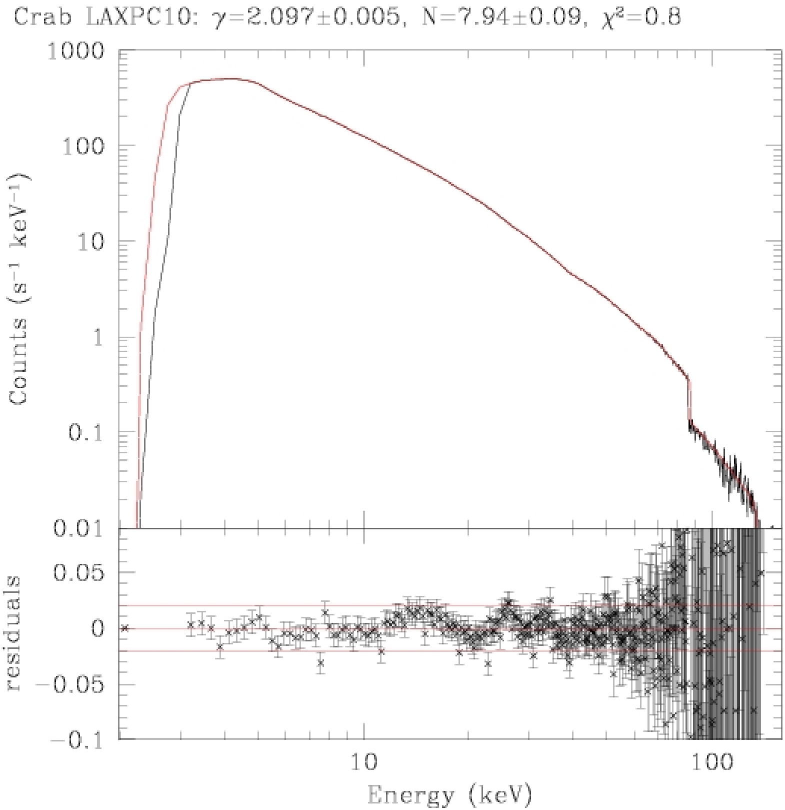

Latitude (°)
6
4
2
0
−2
−4
−6
0
100
200
Longitude (°)
240
260
280
LX10 counts (s⁻¹)
180
200
220
LX20 counts (s⁻¹)
180
200
220
LX30 counts (s⁻¹)

Detector Response Matrix

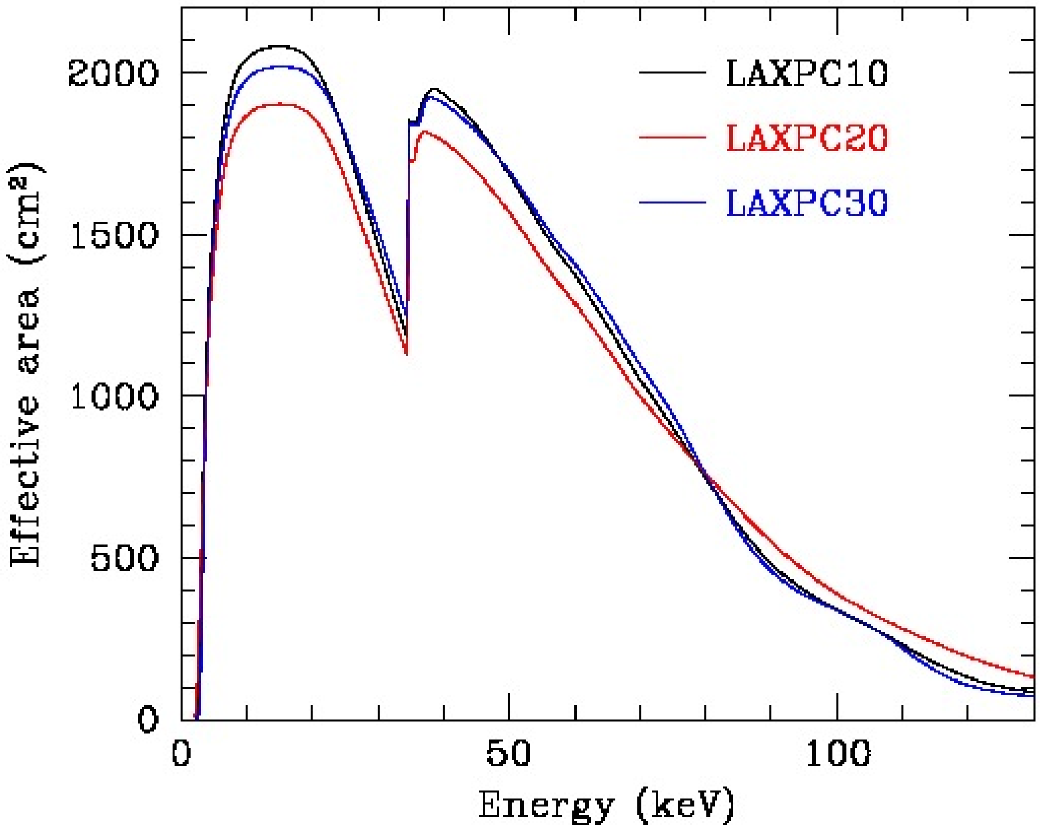
- The channel to energy mapping was adjusted to match the Crab spectrum observed after launch.
- Since the detector gain drifts with time, response matrix is generated for differing gain in the 30 keV calibration peak.
- A log of gain shift is maintained using the calibration source (Am^{241}) in veto anode A8. Normally, events recorded in anode A8 are rejected, but the detector electronics is designed to accept a small fraction of events in A8 which would include the counts due to calibration source.

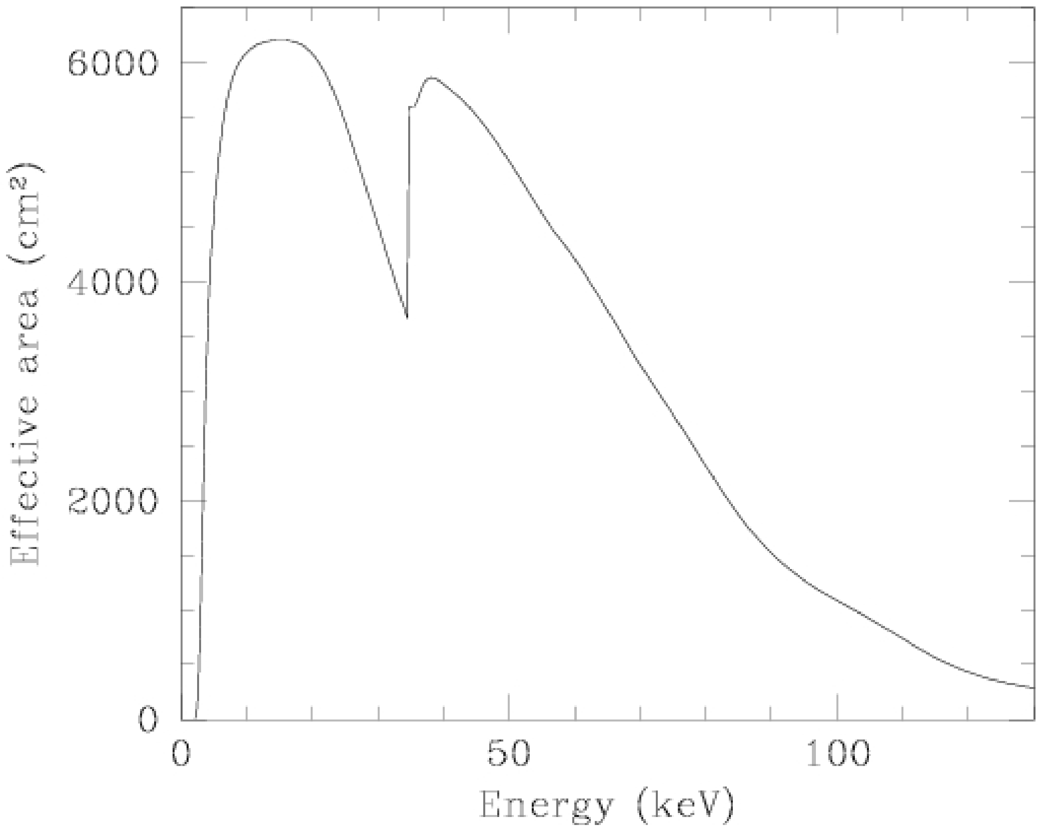
- The calibration source has two peaks around 30 and 60 keV and using them it is not possible to determine the 3 coefficients in channel to energy mapping. Only the shift in 30 keV peak is used to estimate the gain shift. As a result, it is recommended to apply gain-fit while fitting the spectrum, particularly, the offset in gain, which has not been estimated. By calibrating the Crab spectrum at different times, it is possible to estimate the offset and this is provided by the software.

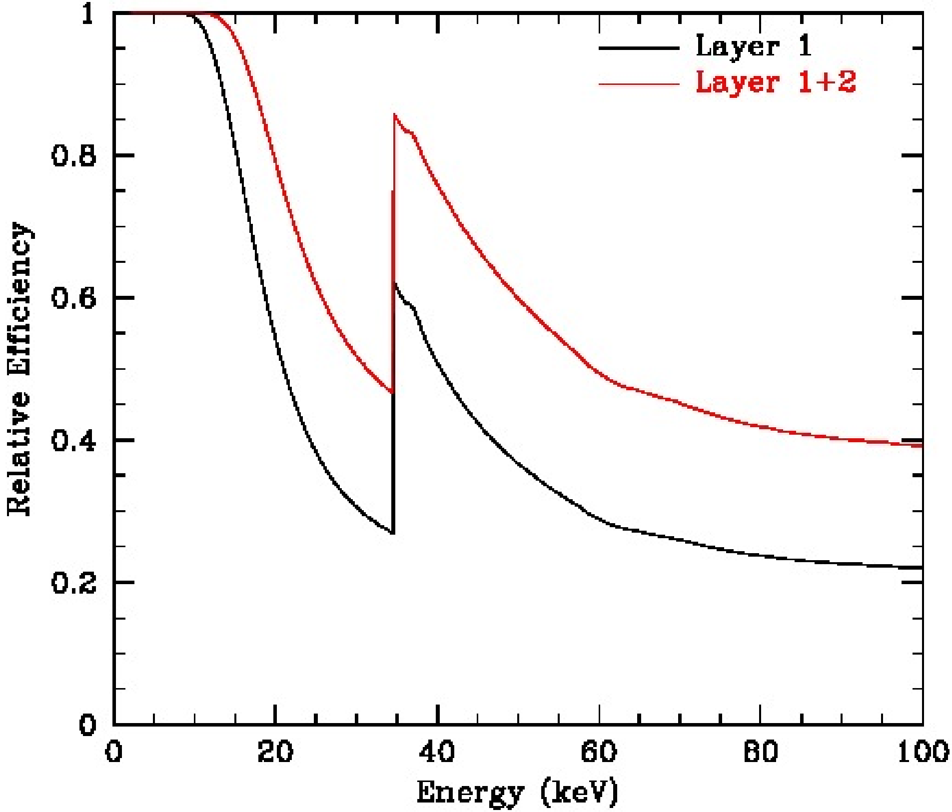
- To take care of even-odd fluctuation in counts with channel the no. of channels is reduced to 512 for LX10, LX30, and to 256 for LX20.
- The effect of dead-time is incorporated in the spectrum and light curve.
- Inclusion of flux leakage from side of the detector which gives a hump around 30 keV from Xenon K X-rays. This effect is not fully accounted for in response matrix and in some cases it may be necessary to include an additional Gaussian around 30 keV.
- To account for leak in LX30 the responses are generated with different density.
- The normalisation for effective area is estimated by cross-calibration with NuSTAR observation.



Crab LAXPC10: γ=2.097±0.005, N=7.94±0.09, χ²=0.8
Counts (s⁻¹ keV⁻¹)
1000
100
10
1
0.1
0.01
residuals
0.05
0
−0.05
−0.1
10
100
Energy (keV)


LAXPC10
LAXPC20
LAXPC30
Effective area (cm²)
Energy (keV)
0
500
1000
1500
2000
0
50
100

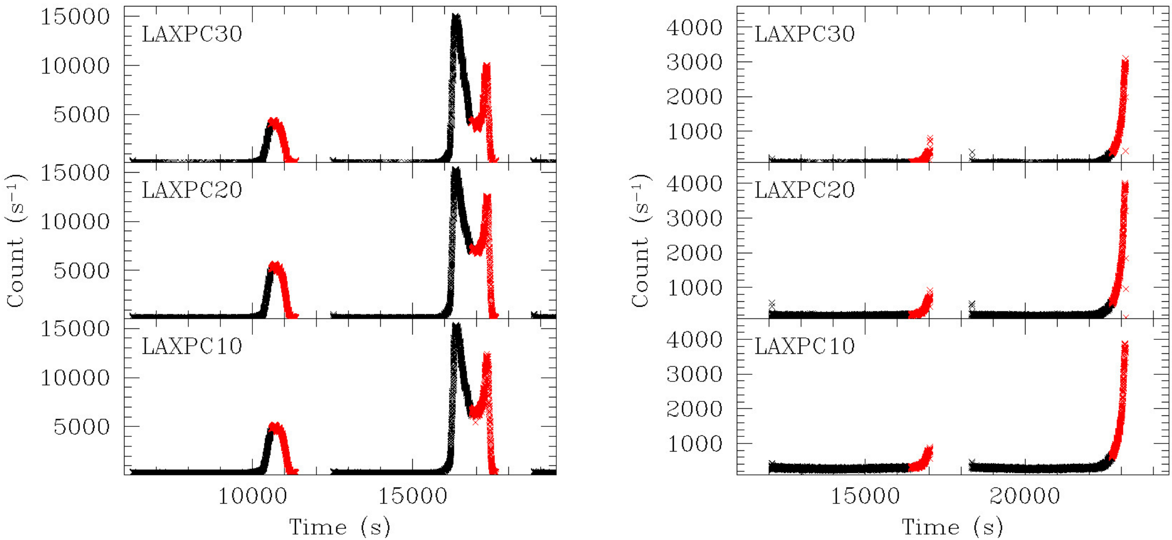

6000
4000
2000
0
Effective area (cm²)
0
50
100
Energy (keV)



Layer 1
Layer 1+2
Relative Efficiency
Energy (keV)
0
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100

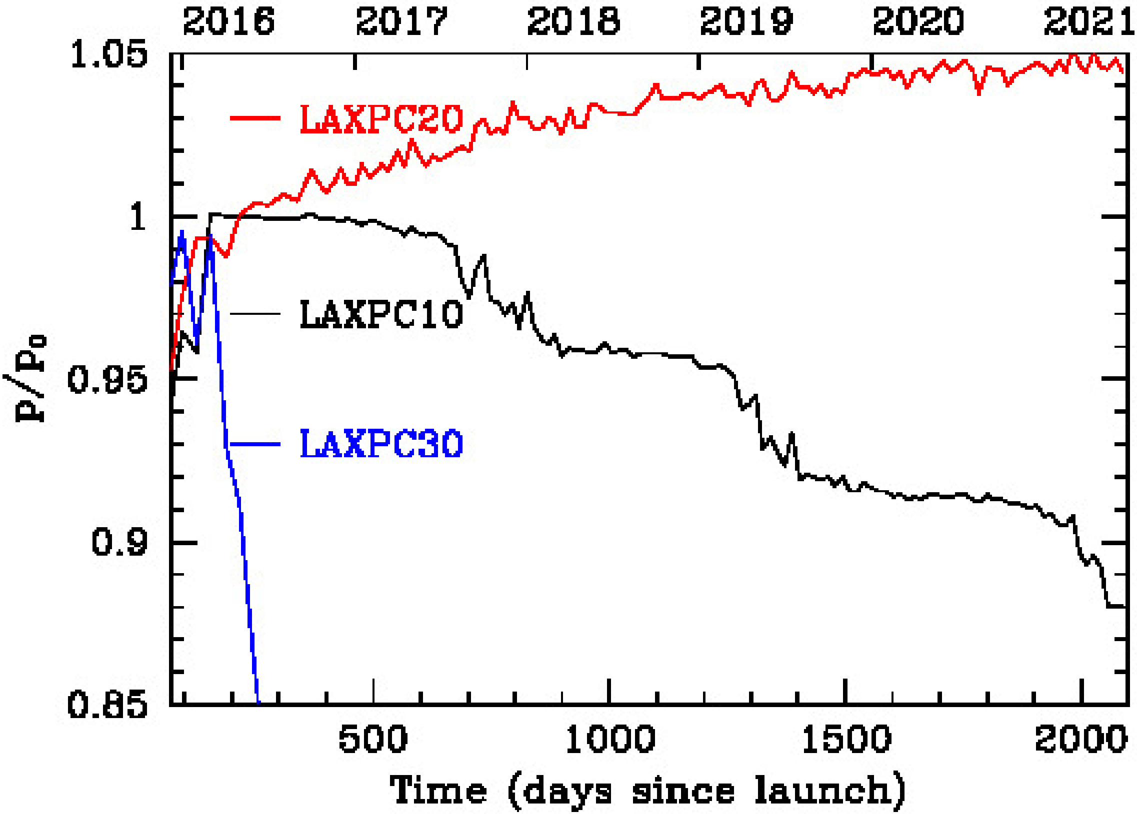
Effect of Geomagnetic Storms

8 September 2017 ($Kp = 8^+$) 28 May 2017 ($Kp = 7$)



Long Term Performance in Orbit

- AstroSat has been in orbit for over 2090 days and has completed over 31000 orbits
- LAXPC has made over 2200 observations with different pointings.
- Long term performance is being monitored using the calibration source in veto anode A8 to check the gain and resolution of the detectors.
- The calibration source has two peaks around 30 and 60 keV which are fitted to get the peak position and energy resolution.

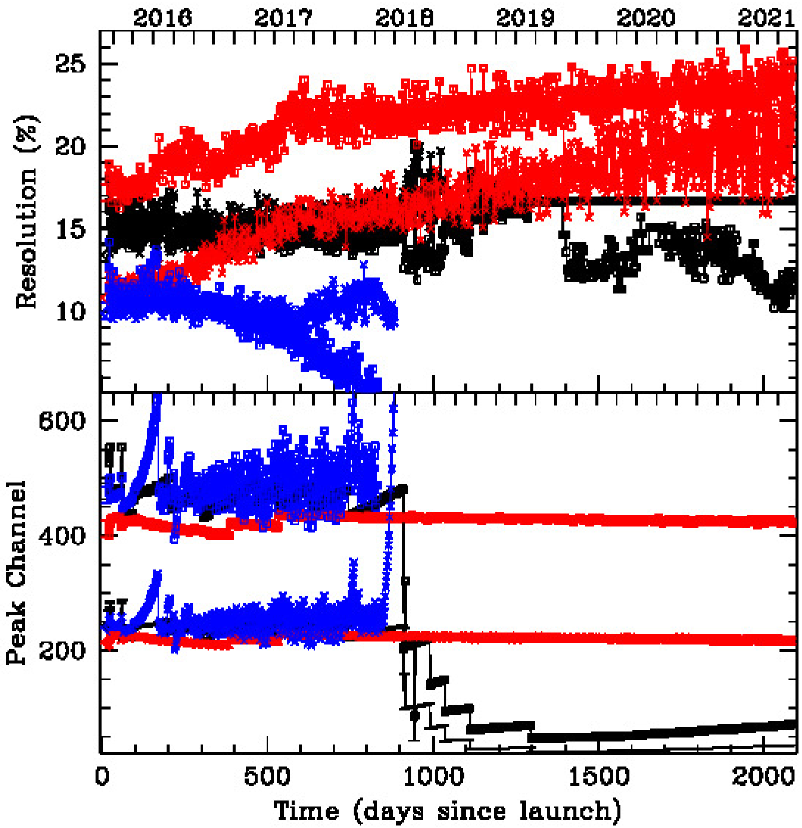

2016
2017
2018
2019
2020
2021
1.05
1
0.95
0.9
0.85
P/P0
LAXPC20
LAXPC10
LAXPC30
500
1000
1500
2000
Time (days since launch)

- LX30 developed a leak soon after launch leading to peak channel shifting upwards. The HV was adjusted from time-to-time to bring the gain in reasonable range.

- On 22 January 2018 the HV of LX30 was reduced to minimum permissible value. After that the gain kept shifting upwards.

- On 8 March 2018 the HV of LX30 was turned off when the pressure had reduced to about 5% of its original value and ULD had reduced to 15–20 keV. Now the pressure is estimated to be around 0.01% of original value.

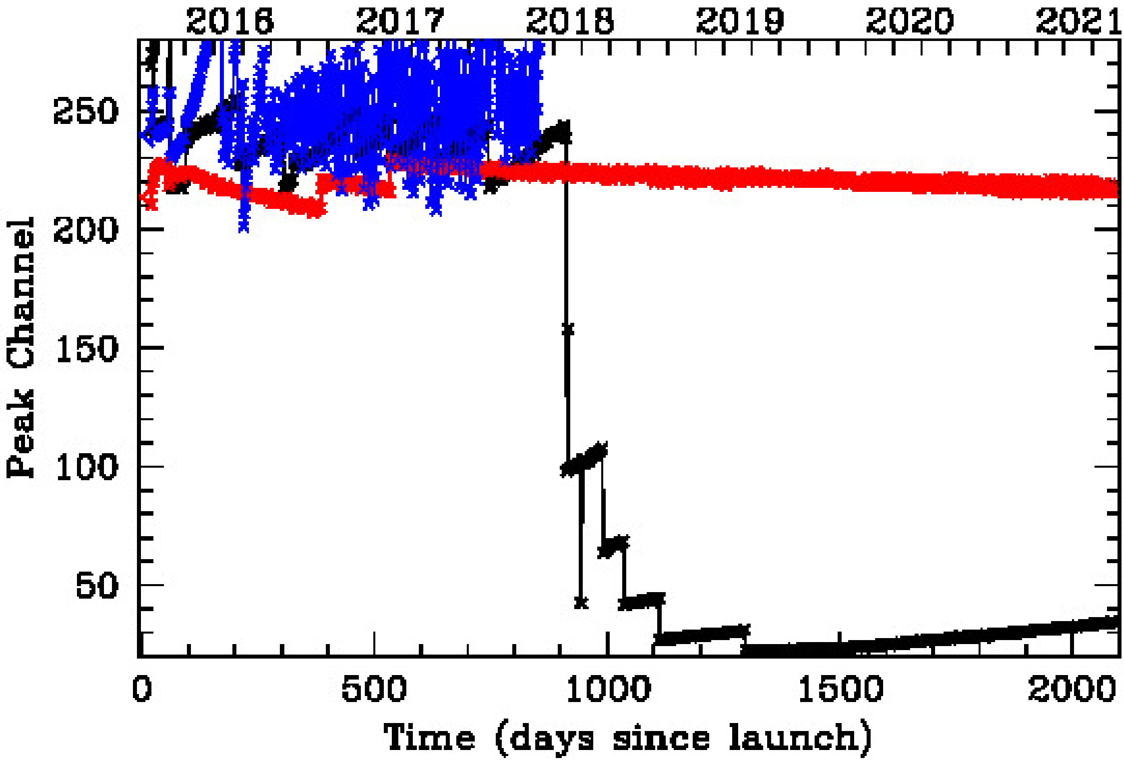
- The gain of LX10 also has been drifting upwards gradually and it also likely has a minor leak and the pressure has reduced by about 10% percent over 5 years.


2016
2017
2018
2019
2020
2021
Resolution (%)
25
20
15
10
Peak Channel
600
400
200
0
500
1000
1500
2000
Time (days since launch)

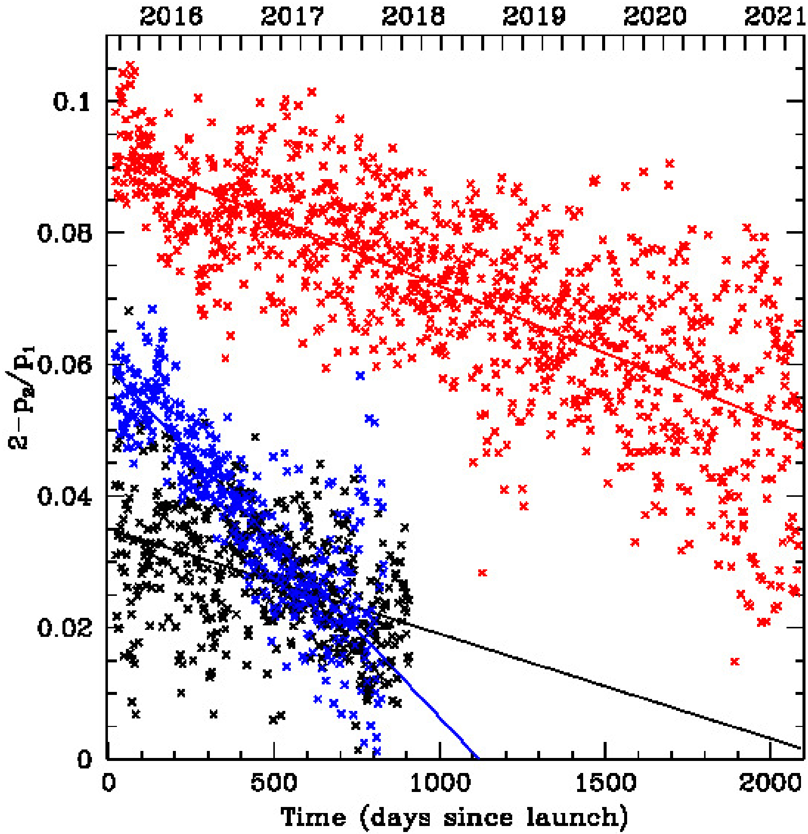
- On 26 March 2018, LX10 showed erratic counts with frequent bursts and its HV was reduced to stabilise the counts. Since then the HV has been reduced a few times. As a result, it is operating at very low gain and currently its low energy cutoff is around 18 keV and ULD around 220 keV.

- The gain of LX20 has been steady and only a few HV adjustments have been made, with the last one in March 2017. Since then the peak position has reduced by about 12 channels. Since LX20 is already operating at high voltage, no further increase in HV has been attempted.

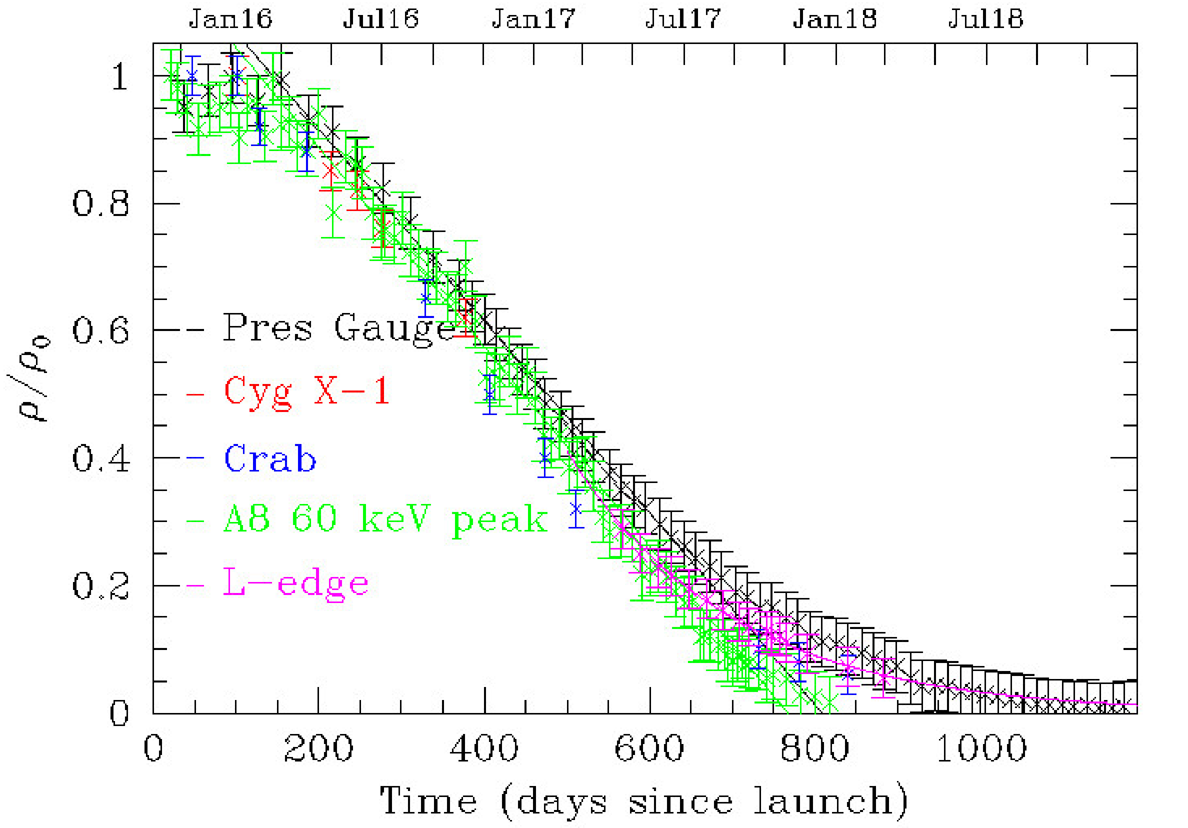
- The energy resolution of LX20 has been deteriorating with time and is now above 20% at 30 keV.



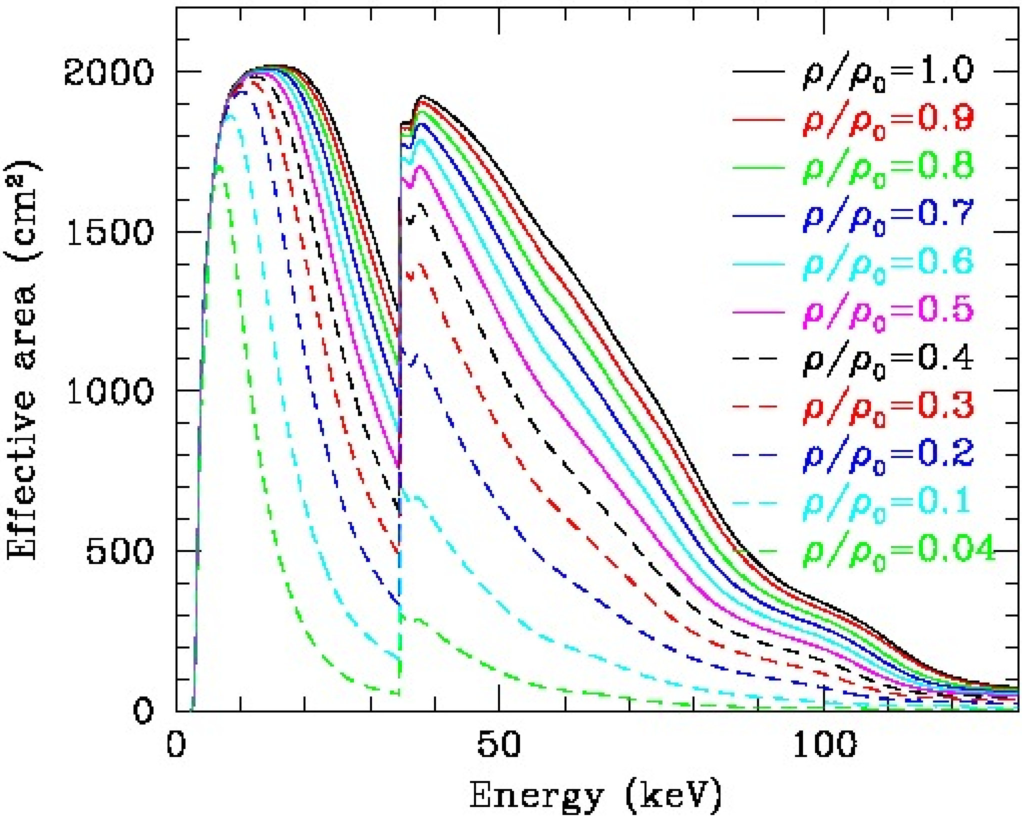
2016
2017
2018
2019
2020
2021
250
200
150
100
50
Peak Channel
0
500
1000
1500
2000
Time (days since launch)



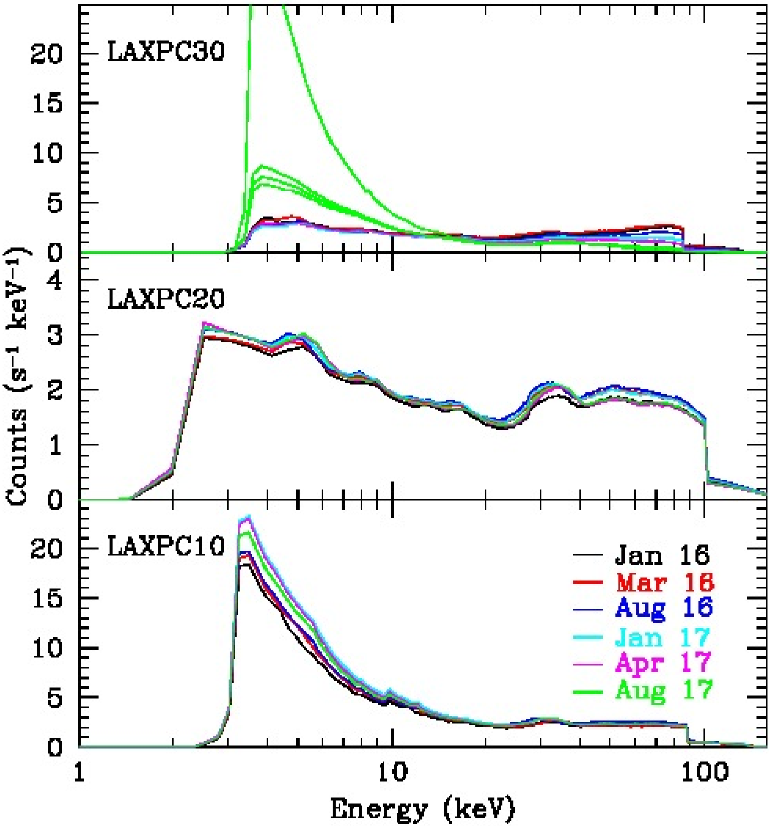
2016
2017
2018
2019
2020
2021
0.1
0.08
0.06
0.04
0.02
0
$2-P_2/P_1$
0
500
1000
1500
2000
Time (days since launch)

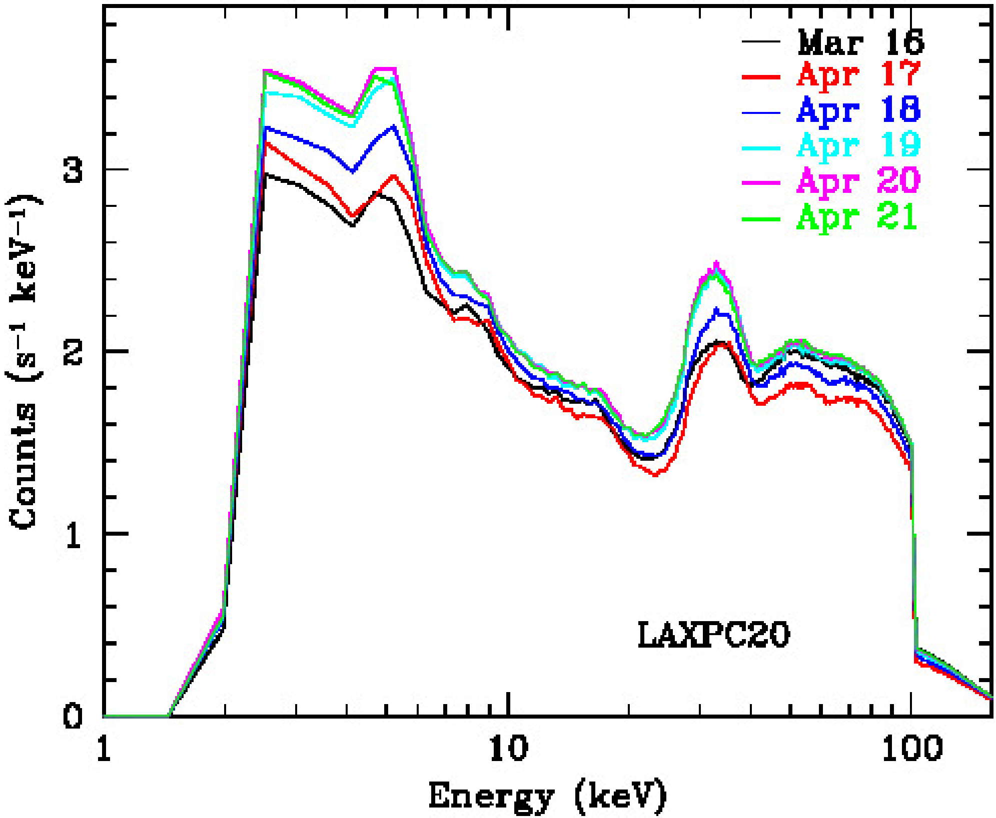


Jan16
Jul16
Jan17
Jul17
Jan18
Jul18
1
0.8
0.6
0.4
0.2
0
ρ/ρ_o
Pres Gauge
Cyg X−1
Crab
A8 60 keV peak
L−edge
0
200
400
600
800
1000
Time (days since launch)

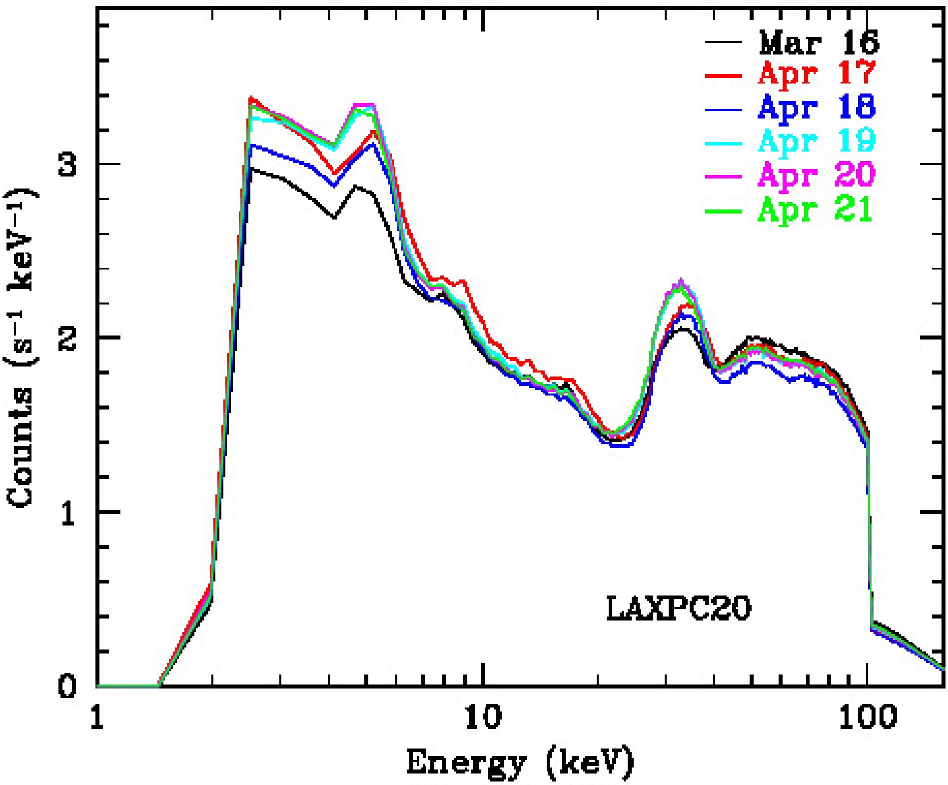


Effective area (cm²)
Energy (keV)
0
500
1000
1500
2000
0
50
100
ρ/ρ0=1.0
ρ/ρ0=0.9
ρ/ρ0=0.8
ρ/ρ0=0.7
ρ/ρ0=0.6
ρ/ρ0=0.5
ρ/ρ0=0.4
ρ/ρ0=0.3
ρ/ρ0=0.2
ρ/ρ0=0.1
ρ/ρ0=0.04

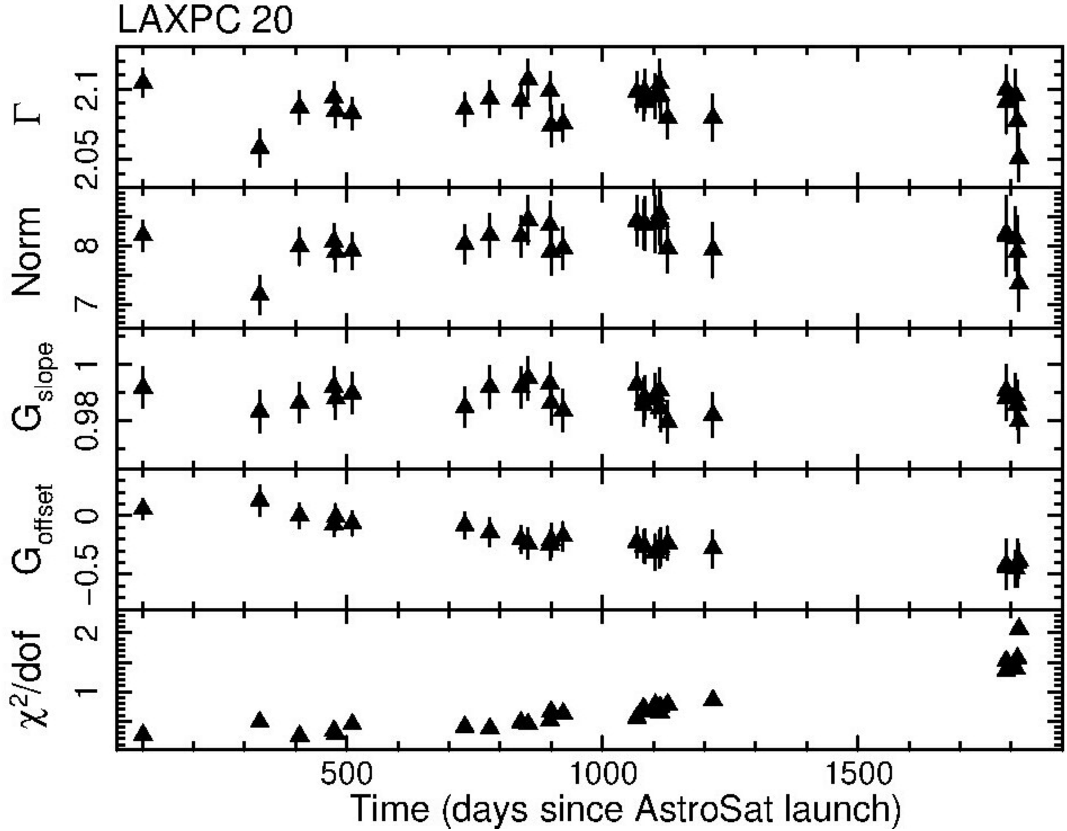

LAXPC30
LAXPC20
LAXPC10
Counts (s⁻¹ keV⁻¹)
Energy (keV)
Jan 16
Mar 16
Aug 16
Jan 17
Apr 17
Aug 17
0
5
10
15
20
1
2
3
4
1
10
100



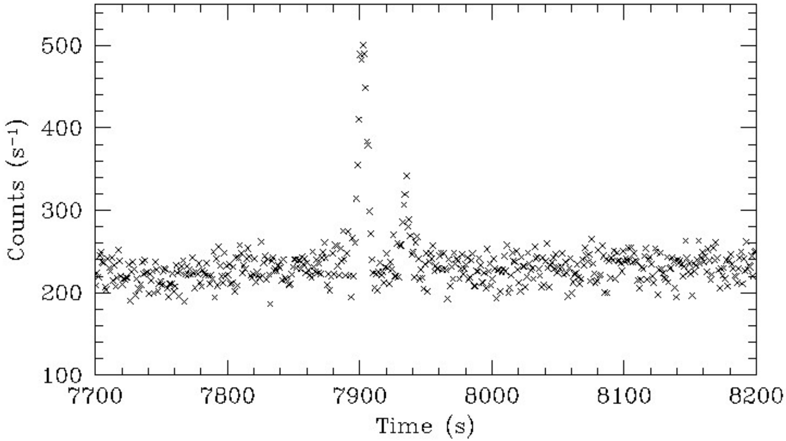
Mar 16
Apr 17
Apr 18
Apr 19
Apr 20
Apr 21
LAXPC20
Counts (s^{-1} keV^{-1})
Energy (keV)
0
1
2
3
1
10
100



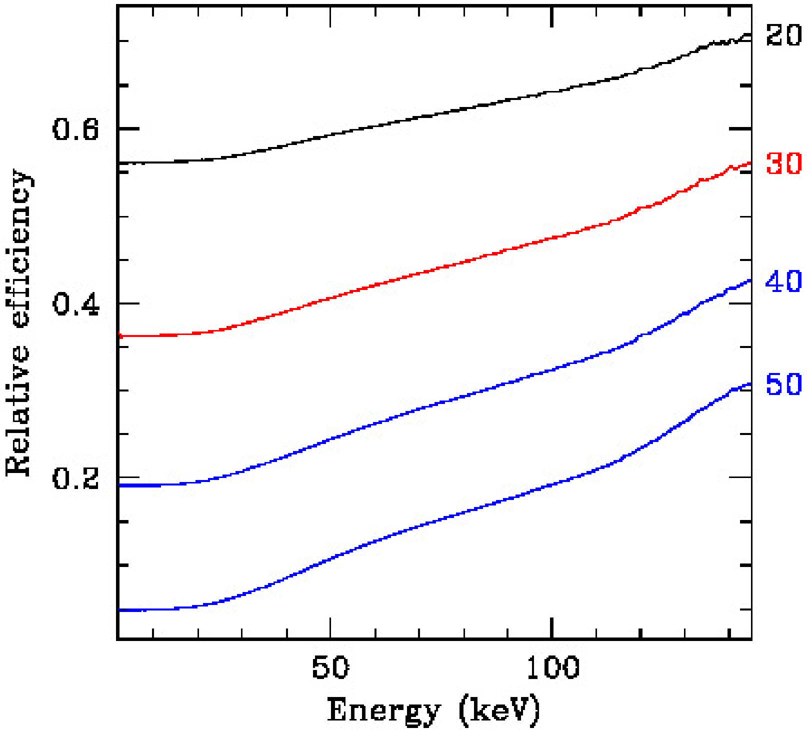
After scaling for the count rate


LAXPC 20
Γ
2.05
2.1
Norm
7
8
G_{slope}
0.98
1
G_{offset}
−0.5
0
χ^2/dof
1
2
500
1000
1500
Time (days since AstroSat launch)

- Because of the large FOV there can be contamination from another source in the FOV. Even sources $> 60'$ can make significant contribution

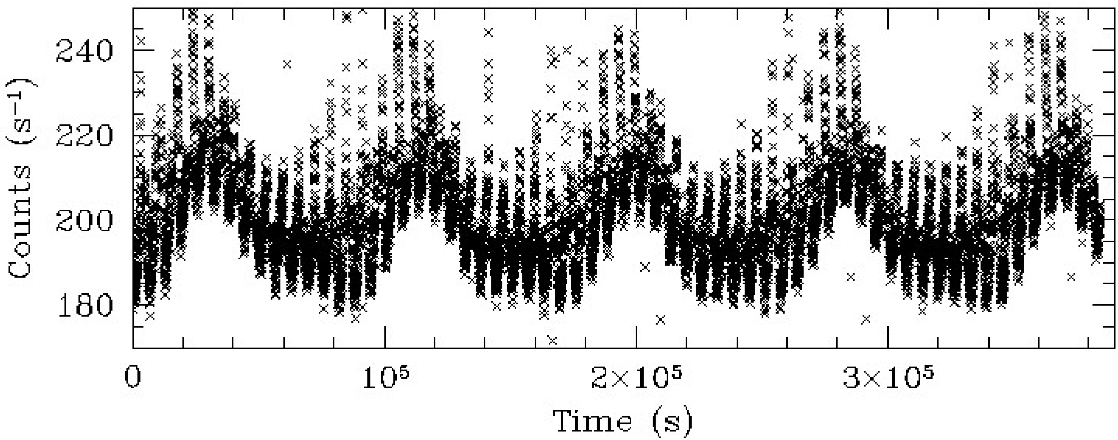


The bigger peak in this SLEW observation is due to GX 5–1 (offset $51'$, 10%) and smaller peak is due to GX 9+1 (offset $62'$, 5%)

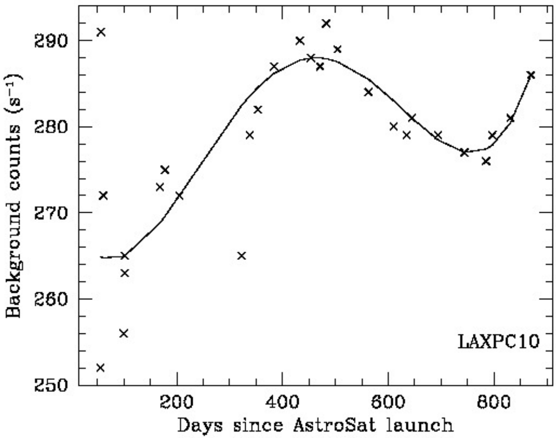

20'
30'
40'
50'
0.6
0.4
0.2
Relative efficiency
50
100
Energy (keV)

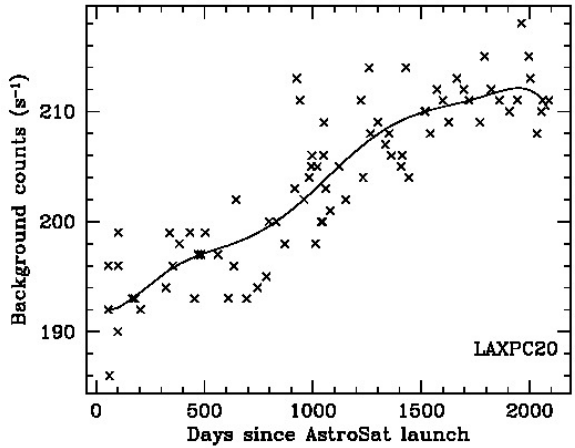
Updated background model

- The background counts show a quasi-diurnal variation



Long term variation in background counts

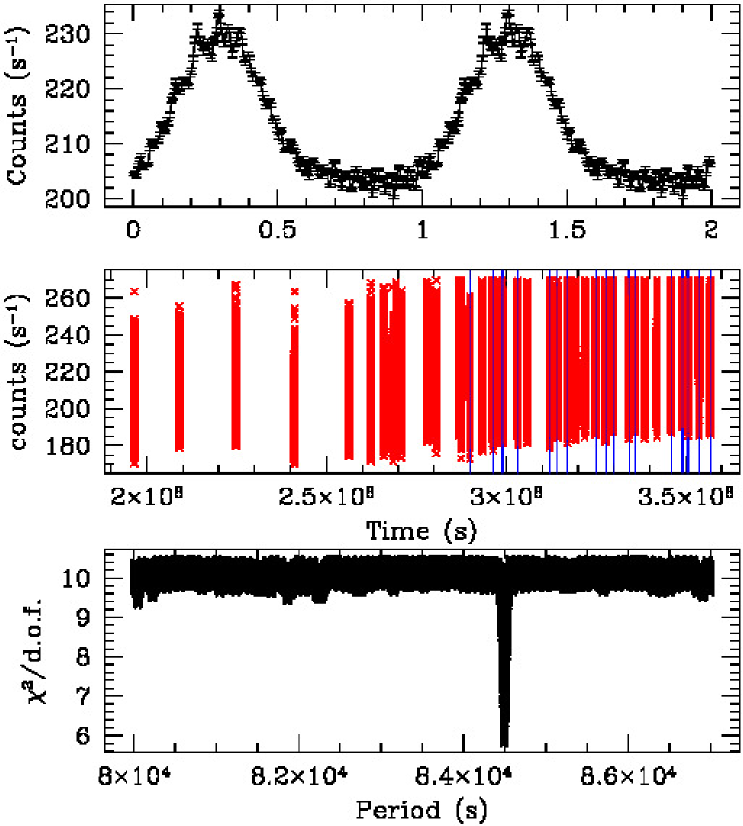


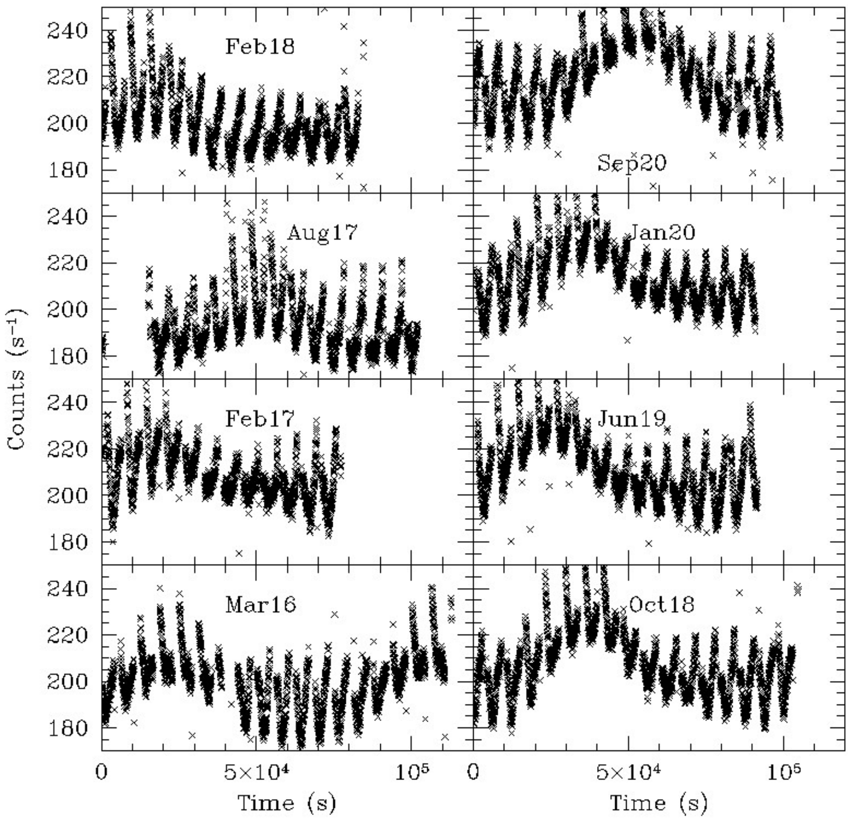


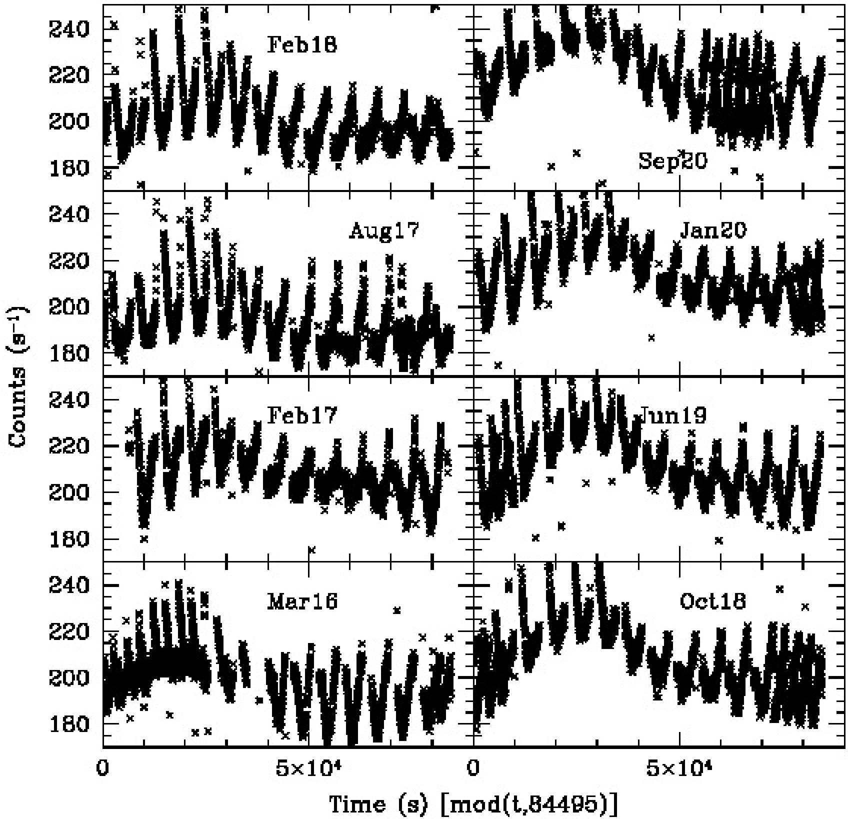
- Apart from the long term variation there is the diurnal variation which has an amplitude of about 30 s^{-1}, which is about 15% of the background counts. To remove this variation it was necessary to estimate the actual period of diurnal variation.

- Using over 5 years of background observation the period of diurnal variation was determined to be 84495 s. The origin of this period is not clear.

- The actual period of AstroSat orbit is 5844.40 s, while the latitude variation gives a period of 5836.62 s, while longitude gives 6269.75 s and altitude yields 5852.08 s.


Counts (s^{-1})
230
220
210
200
0
0.5
1
1.5
2
counts (s^{-1})
260
240
220
200
180
2×10^8
2.5×10^8
3×10^8
3.5×10^8
Time (s)
χ^2/d.o.f.
10
9
8
7
6
8×10^4
8.2×10^4
8.4×10^4
8.6×10^4
Period (s)


Feb18
Sep20
Aug17
Jan20
Feb17
Jun19
Mar16
Oct18
Counts (s^{-1})
Time (s)
Time (s)
240
220
200
180
0
5×10^4
10^5


Feb16
Sep20
Aug17
Jan20
Feb17
Jun19
Mar16
Oct18
Counts (s⁻¹)
Time (s) [mod(t,84495)]
240
220
200
180
0
5×10⁴

- If we take the frequency difference between the latitude and longitude period we get

$$\frac{1}{5836.62} - \frac{1}{6269.75} = \frac{1}{84488}$$

which is close the period found. This is also the period at which the maximum latitude during the orbit is modulated (84496 s).

- Similarly the frequency difference between the altitude and longitude periods give

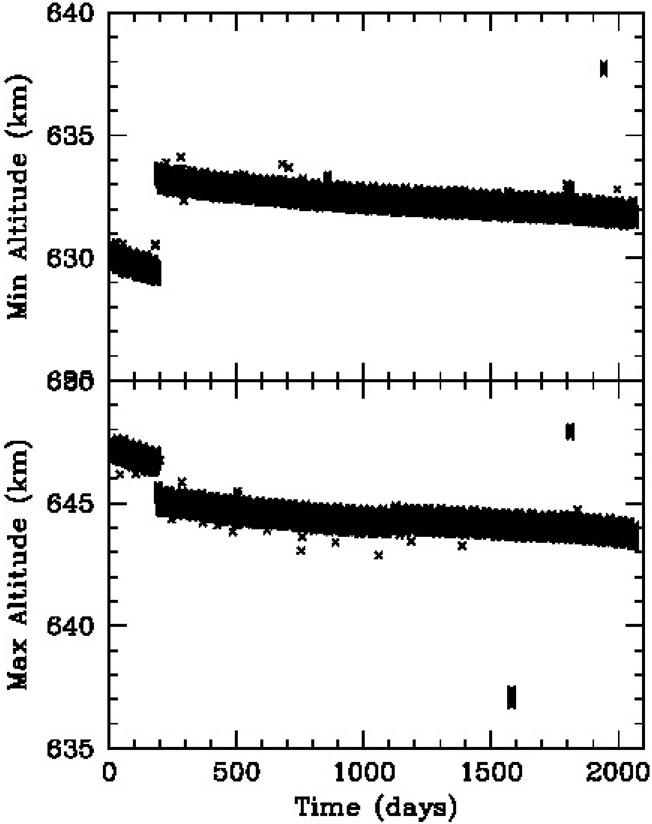
$$\frac{1}{5852.08} - \frac{1}{6269.75} = \frac{1}{87847}$$

which agrees with the period by which the altitude is modulated, i.e.,87872 s.

- The altitude also has a longer term modulation with a period of about 2198700 s or 25.45 days, which is close the frequency difference between latitude and latitude period

$$\frac{1}{5836.62} - \frac{1}{5852.08} = \frac{1}{2209338}$$

- There is some variation with time in all these periods. Since the period basically depends on the altitude, using the mkf file for all observations the maximum and minimum altitude during each orbit were determined



640
635
630
625
Min Altitude (km)
650
645
640
635
Max Altitude (km)
0
500
1000
1500
2000
Time (days)

- Apart from a slow decrease in period, there appear to be 9 orbit maneuvers as follows:

  1. before 03/04/2016 between ObsID 0406 and 0410, when the satellite was in a safe mode,

  2-3. During ObsID 2130 (Cyg X-2) after 30/05/18

  4-5. During ObsID 3458 (J164754...) on 23/01/20

  6-7. During ObsID 3864 (CAL83) on 10/09/20

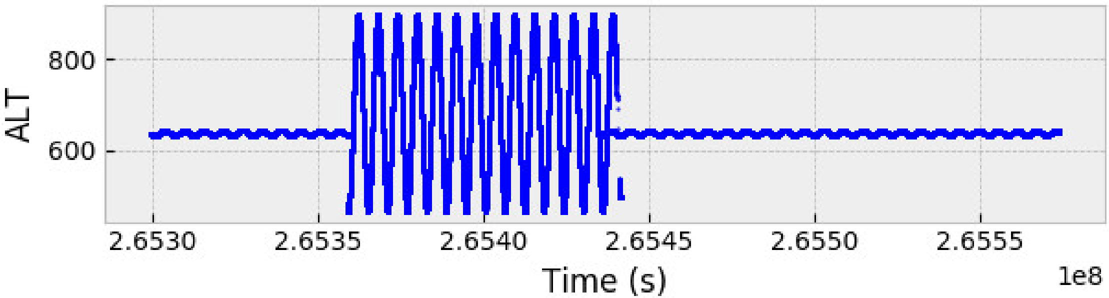
  8-9. During ObsID 4126–4128 (BCD-T8, 2MASS...) on 20/01/21

- Frequency of orbit maneuvers appears to have increased. This would have implication for the lifetime of AstroSat.

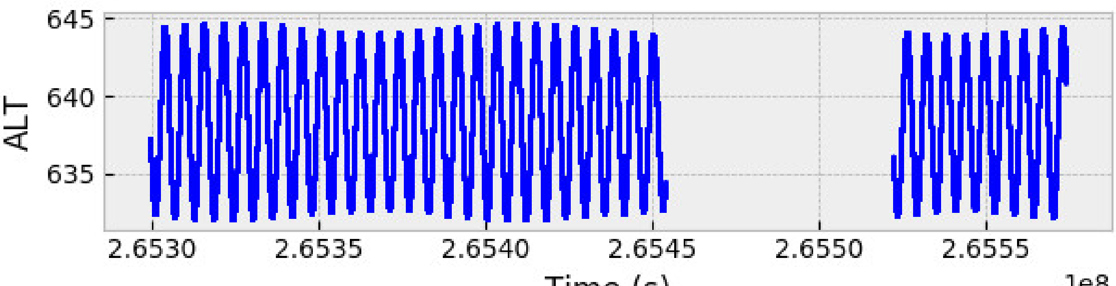
- Although the origin of period is not known the use of updated model improves the background fit significantly.

- During the pair of the last 4 adjustments there is a discrepancy in position of AstroSat between the individual and merged orbit data and also between orbit 14447 and 14448

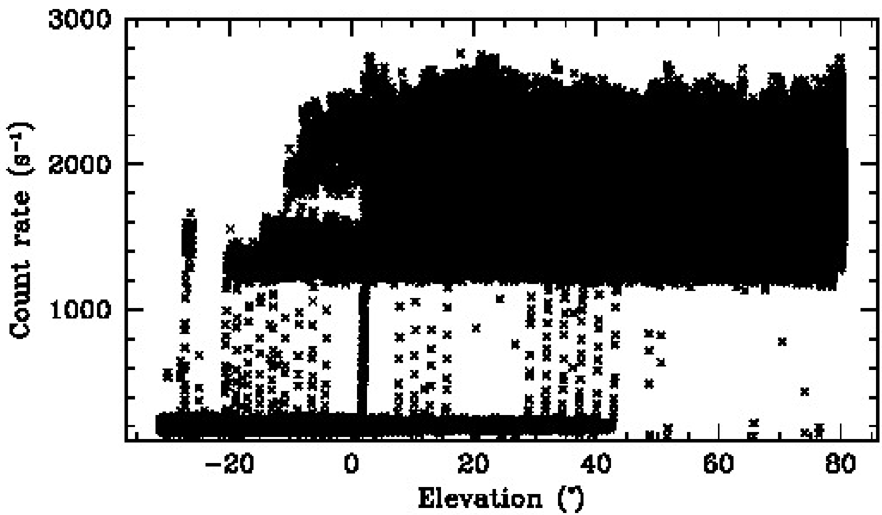
Individual orbits



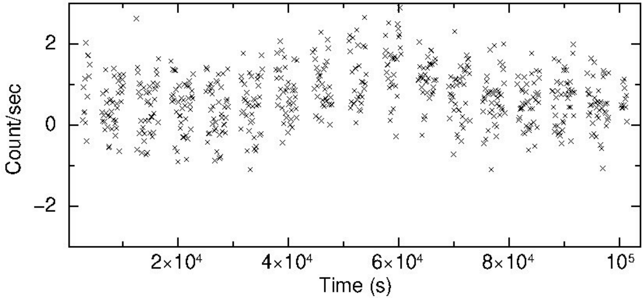
Merged orbits

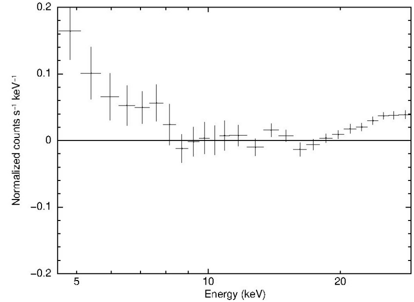


- The LAXPC software uses satellite position (and elevation) to calculate the GTI as well as the background model. Hence it is not possible to use the above mentioned data sets for scientific analysis. E.g., the elevation is incorrect for ObsID 2130.

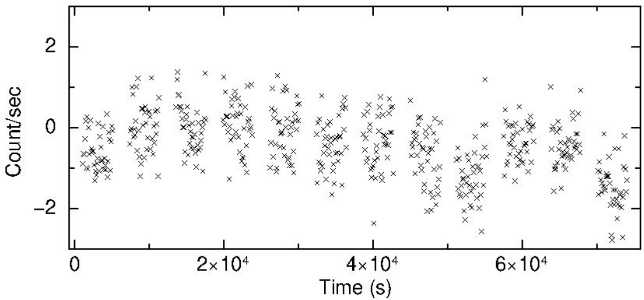


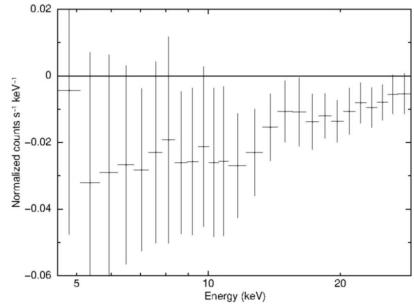
Nov 2020 background



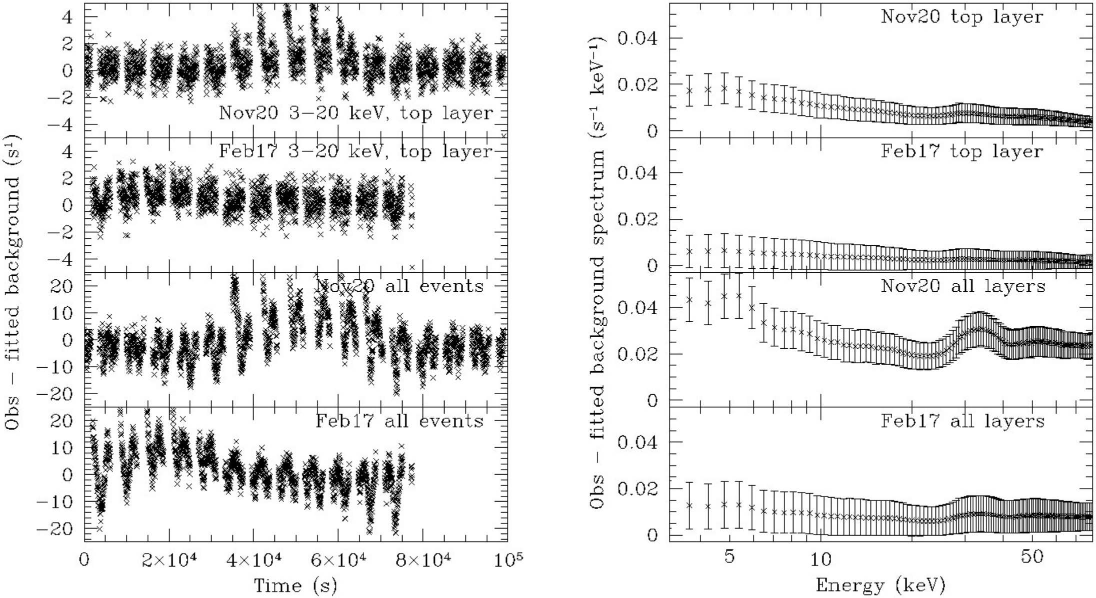


Feb 2017 background

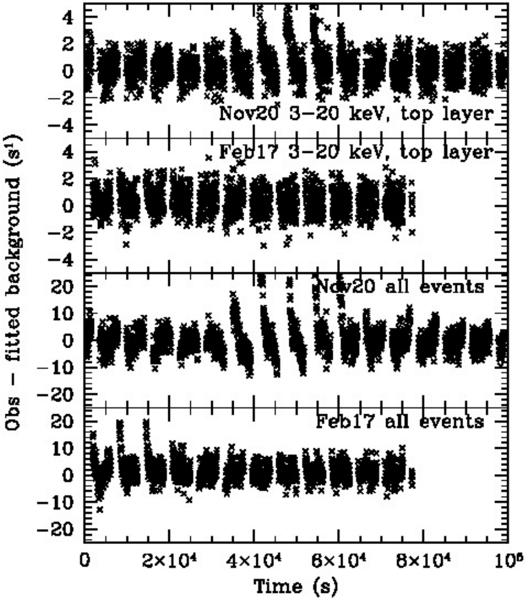


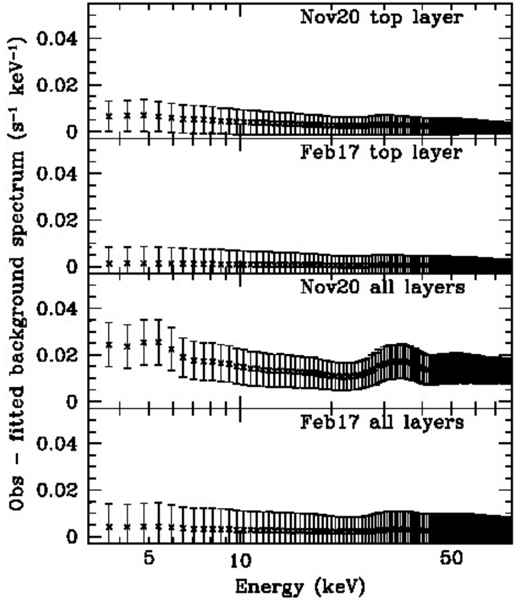


Background model for faint sources, only top layer

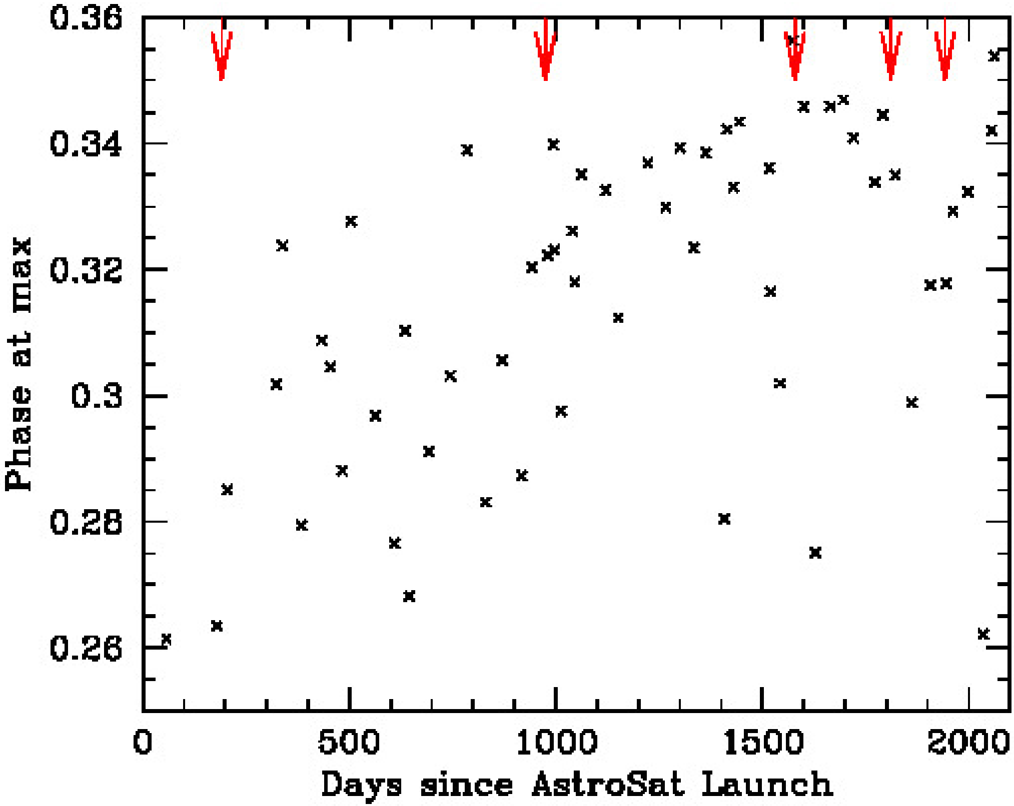


Background fit to lat and lon





Background fit to lat and lon after correcting for diurnal variation



0.36
0.34
0.32
0.3
0.28
0.26
Phase at max
0
500
1000
1500
2000
Days since AstroSat Launch

Summary

- Spectral analysis of LAXPC data needs to account for the gain shift and density variations (for LX30).
- To account for the shift in gain the background spectrum needs to be shifted to align with source before subtraction.
- Using only 2 calibration peaks it is not possible to get the energy to channel mapping. All shifts are being applied by assuming that only linear term needs to be changed to fit the 30 keV peak.
- To account for the shift in gain between the source and the response use the appropriate response with gain shift to analyse the spectrum.

- Considering the fluctuation in background count rate it is not possible to study sources fainter than a few mCrab. Even for bright sources the same will apply at high energies.

- Spectral studies may need to use gain-fit and additional Gaussian around 30 keV may also be needed.

- Software and response files for analysing LAXPC data are available at

  http://www.tifr.res.in/~antia/laxpc.html

  http://www.tifr.res.in/~astrosat_laxpc

  http://astrosat-ssc.iucaa.in