Detection and Characterisation of Cosmic Rays in AstroSat-CZT Imager data

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Abstract The Cadmium Zinc Telluride (CZT) Imager on-board AstroSat consists of pixelated CZT detectors, which are triggered by individual photons bombarding them, and records each such trigger separately as an individual ‘event’ with information about its time, detector co-ordinates, and channel, which scales with the energy of the photon. This makes it prone to detect not only photons from astrophysical sources of interest, but also to a number of other events. Preliminary analysis of the CZTI data already revealed the presence of cosmic rays. In this work, it is shown that in addition, it is also bombarded with higher energy cosmic rays, which produce signatures previously seen in the PICsIT detector on-board INTEGRAL. An algorithm to automatically detect them is presented. It is optimized to not eliminate known ‘double-events’, which are astrophysical produced photons and their Compton-scattered counterparts used for measuring polarization of astrophysical sources. The robustness of the algorithm is highlighted by using examples of Gamma Ray Bursts as target sources. The importance of using such an algorithm is highlighted for the detection of short Gamma Ray Bursts.

1 Introduction

AstroSat is a broad band high energy Indian mission covering UV, soft X-rays and hard X-rays [1]. It comprises mainly of four main instruments: Ultra Violet Imaging Telescope/UVIT [2,5], Soft X-ray Telescope/SXT [6,7], Large Area X-ray Proportional Counter/LAXPC [8,10] and Cadmium Zinc Telluride (CZT) Imager/CZTI [11]. CZTI is a hard X-ray detector sensitive in the energy range 20-200 keV, consisting of an array of CdZnTe crystals. Each detector module consists of 256 independent detectors, called pixels, of size 2.5 mm × 2.5 mm each. The CZT plane consists of four quadrants, each with 16 detector modules, comprising an effective area of 1024 cm². CZTI has imaging capabilities below 100 keV, using the Coded Aperture
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Mask (CAM) placed above collimator slats that surround the detector modules. The collimator is made of Tantalum of size 4 cm × 4 cm, which allows for a field of view (FoV) of 4.6° × 4.6°. In addition to spectroscopic, timing and localization capabilities [12], CZTI can measure the polarization in the hard X-rays with exposure time an order of magnitude smaller than previously existing instruments [13], making it an unique detector at these energies.

In the CZTI terminology, an ‘event’ is a trigger of any of the pixels, associated with an unique time-stamp, the pixel co-ordinates, and the ‘pulse height amplitude’ or PHA, which is linearly related to the energy of the photons that triggered the pixel. Being a wide-field open detector, CZTI detects photons from all directions within its wide FoV. These photons include those from the target source, called ‘science’ events, as well as those induced by other sources. The latter can include a steady rate of events induced by the charged particle environment of the detector, which other than showing predictable variation with the satellite co-ordinates, should show uniform random distribution about the mean. These events are called ‘background’ events. On top of this, events may be generated by the peculiarities in the detector and may not be triggered by photons in the first place. These need to be identified and removed before doing any scientific investigation of the events from the target source both in the temporal and energy domains, and are called ‘noise’ events. Only a careful analysis of the data can precisely define characteristics of noise, and subsequently eliminate them for the study of the science data.

The presence of cosmic ray induced noise events was deduced during the first days of the mission, and a simple algorithm implemented in the existing CZTI pipeline to eliminate them from the science data. They are easily distinguished from science events due to the temporal characteristics: they all ‘bunch’ together within the smallest interval of time resolvable by the CZT pixels, 20 μs [11]. A steady stream of these ‘bunches’ triggered by cosmic rays continuously bombard the detector plane. They temporally track the variation of the cosmic rays bombarding the entire satellite, independently measured by the Charged Particle Monitor (CPM) on-board AstroSat [14].

In this work, we have conducted a careful analysis of the data collected by CZTI for a number of GRBs. It is shown via careful reasoning that improvements in our understanding of bunches can be made. ‘Double-events’ are those that occur on neighbouring pixels at the same time (i.e. within 20 μs), and are used for polarization measurements by CZTI [13][15]. The effect of electronic noise on double-events is quantified by studying the behaviour of the bunched events during GRBs. Moreover, identification of heavy deposition of charge by very high energetic particles is done via patterns on the detector modules that are characteristic of pixelated detectors collecting data at such high time resolutions. A new algorithm is developed which automatically identifies and removes these events from the data to create further cleaned science data.

The software has been tested in the Python programming language. The scripts have being made publicly available [here]. The effects of of cosmic rays via bunches are carefully reinvestigated in Section 2 suggesting improvements of the current data flow in the existing CZTI pipeline. The effect of these ‘bunched’ events on genuine events are quantified. In Section 3 the flagging of grossly noisy elements are re-
examined. In Section 4, the effect of higher energetic cosmic rays on the CZTI data are reported, via an algorithm detailed in the Appendix. In Section 5, concluding remarks are presented.

2 Re-look at ‘cztbunchclean’

The overall instrument configuration, the detectors and electronics, the data characteristics, processing pipeline and default products have been discussed in detail in Bhalerao et al. (2017) [11]. All the work carried out in this paper uses the astronomer-friendly ‘Level 2’ (L2) FITS files created by the Payload Operation Centre (POC) of CZTI, located in the Inter-University Centre for Astronomy & Astrophysics (IUCAA) in Pune, India. This is executed by the first task in the CZT pipeline, documented here, the cztscience2event. The on-board bunchclean identifies the bunches present in the data, and removes the events except three events at the boundaries of each bunch for the purpose of latter identification; more details can be found in the above document. The next task in the pipeline is cztbunchclean, which removes the bunched events in the data remnant after the onboard bunchclean. In addition, currently it removes data for certain lengths of time skipT1, skipT2, skipT3 after the bunches, depending on the number of events in the bunch, termed as bunch_length_threshold. The values for these parameters have been set somewhat arbitrarily. In this section, we take a re-look at this task, and suggest alternatives to the parameters in the existing pipeline. For this, we have additionally used the data in the bunch files created by cztscience2event, to be henceforth termed as ‘bunch-files’.

2.1 Redefining bunches

The understanding behind the idea of bunches is that each bunch is created by one cosmic ray particle generating a series of electronic events within timescales shorter than the instrumental resolution of 20\(\mu\)s. If such is the case, then respective bunches are independent of each other, and the interval between one bunch and the next, \(\Delta T\), is expected to follow a smooth distribution. On plotting the histogram of \(\Delta T\) by using the bunch data, it is clearly seen that such is not the case, see Left of Fig. 1. This leads one to assume that the electronic effects of a single charged particle lasts for more than the time-resolution of the instrument. Hence we propose to redefine bunches such that, if the interval between one bunch and the next is less than a certain threshold \(t_2\), then these two bunches are understood to be created by the same cosmic ray particle and all the data within it are clubbed to a single bunch, henceforth termed a ‘super-bunch’. Empirically, it is seen that the sharp spike is removed on choosing \(t_2 = 60\mu\)s. For \(t_2 = 40\mu\)s, the spike is still clearly visible, whereas for \(t_2 = 80\mu\)s, the spike is replaced by a dip, clearly showing that it is an overkill. Thus, 60\(\mu\)s is optimal, see Right of Fig. 1. It is observed that less than 10% bunches are redefined as ‘super-bunches’. 
Fig. 1. ∆T is defined as the time interval between the end of a bunch and the start of the next bunch. Left: Bunch data after cztscience2event. The histogram peaks at small ∆T clearly showing that the definition of bunches is incorrect. The parameter for bunch redefinition, such that the histogram becomes smooth is referred to as t2. Right: With t2 = 60 µs, the histogram indeed becomes smooth. Although the above plots are taken from one orbit of March background data, this observation is true for all datasets examined. The first point in corresponds to the bunch redefinition timescale, and is an artefact created due to the limitation of the way division is carried out in the binary system; it persists whatever value of t2 is used, but is unimportant for our purposes.

Fig. 2. Left: A sharp drop is seen at timescales lesser than 60 µs if co-added lightcurve, corrected for the exposure, is made from data post bunches, even after redefining bunches. This implies that post bunches, significant amount of electronic noise, created by the bunches, is persistent. Hence, data post bunches is removed up to the parameter t3. Right: After flagging all data post bunches, with t3 = 60 µs, the co-added lightcurve looks flat as expected, all the way up to 2 ms, validating the assumption. All errors assume that the data is Poissonian, which is strictly true for the part away from the spike in Left.

2.2 Post-bunch cleaning

As noticed earlier, the electronic effects of cosmic-ray particles persist for some amount of time post-bunch, after initially triggering a series of events in the detector. We parametrize this timescale as t3, similar to skipT1, skipT2, skipT3. To estimate the optimum value of t3, we plot co-added lightcurves of events after the bunches. That
We experiment with different values of $t_3$. On choosing $t_3 = 60 \mu s$ and removing data for $t_3$ after each bunch (including superbunches), the co-added lightcurve indeed becomes flat around unity, implying that the removal of cosmic ray induced noise is finally complete. Right of Fig. 2 demonstrates this.

We have re-examined whether flagging only the affected detector modules also give the same result. For this we used long stretches of the same data, and experimented with different values of `bunch_length_threshold` to check whether heavier bunches affect nearby detector modules as well. It is found that that there is no difference to the resulting cleaned data if selective cleaning is done to only affected detector modules or not, based on `bunch_length_threshold`. The optimized value of $t_3$ is so small that most of the data successive to the bunches are mostly in the same modules, hence no difference is made. Thus, instead of three parameters for post bunch cleaning, only one is sufficient. $t_2 \sim t_3$ leads one to assume that the physical mechanism behind both the effects are same, that is electronic noise in the hardware, which is quantified in the next subsection.

The newly proposed method of cleaning the L2 data of bunches, constituting the two steps demonstrated in Section 2.1 and 2.2, is to be henceforth collectively and simply called ‘bunchclean’, as against ‘on-board bunchclean’ which leaves three events from each bunch in the dataset, and the pipeline task `cztbunchclean` which invokes the usage of the parameters `skipT1`, `skipT2`, `skipT3`, `bunch_length_threshold`.

### 2.3 Using bunches to quantify electronic noise created by source photons

We have carried out a preliminary examination of lightcurves of bunches for a few datasets, i.e. the time-series of the number of bunches detected, see Fig. 3 for an example. Sudden increase of the bunch-rate lasting for a few seconds are seen in such lightcurves, corresponding to possible increase of cosmic ray induced events. These features appear randomly in different datasets and quadrants. Moreover, they are almost always due to bunches with bunch-length (total number of events constituting a bunch) equal to 3 instead of higher. Sometimes bunches of greater lengths show gradual increase from the continuum level, but these features are not as sharp; moreover, they appear uncorrelated to bunches of length 3.

Temporal features in the bunches lasting for $\gtrsim 10$ s always appear at the same instances for bunches of different lengths. These are extremely rare ($\sim$ once in 10
Fig. 3 Bunch lightcurves for bright GRB160821A, with the time axis offset to the known GRB trigger time (note that the trigger time in all quadrants of CZT data as well as Veto for this GRB is offset by ~150 s from the value reported by IceCube). Such an enhancement is not expected if all bunches are due to cosmic rays. Left: All bunches. Right: Bunches with total number of events greater than 3 also show enhancement. Increasing this threshold does not suppress this effect, implying that GRB photons trigger electronic events mimicking as short as well as bunches.

orbits of data) phenomenon, and seem to affect Q3 the most, followed by Q2; however this statement is subject to low-count statistics. If it is true on the other hand, it can be understood to be caused by the fact that these quadrants are in the open side of the satellite and is hence prone to high energetic charged particles: Q3 is open from two sides as compared to one for Q2, whereas Q0 and Q1 are closed by high-Z absorbers from all sides.

If bunches are all indeed created by cosmic ray photons, then they should not show any enhancement during GRBs. Fig. 3 demonstrates that bunches do exhibit such an unexpected enhancement, although this phenomenon is extremely rare, seen for only the brightest of GRBs, e.g. GRB160623A, GRB160802A, GRB160821A. During these bright flashes, the chance-coincidence of single events with others may mimic double-events, and similarly, their chance-coincidence with double-events may mimic bunches. Let us denote the average single-event rate as $r_{1,b} \sim 200 \text{ s}^{-1}$, the average double-event rate as $r_{2,b} \sim 70 \text{ s}^{-1}$ etc., the temporal resolution of CZTI as $\delta t = 20 \mu\text{s}$, and the excess single-event rate during a bright GRB as $r_1 \sim 2000 \text{ s}^{-1}$. Then the chance-coincidence production rate of double-events during a GRB is $r_1 r_{1,b} \delta t = 8 \text{ s}^{-1}$, and the chance-coincidence production rate of bunches is $r_1 r_{2,b} \delta t = 2.8 \text{ s}^{-1}$. The chance-production rate of higher length bunches will be even smaller, and hence can be neglected. Thus, we see that only chance-coincidence cannot explain the enhancement of bunches during bright GRBs, falling short by at least one order of magnitude. Hence the identification of all bunches with cosmic rays is questionable. Moreover, the enhancement correlates with the GRB flux, being ~80 per second for GRB160623A, GRB160802A and ~150 per second for GRB160821A, the latter being brighter than the former two by roughly the same factor. We attempted to segregate this effect into bunches of different lengths, i.e. examined that whether the enhancement of the bunch-rate is only for bunches lesser
Fig. 4  Top: Bunch-rate versus event-rate (corrected for livetime) away from the duration of the very bright GRB160821A. \( r \) is the Pearson correlation coefficient, \( m \) is the slope of the fitted straight line. Left: In the raw data including bunches, i.e. before bunchclean. Right: After bunchclean: the correlation is gone, and the scale in the x-axis is reduced by half. The slope is reduced by a factor of ~ 3. Bottom: During the duration of the bright GRB160802A. Left: Before bunchclean. Right: After bunchclean; the correlation is still present. It is primarily driven by the small number of bins corresponding to the GRB excess. The slope obtained is comparable for all the three bright GRBs examined, before as well as after bunchclean. This clearly proves that there is a driving mechanism of the bunch excess by the GRB excess, independent of datasets used or the duration or flux of the GRBs. The similarity in the slope with that of the data devoid of GRBs post cleaning (Top-Right) is also indicative of the universality of this driving mechanism, implying that all source photons, including sky background, create such an electronic effect. Not all bunches can hence be thought to cosmic ray triggered. However, this gives an overall scaling in the number of bunches as well as double events. All bunches, whether induced by cosmic rays or this electronic mechanism, need to be removed anyway.

than a certain length. Although the enhancement during the GRBs is progressively lesser for bunches of higher lengths, for GRB160821A the enhancement is clearly seen for bunch lengths at least up to 6 (see Right of Fig. 3).

The bright GRBs provide the opportunity to study electronic effects that remain otherwise hidden in the data. For these GRBs, we create time-series of the total data, as well as the number of bunches, binned at the same timescale. Then we plot these two time-series data against each other, shown in Fig. 4. First we consider time intervals that do not include the GRBs. A clear correlation is seen between the two time
series. However, the correlation vanishes on executing `bunchclean`. The correlation, and its absence on implementing bunchclean on the dataset, is simply due to the fact that the overall event-rate depends on the cosmic ray induced events. This becomes clear by considering the fraction of the total events in the L2 data that happen to be bunches.

From the on-board bunch data available in the bunch files, we compute that the average bunch-length is 6. We note that, although it varies with datasets and orbits, the average bunch-rate is 70. Hence, the average event-rate in the raw data (i.e. before on-board bunchclean) due to the bunches remaining in the L2 data is $\sim 400$. We also note that the event-rate in the data after on-board bunchclean is also of the same order ($\sim 400$), and this is consistent with the known fact that the total event-rate before on-board bunch-cleaning is roughly twice the average number of events before bunchclean. This can be further illustrated from the slope of the best-fit straight line, which comes out to be $\sim 0.16$:

$$\text{slope (0.16)} = \frac{\text{avg bunch rate}}{\text{avg data rate}} \implies \text{avg bunch rate} = 0.16 \times \text{avg data rate}.$$  

$$\therefore \text{avg event rate due to bunches} = \text{avg bunch length} \times \text{avg bunch rate} = 6 \times (0.16 \times \text{avg data rate}) = \text{avg data rate}.$$  

Next, we plot the two time-series by considering data only around a GRB, as shown in Fig. 4, Bottom. Again a clear correlation is seen, irrespective of whether bunches are removed or not. However, the slope is reduced by a factor of $\sim 3$ as compared to the slope from the correlation seen earlier (i.e. for data not including the GRB time). Moreover, this slope is consistent between all the three GRBs for which bunch-excess is seen. The excess of event-rate from the background rate is less than 500 counts per second for weaker GRBs. 500 falls at the lower end of the correlations, explaining why significant bunch excesses are not seen during weaker GRBs. It implies that the inherent cause of these excesses are similar for all GRBs, and the effect is linear in the rate of incident photons. The slope can be used to calculate the probability of bunches being created from genuine photons, if it is assumed that all incident photons, whether they are from GRBs, background or created by cosmic rays, create additional electronic effects that mimic bunches. This assumption is in fact corroborated by the fact the slope obtained from the fit during the GRBs is of the same order as that obtained from the fit from the data away from the GRBs post bunchclean, as illustrated in Fig. 4, Top-Right. This conclusion is also seen to be independent of the dataset used, pointing to an universality of the driving mechanism.

Since the slope is $\sim 0.05$, the average number of bunches created by genuine photons is $0.05 \times 400 = 20$. That is, on an average, 20 out of 70 bunches are not induced by cosmic rays. However, the impossibility of distinguishing cosmic-ray induced bunches with bunches created by photons, as well as the identification of the source photons from the artificial electronic events within the latter kind, means that it
is always safe to remove bunches irrespective of the causal mechanism. The purpose of cleaning the data is to remove all events that are known to be created by anything other than source (including sky background) photons.

Assuming that the number of events in the electronically-generated bunches is $4^1$, the number of such events flagged during bunchclean $\sim 20 \times 4 = 80$. After all processes of cleaning, we are left with a total number of $\sim 200$ events (both single and double events), which means out $\sim 400$ events that are flagged during on-board bunchclean + bunchclean, $\sim 20\%$ are events due to source photon + associated electronic noise while the rest are events from genuine cosmic rays. If we extrapolate this idea to double events, we can say that $20\%$ of the remaining double events are generated by electronics, and since these are also likely to be in adjacent pixels, they can mimic what we think are Compton-scattered double-events. This fraction is significantly higher than that can be produced by chance-coincidence of single events during extremely bright GRBs as calculated earlier, and can affect polarization measurements of these bright GRBs.

3 Re-look at flagging gross noisy pixels

In the previous section, we have extensively discussed the task cztbunchclean of the CZT pipeline, and suggested an alternative task, simply referred to as the ‘bunch-clean’, consisting of two successive steps. In this section, we discuss the task cztpix-clean in the current pipeline, which is the next successive step in the pipeline that takes up the removal of the noise events from the data. This task consists of two logical steps: the identification of extremely hot pixels and removal of all data from them, and the identification of pixels which are temporarily giving unexpected results.

Currently, the way to identify the grossly misbehaving pixels is to iteratively identify and flag those which show greater than $5\sigma$ deviation in the total detector plane histogram (DPH), i.e. the histogram of the counts in the CZT plane, from the entire observation. Two modifications are attempted: one is to correct for the effective areas of the pixels (from CALDB file available along with the pipeline); the other is to make the DPHs every $t_{\text{avg}}$ during the observation, and scaling each DPH with its total counts before looking for outliers in the added DPH. The latter takes care of the variation of the event-rate within the particular observation, i.e. the variation of the background counts with the satellite position. Both the modifications are attempted individually as well as together, in the latter case in both possible orders. It is seen that the effective area of ‘spectroscopically bad pixels’ generally get over-corrected if CALDB data is used, and this leads to the identification of these pixels as gross noisy pixels. Flagging spectroscopically bad pixels from the data itself, however, does not lead to any change in the converged solutions, whether the lightcurve weighting is done or not. This holds true up to $t_{\text{avg}} = 2$ s, below which statistical uncertainties in the lightcurve actually leads to incomplete identification of the gross noisy pixels. We conclude that the solutions obtained by the current method is optimal and also the

$^1$ Although excess in the counts of different bunch-lengths are seen during GRBs, the excess becomes less prominent for bunch-lengths very much greater than 3, resulting in the average number of events in the bunch-excess to have bunch-length of 4.
most efficient. This is true even if there are bright GRBs in the data, because GRBs illuminate the entire quadrant instead of selective parts. Henceforth, we parametrize this step with \( \text{gross cutoff} \), which is the deviation (in units of \( \sigma \)) that is used to identify gross noisy pixels. The optimized value of 5 does a satisfactory job in the sense that the solutions always converge to the same gross noisy pixels, roughly 10 per quadrant, and are independent of the duration of the observation used (unless it is too small).

It is noted from the lightcurves of gross noisy pixels thus identified exhibit random and sudden features which are entirely uncorrelated with bunches, GRBs, features in the lightcurve of the Veto data, or even to each other. Occasionally they create loss of data-acquirement in other pixels because the number of events in these singular pixels themselves can be greater than the total allowed by on-board electronics. This effect is known, is taken care of while writing the ‘good time interval’ (GTI) columns in the L2 file created by the current data pipeline. The exposure correction of lightcurves, known as the ‘livetime correction’, accounts for this data loss.

4 DPHclean

The second part of the current task \texttt{cztpixclean} identifies temporarily ‘flickering’ pixels somewhat arbitrarily, based on the lightcurves of each pixel, and removing data if the countrate for an individual pixel becomes greater than a certain value. This might result in the removal of data during bright GRBs, which is what is indeed seen in the case of the bright GRBs. Currently, the CZT POC processes the data for bright GRBs separately to prevent the removal of GRB events. A careful re-look at this step of the task is made in the next section, leading to the discovery of higher energy cosmic rays in the data.

In the lightcurves made from the data after bunchclean and removing gross noisy pixels, strong temporary features lasting upto a few hundred milliseconds are observed (see Fig. 5). By making detector plane histograms (DPHs) of the events that create these features, it is seen that these events cluster in some parts of the detector plane rather selectively. The timescale for detecting such clustering is examined, parametrized by \( t_{\text{look}} \). Initially, such clustering are observed to be present for 5\( \sigma \) outliers in lightcurves binned at 100 ms. The events that contribute to the clustering are spread over timescales less than 100 ms, and only very rarely involve two consecutive bins of 100 ms. The automatic identification of such clustering in the DPHs, henceforth called ‘DPHstructures’, is implemented by an algorithm called ‘DPHclean’ detailed in the Appendix. Since this algorithm is independent of the total number of events in the DPH, the only constraint on \( t_{\text{look}} \) is that it should be more than the duration of such events. 100 ms is optimized in this regard, catching such clustering as well as being an order of magnitude smaller than the \( T_{90} \) of short GRBs, thus making it safe to allow independent identification of short GRBs even after the implementation of DPHclean.

A large fraction of the events clustered in DPHstructures occupy regions only a few pixels wide, see Fig. 6. Some of these DPHstructures includes pixels which register counts 4 or higher in 100 ms bins. Here it is pointed out that in case a DPH
shows clustering, only those events in the DPH that are responsible for the same are removed from the data by DPHclean. It that has the ability to identify them, and in the presence of such clustered events even during bright GRBs, the algorithm selectively picks out only the events in the cluster and removes them, instead of the GRB photons. The advantage of such selective identification is evident. It is noticed that running this algorithm on all DPHs made from a given set of data reduces the noise significantly more than selectively running it on (say 5-sigma) outliers in the lightcurve. To highlight the case that randomly distributed GRB photons are left unharmed by DPHclean, Fig. 5 compares the lightcurve binned at $t_{\text{look}} = 100$ ms before and after implementing this step.

In Fig. 7 are plotted the lightcurves of bunches and DPHstructures, both binned at 100 s intervals for a full orbit data. The overall rise towards the end of the orbit as the satellite enters the South Atlantic Anomaly (SAA) is clear for bunches, whereas for DPHstructures, it is only marginal. However, this similarity points to the origin of
both kinds of events in charged particles. The quadrant-averaged orbit-averaged rate of DPHstructures is $0.245 \text{ s}^{-1}$.

We have investigated any possible temporal correlation of bunches with DPHstructures, to understand whether DPHstructures could be caused by heavy bunches. In Fig. 8 is shown the histogram of the difference between the start-time of a DPHstructure with the end-time of the bunch that just precedes it. No causality is found at time intervals less than 1 ms. That is, bunches and individual DPHs are statistically independent events.
Fig. 8  Histogram of the time difference between the start of a DPHstructure with the end of the bunch just preceding it, denoted here as $\Delta T$. There is no non-statistical rise of the number of such coincidences all the way up to $\sim 100$ ms, indicating that there is no causal correlation between bunches and DPHstructures.

Segreto et al. (2003) [16] studied the detector characteristics of the PICsIT detector plane of the IBIS instrument on board INTEGRAL, and found events similar to DPHstructures. To investigate their cause, they plotted detector delay histograms (DDHs) corresponding to each DPHstructure. DDHs are histograms on the detector plane of the delay of the events contributing to a particular DPHstructure with respect to the first event. They found the evidence of two kinds of events: linear tracks, and a particular kind of delay pattern— a gradual increase of the delay towards the centre of the ellipses that were illuminated. They explained these by the bombardment of the detector plane by charged particles or cosmic ray showers generated by hadronic and leptonic processes very close to the detector. They demonstrated that the delay in the first and last events in a particular DPHstructure being $\sim 100$ ms could be explained by the saturation of the pixels by the extreme high energies of the charged particles, the pattern on the detector tracing the density of the cosmic ray showers in the logarithmic scale. Inspired by these findings, we plot DDHs for our DPHstructures, some examples are given in Fig. 9. We see two kinds of events:

1. Those tracing linear tracks indicating trajectories of physical entities along them (Fig. 9, Top). This points to the origin being charged particles which deposit their energy over multiple pixels that fall on its trajectory of motion through the detector.
2. Those with the delay being more in the inside of a cluster compared to its boundaries (Fig. 9, Bottom).

Both the kinds of events are in striking similarity with the DDHs observed in PICsIT on board INTEGRAL, and naturally leads one to the hypothesis that DPHstructures in CZTI are also created by the bombardment of high-energy charged particles or cosmic ray showers.
Fig. 9 Detector Delay Histograms: Plotted in color are the delay of the particular event from the first event in the cluster, in milliseconds, as a function of the position in the detector plane. These examples last unusually long, covering two consecutive bins. In Top, we observe linear tracks, the delay increasing along the track in Top-Right. The delay patterns in Bottom are remarkably similar to those seen in PICsIT on INTEGRAL due to phosphorescence-decays from events triggered by cosmic ray showers.

Some cosmic rays might deposit their energies over multiple pixels instead of a few because being more energetic than their counterparts that create bunches, they are above the detectable energy threshold of the pixels, thus saturating them. When the pixel output current drops below this threshold, they start registering events. The saturation timescale observed in the detectors then corresponds to the delay from the onset of the events created by these cosmic rays on the detector plane. The fact that DPH structures are much less frequent than bunches, also corroborates such a hypothesis. Also, it naturally explains the delay pattern of the second kind, that is those with progressively higher delays towards the centre of the pattern [16]. When a cosmic ray shower hits the detector, the density of the particles in the shower are traced by the delay in the DDH. The delay timescale in the detector pixels are thus deduced to be a few 100 milliseconds.

The energy of the cosmic rays cannot be calculated directly. However, we place constraints on the energy of both bunches and DPH structures from the observed rate of the events, assuming a standard spectrum of cosmic rays [17]:
Fig. 10 The limits of the energies of three kinds of events: bunches, high-frequency DPHstructures, and low-frequency DPHstructures. The lower limit of the bunches is $\sim 7$ GeV. The frequency cut of DPHstructures is based on the number of unique points in the DPHstructures, and is put roughly at the start of the tail of this curve, see Fig. [6]. The higher end of the low-frequency DPHstructures is 100 TeV, but shown here only till 1 TeV for representational purposes.

\[
d\frac{N}{dE} = 1.8 \times 10^4 \frac{\text{nucleons}}{\text{s} \text{m}^2 \text{sr} \text{GeV}} \left( \frac{E}{1 \text{GeV}} \right)^{-2.7}.
\]

We assume that the DPHstructures illuminate 10 pixels on an average, which is an area of 160 cm$^2$, and integrate over all solid angles, between energy limits $E_{\text{min}}$ and $E_{\text{max}}$ and match them with the observed rates of bunches and DPHstructures. For the purpose of continuity, we divide the DPHstructures into two kinds of events on the basis of their frequency, with the criterion being the number of unique points in the DPHstructure $\lesssim 10$. The orbit-averaged, quadrant averaged, rates of bunches, high-frequency and low-frequency DPHstructures are respectively $70 \text{ s}^{-1}$, $0.200 \text{ s}^{-1}$, and $0.044 \text{ s}^{-1}$. Assuming an upper limit of the low-frequency DPHstructures as 100 TeV, the energy-limits thus derived are shown in Fig. [10]. The lower limit of the bunch energies comes out to be $\sim 7$ GeV.

Finally, the question that remains unanswered is: What is the physical mechanism that creates the $\sim 100$ ms timescale saturation effect in the pixels? For PICsIT, the timescale was explained by fluorescence states of the CsI detectors, which is not possible for CdZnTe detectors of the CZTI. The only explanation is the following: The extreme high energy of the cosmic rays that hit the individual detectors lets current pass through the RC-circuit that provides stability to the source of power to these detectors. That is, due to the extremely high energy deposited in the individual detectors in an extremely small time, they successfully exchange power from the power source, thus remaining saturated until the impending RC-circuit has stabilized. Then the timescale of the saturation is given by the time-constant of the impending
Table 1 Optimal values of chosen parameters in the proposed pipeline. $t_2$ and $t_3$ are discussed in Section 2, gross cutoff in Section 3, $t_{\text{look}}$ in Section 4, and threshold and allowable in Appendix.

| Parameter       | Proposed optimal values |
|-----------------|-------------------------|
| $t_2$           | 60 $\mu$s               |
| $t_3$           | 60 $\mu$s               |
| gross cutoff    | 5                       |
| $t_{\text{look}}$ | 100 ms                  |
| threshold       | 0.70                    |
| allowable       | 3                       |

Fig. 11 Left: All events at start. Right: All single events post cleaning.

RC-circuit, which is $\sim$ 100 ms. Unfortunately, there is no way to directly corroborate such a hypothesis, and we are forced to leave it there.

5 Conclusions

The two tasks in the existing CZTI pipeline, the $\text{cztbunchclean}$ and the $\text{cztpixclean}$, have been investigated thoroughly in this work, using data from multiple GRBs as test cases. Through careful investigation, a complete understanding of the effect of cosmic rays on CZTI data is presented. The term ‘noise’ is understood rigorously, via patterns in the data that are representative of events definitely not triggered by astrophysical source photons, in this case GRB photons. Modifications to $\text{cztbunchclean}$ are suggested. For $\text{cztpixclean}$, no modification to its first part involving the removal of data from grossly noisy pixels is required. However, a smarter and more robust algorithm called the ‘DPHclean’ is suggested to replace the second part of this task, which currently involves the detection of temporarily flickering pixels by the average countrates as a function of time. The reason behind the flickering of pixels is identified to be higher energy cosmic rays that create predictable patterns on the detector plane, here called ‘DPHstructures’. The robustness of the algorithm is extensively demonstrated.

The optimized values of the parameters for the revised tasks in the pipeline are listed in Table 1. ‘Livetime corrections’ refer to the corrections to lightcurves due
to the reduction of the exposure time of the detectors while cleaning the data of noise. Such corrections are initially calculated from L2 good time interval (GTI) data, updated sequentially after each step proposed, and implemented on the lightcurves. Livetime corrected lightcurves for a stretch of data before and after GRB160802A, at the start with L2 data, and after all steps of cleaning, are shown in Figs 11 and 12.

The current CZTI pipeline requires careful reprocessing of data of bright GRBs due to the conservative nature of the removal of “noise” from science data, which removes some GRB photons as well. This not only makes the continuum data before and after the GRBs more noisy, it also makes it currently impossible to independently search for GRBs in the wealth of CZTI data, limiting the searches to ones triggered by alerts from other space-based missions. Comparison of the number of GRBs detected by CZTI with such triggered searches, with predictions from the study of the luminosity function of GRBs, reveals that a good fraction of GRBs are yet to be found – both the long [18] and the short [19] kinds. This requires development of an automated algorithm that searches for GRBs independently detected by CZTI. In this work, it is extensively demonstrated that the proposed modifications will segregate science data with noise in the same stead for continuum count-rates and bright GRBs, and have been developed keeping the natural durations of GRBs durations in mind. Thus, these modifications are a crucial precursor to an automated GRB-detection algorithm.

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Fig. A.1 Histograms of $N_{\text{points}}$ (Top-Left), $M_{\text{sum}}$ (Top-Right) and $N_{\text{pairs}}$ (Bottom) with different values of $\text{threshold}$. Since most of the pairs are non-identical, $N_{\text{points}}$ is more likely to be even than odd, hence it shows regular dips at odd integers. It is observed that these parameters are insensitive to the value of $\text{threshold}$ chosen. Hence, it is fixed at its most conservative upper limit throughout the work.

Appendix: Algorithm for detecting ‘DPHstructures’

The aim of such an algorithm is to consider a DPH, and numerically decide whether the DPH shows any clustering or not. It is to output a flag 0 if clustering is detected or 1 if it is not. A requirement of such an algorithm is that it should be independent of the total number of events in the DPH, since it is to be run on DPHs made during average count-rates as well as during GRBs. The algorithm is detailed below:

- Consider only those pixels in the DPH which register non-zero counts. If there are $n$ such pixels, there are $\binom{n}{2}$ pairs. For each pair, calculate a measure of ‘hotness’,

$$m_{ij} = \frac{c_i \times c_j}{D_{ij}},$$

where $c_i$ is the counts in the $i^{th}$ pixel and $D_{ij}$ is the distance between the pixels (in units of detx/dety, which is unity). This quantity is large if count in either pixel is large, and/or if the distance between the constituents making the pair is small.

- If

$$m_{ij} > \text{threshold},$$

call it a ‘hot pair’. It is to be noted that the maximum allowable value for threshold is

$$\text{threshold}_{\text{max}} = \frac{1 \times 1}{\sqrt{2}} = 0.707,$$

which is the case for two diagonally-located neighbouring pixels registering 1 count each. If threshold is larger than this, we will miss these hot pairs, thus defeating the purpose.

- Construct the set of all pixels which contribute to any such hot pair.
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Fig. A.2 Left: Histogram of the parameter $M_{\text{sum}}/N_{\text{points}}$ for the DPHs which are not flagged. It rarely goes close to 3, which is the value of $allowable$ used for flagging. Right: Same for the ones that are flagged. Note that although the total number of flagged DPHs in a typical dataset is much smaller than the number of DPHs that are flagged, most of them do not have any hot pairs, hence both $M_{\text{sum}}$ and $N_{\text{points}}$ are zero. Left includes only those within finite values of $M_{\text{sum}}$ and $N_{\text{points}}$, explaining why the total number is smaller than in Right. The sharp increase at values close to 4 in Right, compared to the rarity of those in Left below 3, demonstrates that the distinction is real. The reality of this distinction is also verified by manual examination of each DPH for long stretches of data which preferentially include weak as well as bright GRBs, examples of which are given in Fig. A.4.

Fig. A.3 Random DPHs are simulated with the event-rate as input. The parameter $allowable$ is allowed to vary, and flagging is carried out on the random DPHs based on these variable values. The plot show the resulting number of DPHs flagged as a percentage of the total number of DPHs simulated (5400), as a function of the variable. Average count-rate of 150 per second, and high count-rate during bright GRBs, 1500 per second, are considered. The flagged percentage is 0 for $M_{\text{sum}}/N_{\text{points}} > 3$, proving the robustness of the algorithm for both the average data and during GRBs. In fact, it is more robust when the count-rate is more, i.e. DPHs during bright GRBs have ~ 0 probability of getting flagged.
Fig. A.4  Top: On the left is a DPH which shows clustering (the color-bar is of counts), with the identified clustered events shown in the right. Bottom: On the left is a DPH that does not show clustering. The pairs that are used to test the clustering are explicitly shown in the right to demonstrate that the presence of such random pairs are not enough to flag this DPH.

- Modify the choice of hot pairs: if a pair is such that it consists of two neighbouring pixels only, each registering one count, and there is no hot pixel in its immediate neighbourhood, then do not consider the pair for the following steps. This ensures that actual double events are not considered whereas neighbouring pixels with one count each in the neighbourhood of a cluster are retained.
- Calculate the ‘gross’ parameters:
  1. total number of non-identical points contributing to the identified hot pairs: $N_{\text{points}}$;
2. the sum of the measures of the hotness for each such hot pairs:

\[ M_{\text{sum}} = \sum_{\{\text{all pairs}\}} m_{ij} ; \]

3. the number of hot pairs detected (note that even if one pixel contributes to two/more hot pairs, all these pairs are counted): \( N_{\text{pairs}} \).

- Construct a parameter based on these gross parameters as a proxy for the randomness in the DPH. When the value of this proxy exceeds a certain cutoff, parametrized by allowable, then the DPH is flagged, i.e. deemed to show clustering; otherwise not.
- If the DPH shows clustering, identify only those in it that contribute to this flagging. Particularly, remove any lingering isolated single or double event that may have correlated with a pixel registering multiple counts, owing only to their proximity.

To optimize the values of threshold and allowable, we resort to simulations of random DPHs, with mean count-rate of single and double events as inputs. The mean count-rate is typically 90 for single and 60 for double events, so in a 100 ms timescale, they are 9 and 6 respectively. First the number of single and double events to be chosen for a particular DPH to be simulated are drawn from Poisson distributions with the given means. Then, these many values of detx and dety are drawn from a uniform random distribution of all possible detx and dety values (0 to 63). For double events, one of the neighbouring events is first chosen randomly and the other is drawn randomly from the neighbouring coordinates, taking due care of corners and edges. For the case of GRBs, the mean count-rates input into the simulation process are increased, as discussed below (see Fig. A.3).

For each such simulated DPH, the gross parameters \( N_{\text{points}} \), \( M_{\text{sum}} \) and \( N_{\text{pairs}} \) are calculated, and this is done on multiple DPHs (typically 5400 for one full orbit) with different inputs to the parameter threshold. The identification of hot pairs based on threshold is insensitive to the value of this parameter, as demonstrated in Fig. A.1. Hence it is safe to keep it fixed at its most conservative maximum value, i.e. 0.70, which will detect diagonally-placed neighbouring pixels each registering a count.

Next, we experiment the construction of allowable based on the three gross parameters, and flag random DPHs based on the different experimental values of these parameters. It turns out that both allowable = \( M_{\text{sum}} \) = 8 and allowable = \( N_{\text{pairs}} \) = 8 flag less than 1% random DPHs, but this conclusion is seen to break down in the presence of bright GRBs like GRB160802A, since the number of photons in the DPH are \( \sim 10 \) greater than the usual, resulting in random pixels getting paired and marked as hot pairs. Normalizing any of the parameters by the total number of photons does not help because extremely bright DPHstructures has total number of counts comparable to the total counts in random DPHs during GRBs, simply because the clustering illuminates its neighbourhood very brightly. Hence we define allowable = \( M_{\text{sum}}/N_{\text{points}} \), which normalizes for the additional \( M_{\text{sum}} \) contribution from the pairs that are created due to chance co-incidence of a larger number of random events during GRBs. This simple modification fantastically tells clustered DPHs from random ones, see Fig. A.3. The reason is that, although the total number of counts in a clustered DPH is large, the clustering is spread over a few pixels, and the same pixels register many events; on the other hand, random DPHs with increased total counts, where the \( M_{\text{sum}} \) is increased by co-incidental pairing of random events, have many such pairs which are themselves randomly distributed over the entire quadrant. In comparison, allowable = \( M_{\text{sum}}/N_{\text{points}} \) does not do a better job because the small number of neighbouring pixels in a cluster tend to pair up with most of the other pixels in the cluster.

Random DPHs from GRBs and during average count-rates are examined along with DPHs that show clustering: it is seen that allowable = \( M_{\text{sum}}/N_{\text{points}} = 3 \) distinctly separates clustered DPHs from random ones, whether they are during a GRB or otherwise. This is verified first visually by looking at a significant number of DPHs by eye, and also demonstrated in Figs A.2 and A.3. Examples of detected DPHstructures and also DPHs with non-detections are shown in Fig. A.4.

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