

Miniaturized X-ray telescope for VZLUSAT-1 nanosatellite with Timepix detector

To cite this article: T. Baca *et al* 2016 *JINST* 11 C10007

View the [article online](#) for updates and enhancements.

Related content

- [Microtomography with photon counting detectors: improving the quality of tomographic reconstruction by voxel-space oversampling](#)
J. Dudak, J. Zemlicka, J. Karch *et al*.
- [Characterization of the Dosepix detector with XRF and analog testpulses](#)
I Ritter, G Anton, R Ballabriga Sune *et al*.
- [Characterization of GaAs:Cr-based Timepix detector using synchrotron radiation and charged particles](#)
P. Smolyanskiy, G. Chelkov, A. Guskov *et al*.

Recent citations

- [Low-dispersion spectroscopy with cubesats and photographic plates](#)
R. Hudec
- [Optimization of mirror spacing or pore width of lobster eye optics](#)
V. Tichá and R. Willingale
- [VZLUSAT-1: Health monitoring system, preliminary results](#)
O. Nentvich *et al*



IOP | ebooks™

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the collection - download the first chapter of every title for free.

18TH INTERNATIONAL WORKSHOP ON RADIATION IMAGING DETECTORS
3–7 JULY 2016,
BARCELONA, SPAIN

Miniaturized X-ray telescope for VZLUSAT-1 nanosatellite with Timepix detector

T. Baca,^{a,1} M. Platkevic,^b J. Jakubek,^c A. Inneman,^d V. Stehlikova,^a M. Urban,^a O. Nentvich,^a
M. Blazek,^a R. McEntaffer^e and V. Daniel^f on behalf of Medipix2 collaboration

^aFaculty of Electrical Engineering, Czech Technical University in Prague,
Technicka 2, 16627 Prague 6, Czech Republic

^bInstitute of Experimental and Applied Physics, Czech Technical University in Prague,
Horska 3a/22, 12800 Prague 2, Czech Republic

^cADVACAM s.r.o.
Na Balkane 2075/70, 130 00 Praha 3, Czech Republic

^dRigaku Innovative Technologies Europe s.r.o.,
Novodvorska 994, 14221 Prague 4, Czech Republic

^eDepartment of Physics and Astronomy, University of Iowa,
704 Van Allen Hall, Iowa, U.S.A.

^fAerospace Research and Test Establishment, Prague,
Beranovych 130, 19905 Prague, Czech Republic

E-mail: tomas.baca@fel.cvut.cz

ABSTRACT: We present the application of a Timepix detector on the VZLUSAT-1 nanosatellite. Timepix is a compact pixel detector (256×256 square pixels, $55 \times 55 \mu\text{m}$ each) sensitive to hard X-ray radiation. It is suitable for detecting extraterrestrial X-rays due to its low noise characteristics, which enables measuring without special cooling. This project aims to verify the practicality of the detector in conjunction with 1-D Lobster-Eye optics to observe celestial sources between 5 and 20 keV. A modified USB interface (developed by IEAP at CTU in Prague) is used for low-level control of the Timepix. An additional 8-bit Atmel microcontroller is dedicated for commanding the detector and to process the data onboard the satellite. We present software methods for onboard post-processing of captured images, which are suitable for implementation under the constraints of the low-powered embedded hardware. Several measuring modes are prepared for different scenarios including single picture exposure, solar UV-light triggered exposure, and long-term all-sky monitoring. The work has been done within Medipix2 collaboration. The satellite is planned for launch in April 2017 as a part of the QB50 project with an end of life expectancy in 2019.

KEYWORDS: On-board space electronics; Space instrumentation; X-ray detectors and telescopes

¹Corresponding author.

Contents

1	Introduction	1
1.1	Contribution and Outline	2
2	The mission	2
2.1	Observation candidates	2
3	X-ray telescope	2
3.1	X-ray optics	3
3.2	Timepix board payload	3
3.3	Sensor selection	4
3.4	Data outputs	5
3.5	Single photon event filtering	6
3.6	Measurement modes	6
4	Testing and experiments	7
5	Conclusion	8

1 Introduction

Miniature satellites, widely known as CubeSats, become frequent subjects of research among universities and small research groups. The simplest CubeSat falls into a category of a small cube probe with dimensions around 10 cm per side and weight up to 1 kg, usually deployed in Low Earth Orbit (LEO). Nowadays, CubeSats are based on a standard firstly specified by [4] which further led to a development of hardware and software platforms like GomSpace [5]. The CubeSat standard specifies variety of nanosatellite form factors, namely 1U (single unit), 2U and 3U with dimensions $10 \times 10 \times 11$, $10 \times 10 \times 22$ and $10 \times 10 \times 33$ cm respectively. The platform is widely used as an educational tool and allows low-cost verification of small instruments in space.

The following text describes a payload onboard nanosatellite VZLUSAT-1 which is a demonstration mission developed in the Czech Republic. The satellite houses several experiments with the aim to test and verify new commercial and experimental payload in space. VZLUSAT-1 is 2U CubeSat which transforms to 3U by deploying the X-ray telescope and solar panels. The aim of the project is to test and verify the technology of a small, wide-field telescope which could be in the future a tool for X-ray all-sky monitoring. All-sky monitoring is an important part of searching for extra-terrestrial Gamma Ray Bursts. These are usually short events lasting up to several days, which can be effectively discovered by wide-field space telescopes.

1.1 Contribution and Outline

In this paper, we propose a miniature X-ray telescope onboard VZLUSAT-1 nanosatellite. The telescope is a combination of a Lobster-Eye (LE) X-ray optics and a detector board comprising Timepix sensor. The presented solution is capable of onboard image processing, simple data analysis and allows to automate exposures of observation candidates, mainly the Sun.

The paper is structured as follows. In section 2 we introduce the satellite in a context of QB50 mission. In section 3 we describe the telescope's main parts, the optics, and the detector board. We present the integration of the Timepix sensor in section 3.2 followed by the description of measurement modes and processing methods in section 3.4. Lastly we discuss experiments and testing of the telescope in section 4. The conclusions are drawn in section 5.

2 The mission

VZLUSAT-1 is a part of QB50 mission [7], which focuses on distributed measurements of Earth's lower thermosphere during atmospheric descend. As the name suggests, there are 50 nanosatellites scheduled to be launched with complementary atmospheric sensors. The mission is split into multiple stages, launching portion of the satellites from International Space Station, while others are carried by dedicated booster rockets. VZLUSAT-1 is scheduled to be launched in April 2017 to 450 km Sun-synchronous LEO. Its life expectancy is estimated to 2 years. Beside the QB50 mission sensors, other scientific experiments are carried onboard including the presented X-ray telescope. Radiation-hardened composite, of which the satellite's housing is made, is tested for its material properties, while the release of volatiles is measured. The satellite is equipped with active electromagnetic stabilization which will allow basic detumbling after the launch and is supposed to stabilize it pointing along its orbital trajectory. Duplex radio link enables to download measured data regularly as well as upload scripts that control the instruments.

2.1 Observation candidates

Among all sources, the Sun is the most prominent X-ray source. The X-ray photon flux can vary from tens to thousands of photons per second per 1 cm^2 , depending on the current solar activity. Other possible sources for observation are Terrestrial Gamma-ray Flashes as a consequence of lightning bolt activity and thunderstorms on Earth. Lastly, sources outside of our Solar system are also considered, Scorpius X-1, Crab nebulae and Mrk 421.

3 X-ray telescope

The X-ray telescope consists of two main parts — X-ray optics and a detector board. A pantograph-based mechanism was designed to deploy the optics from the body of the satellite, which allows using a larger focal length. The mechanism is spring-loaded and just like a deployment of additional two panels it is triggered during first phases of the mission, after ejecting from the booster rocket. The telescope's focal length is 250 mm after its deployment, see figure 1 for illustration. The detector board is situated amidst other payload boards. Space is dedicated to allowing passing of X-ray photons to the detector unobstructed, while other unwanted paths are radiation shielded. The telescope is designed for 3° field of view and 5–20 keV energy range.

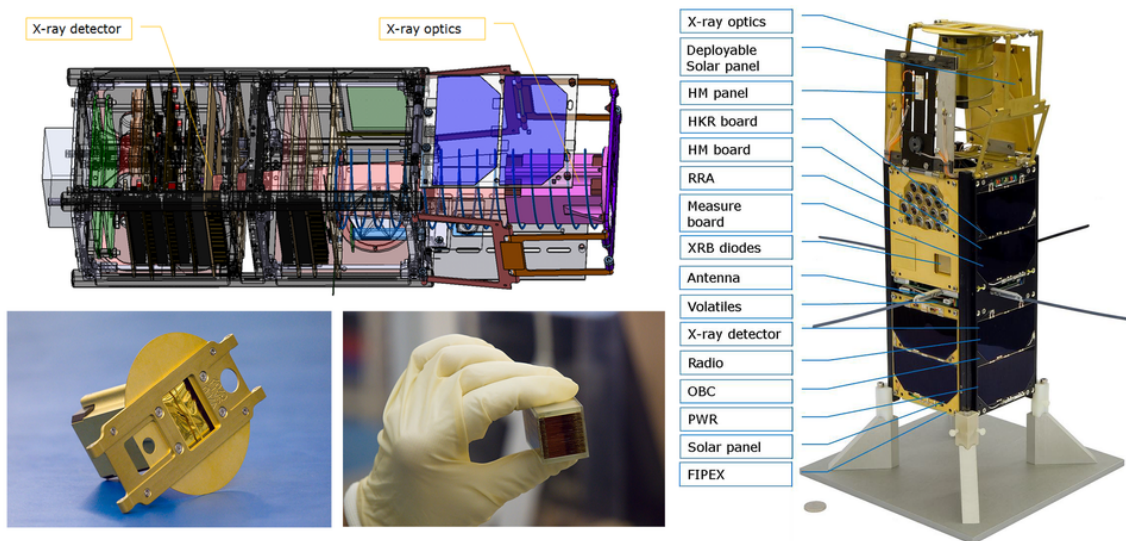


Figure 1. Photo of the satellite with the optics deployed (right), optics in and out of its housing (bottom-left) and a rendered model of the satellite (top-left).

3.1 X-ray optics

Optics for focusing X-ray photons is known to be a sizable and heavy part of most of the X-ray space observatories. Building small and lightweight modules is crucial in the development of small satellites designed for real-time all-sky monitoring. VZLUSAT-1 is equipped with 1-dimensional optics inspired by lobster’s eye, which is a simplified version of 2-dimensional model presented in [9]. It consists of 50 glass foils which are gold-coated on both sides to allow reflections of X-ray photons. The optics concentrate the light on a focal plane by reflecting it in between the foils. Its aperture is 29×19 mm and focal length is 250 mm. The light is gathered from the field of view of 3° which is considered wide-field comparing to other space telescopes. A coded mask in the form of a thin tungsten bar is placed in front of the optics to localize observed object’s position in the second dimension. Figure 1 shows the optics in and out of its housing.

3.2 Timepix board payload

The sensor board is the part of the telescope which provides data acquisition, readout, exposure parameter setting, image processing, and data compression. It houses the USB Lite interface [1] with the Timepix sensor and manages the communication with its embedded microcontroller as well as communication with satellite’s main computer. The USB Lite interface has been modified to support communication over UART while the USB connectivity has been removed. An anodized aluminum heatsink is placed directly in between the detector and the USB Lite interface allowing sufficient passive cooling of the detector even in a vacuum. Experiments in thermo-vacuum chamber showed that the heatsink’s temperature does not exceed 60°C even during continuous measurement.

The payload board is built around Atmel ATxMega128a4u, an 8-bit microcontroller with 8 kB of internal RAM. Additional 256 kB of external non-volatile FRAM memory provide a temporary space used for image processing as well as persistent memory for storing settings. To fully interpret the images from Timepix sensor, deserialization and derandomization methods are implemented in

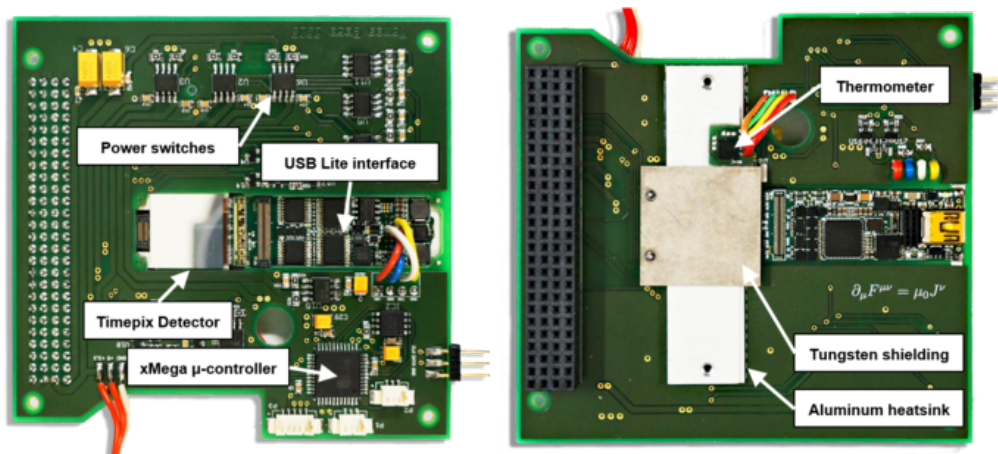


Figure 2. The detector board with all its components including USB Lite interface with Timepix2 ASIC chip, Atmel microcontroller, heatsink and power switches.

the Atmel processor together with full control of the USB Lite interface. Single equalization matrix is stored in a compressed form in a program memory of the processor.

An additional hardware of the board allows the satellite’s main computer to cut off power and communication lines to the payload itself. Several other sensors are connected to the microcontroller. Thermometer monitors the temperature of the heatsink and triggers a safety shutdown in a case of overheating. Infrared and wide-field UV sensors are connected to support a better estimate of satellite’s orientation above Earth. Narrow-field UV sensor provides an automatic trigger in the case of Adrenaline mode (see section 3.6 for more details).

3.3 Sensor selection

Several constraints define what detector and readout can be used on a small satellite such is ours. Mainly due to the CubeSat’s small size, power input from its solar panels is not sufficient for any potential active cooling of a sensor like a CCD. The size and weight of the instrument are also a defining factor. We adopted the Timepix readout chip and USB Lite interface. The interface was developed in the frame of the Medipix2 Collaboration at the Institute of Experimental and Applied Physics (IEAP) of the CTU in Prague [1]. Timepix is a hybrid semiconductor pixel detector with 256×256 pixels having $55 \mu\text{m}$ pitch. It does not require any special cooling besides removing its built up heat. Despite its name, USB Lite interface allows us to interface the Timepix on a low level using UART serial line while providing all necessary interface to the ASIC (Application-specific Integrated Circuit), namely supply and bias voltages, LVDS communication and clock.

As a detector, $300 \mu\text{m}$ of silicon was selected. Such detector material allows capturing of photons in the range of 5–20 keV, which corresponds to the energy range of the highest gain of the optics. See figure 3 for comparison of the photon attenuation of $300 \mu\text{m}$ of silicon and the gain of the Lobster-Eye optics.

There have been applications of Timepix sensor in space, namely onboard ISS [3] and PROBA-V [2]. In the case of VZLUSAT-1, there is no radiation shielding in the direction of the optics. Thus this will be the first time Timepix is exposed directly to the radiation background.

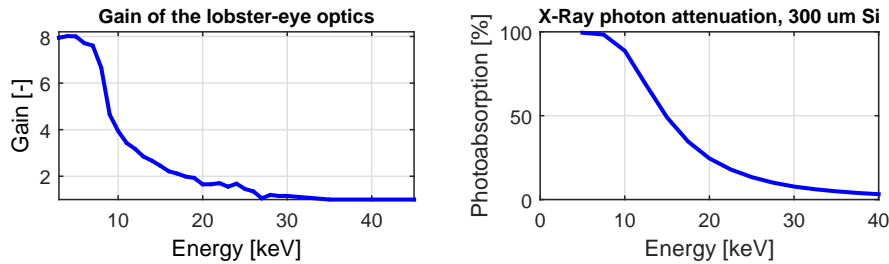


Figure 3. Comparison of the gain of the Lobster-Eye optics and X-ray photon attenuation of 300 μm Silicon (source NIST). The gain was obtained from experiments at the University of Iowa.

3.4 Data outputs

Several formats of data can be saved in onboard computer's memory to be further selected for download. The selection should be an educated decision based on a single packet of data called *Metadata*. It contains factual data about a single image upon which can be deduced whether the image's content is acceptable. The key items follow as:

- time of the exposure (time is synchronized with the ground segment),
- attitude and position of the satellite at the time of the exposure,
- pixel hit count (before and after filtering),
- minimum and maximum value of all pixels (before and after filtering),
- exposure parameters (threshold, bias, exposure time),
- measuring mode [Time Over Threshold, Medipix],
- filtering [on, off],
- data format [raw image, binning, image projections, energy histogram],
- data address (where in the memory to find the actual image),
- heatsink temperature.

Besides Metadata, there are six variants of the image data (see figure 5), from which any combination can be saved for later download. *Raw Image* contains every non-zero pixel and its value. Its size is variable and can take up to 3300 packets. *Binning 32* (1 packet) contains binned image of 8×8 resolution, *Binning 16* (4 packet) is 16×16 large and *Binning 8* (16 packet) is 32×32 pixels large. *Image projections* (16 packets) are horizontal and vertical projections of the active pixels in the image. This method is sufficient for us due to expected low pixel count in images, and their values (using Medipix mode) will be equal to one in most cases. The projection will be particularly useful during the reconstruction of the observed object's position. A single peak (maximum of the focus) and a trough (minimum in the mask's shadow) can be found precisely in image projections despite their relatively small packet size. Finally *Image energy histogram* (1 packet) is a 16-bin histogram of pixel values, meant to be used in Time Over Threshold mode.

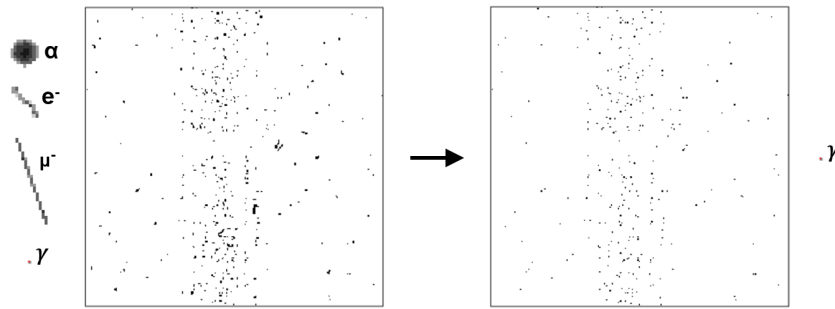


Figure 4. Filtering removes blobs larger than a single pixel. 1 s exposure, Au target, 40 kV, 0.05 mA, with β radiation source simulating radiation background.

After being processed and filtered, data are split into 64 B packets which are then transferred to the main onboard computer to be stored in its memory, where they wait for a download. Packets are created in a way that allows partial reconstruction of the outputs even if an arbitrary combination of them is missing or corrupted. This fault tolerance is necessary as communication outages are likely to appear. The download speed is expected to be as high as 1 kBit/s via UHF. Thus the various sizes of the data outputs will help with efficient utilization of the communication bandwidth.

3.5 Single photon event filtering

Timepix sensor is capable of detecting a variety of ionizing radiation, from single X-ray photons, over electrons and muons to baryonic matter such as protons and Alpha particles. However, the later ones are considered an unwanted signal for our mission. ESA's PROBA-V mission [2] gives an example of radiation background at 700 km LEO, using the same detector. Since most of the data will probably not be downloaded as raw images, onboard filtering of the unwanted particles is necessary. Because photons rarely leave a mark larger than a single pixel, filtering out other particles is based on removing larger connected blobs in the image. The algorithm of blob removal eliminates pixels with within 4-neighbourhood of every other pixel. Figure 4 illustrates the results of a ground-based experiment with and without filtering involved.

3.6 Measurement modes

Several measurement modes were implemented. Manual and time-triggered exposures are a way of directly controlling the telescope, semi-autonomous periodically triggered exposures are designed for long-term dosimetry and finally, automatic exposures can be triggered by the Sun's UV light.

Simple Imaging takes a single exposure with predefined parameters and saves the outputs to the main computer regardless of their content. This mode can be triggered directly or by uploading a time-stamped scripts. From the time of issuing the command to the shutdown of the board, it takes approx. 30 s to capture, process and save a single image taken with 1 s exposure.

Scanning mode extends the Simple imaging mode by analyzing the pixel hit count and saving the outputs only if it exceeds a predefined threshold. The threshold can be changed by mission control. The Metadata are being saved for every exposure. Scanning mode is designed for long-term dosimetry with an option of automatically saving possibly interesting images. Additionally, it can be set for repeating periodically without the necessity of commanding it manually by scripts.

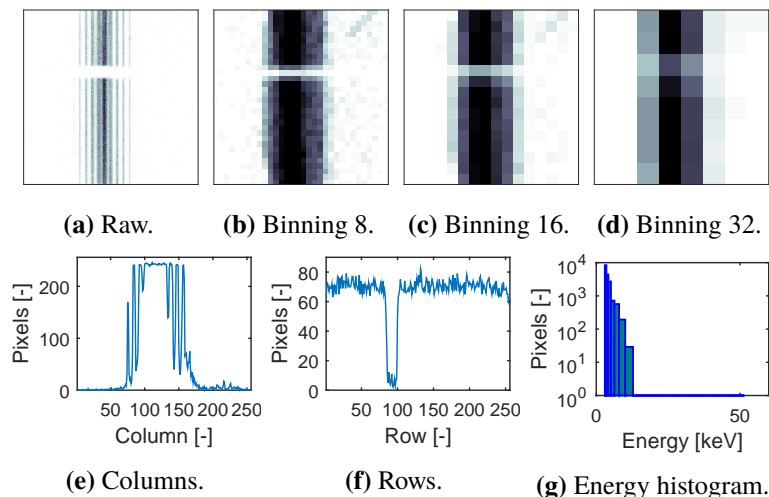


Figure 5. Exposure of 20 s, Au target, 40 kV, 0.05 mA, Time Over Threshold. Note the shadow created by the tungsten coded mask.

Adrenaline mode is focused on capturing the Sun. Instead of exposing immediately after execution of the command, the Timepix is prepared and waits for 60 s for a trigger. A signal from narrow field-of-view UV sensor is then used to start the exposure after exceeding a set threshold. Additional functionality is implemented to estimate the threshold, which is necessary to avoid false positive triggers.

4 Testing and experiments

VZLUSAT-1 was developed and constructed under the leadership of Aerospace Research and Test Establishment in Prague. It was assembled in a clean room and was subjected to testing and verification required by the QB50 mission. It was put through vibration and shock tests, temperature cycling in thermo-vacuum (TV) chamber and long-range radio test. More importantly, the final hardware and software of the telescope were tested while the spacecraft was undergoing temperature cycling. A tunnel was installed to the TV chamber which allowed mounting of Amptek Mini-X X-ray source in 3.2 m distance from the telescope. All functionalities were examined including a potential failure of the optics deploying mechanism. In such scenario, the optics is still beneficial and can serve as a Soller slit. Benefits of the filtration algorithm were verified with a β radiation source simulating cosmic radiation background.

The filtration method proved to be useful only when the image is sparsely filled with events. As stated in section 2.1, we expect to have a small signal coming from observed objects. Thus the exposure parameters will be based mainly on the background noise. Figure 6 shows an example of a short exposure with the signal consisting of 236 photons, whereas the pixel count before the filtration was 668. Figure 5 shows an exposure with high photon count which demonstrates the focusing ability of the optics. Note how the position of the source can be found in both examples.

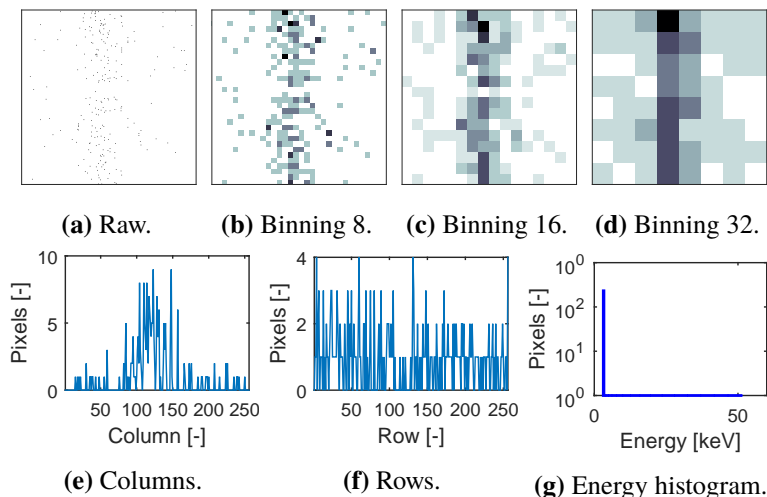


Figure 6. Exposure of 1 s, Au target, 40 kV, 0.05 mA, with filtering of single-photon events, with β radiation source simulating radiation background. (a) was already filtered, see figure 4.

5 Conclusion

The VZLUSAT-1 mission is supposed to demonstrate detection of terrestrial and extraterrestrial X-ray sources with miniature X-ray telescope. The telescope utilizes 1-D Lobster-Eye optics and Timepix detector. The description of the instruments is presented together with ground test data. The telescope will fly onboard the VZLUSAT-1 satellite in April 2017 as a part of QB50 mission with expected lifetime at least one year.

Acknowledgments

The research was carried out within the Medipix2 Collaboration and has been supported by project TA04011295 of the Technology Agency of the Czech Republic.

References

- [1] Z. Vykydal et al., *USB Lite – Miniaturized readout interface for Medipix2 detector*, *Nucl. Instrum. Meth. A* **633** (2011) S48.
- [2] M. Francois et al., *The PROBA-V mission: the space segment*, *Int. J. Remote Sens.* **35** (2014) 2548.
- [3] D. Turecek et al., *Small dosimeter based on Timepix device for International Space Station*, [2011 JINST 6 C12037](#).
- [4] R. Nugent et al., *The cubesat: The picosatellite standard for research and education*, in proceedings of *AIAA Space Conference and Exposition*, San Diego, CA, 9–11 September 2008, AIAA 2008-7734.
- [5] L. Alminde and K. Kaas Laursen, *A strategic approach to developing space capabilities using Cubesat technology*, in proceedings of the *4th International Conference on Recent Advances in Space Technologies*, 2009, pp. 43–47.
- [6] H. Heidt, J. Puig Suari, A.S. Moore, S. Nakasuka and R.J. twiggs, *CubeSat: A new generation of picosatellite for education and industry low-cost space experimentation*, in proceedings of the *14th*

Annual AIAA / Utah State University Conference on Small Satellites, Logan, UT, 11–26 September 2000, SSC00-V-5.

- [7] J. Muylaert et al., *QB50: An international network of 50 cubesats for multi-point, in-situ measurements in the lower thermosphere and for re-entry research*, talk given at *ESA Atmospheric Science Conference*, Barcelona, 2009.
- [8] L. Pina et al., *X-ray monitoring for astrophysical applications*, *Proc. SPIE* **9207** (2014) 92070T.
- [9] V. Tichy et al., *Lobster eye optics for nano-satellite x-ray monitor*, *Proc. SPIE* **8076** (2011) 80760C.

2016 JINST 11 C10007