X-ray Lobster Eye all-sky monitor for rocket experiment

V. Dániel, A. Inneman, L. Pína, V. Zadražil, T. Báča, et al.

V. Dániel, A. Inneman, L. Pína, V. Zadražil, T. Báča, V. Stehlíková, O. Nentvich, M. Urban, V. Maršíková, R. McEntaffer, J. Tutt, T. Schulz, "X-ray Lobster Eye all-sky monitor for rocket experiment," Proc. SPIE 10235, EUV and X-ray Optics: Synergy between Laboratory and Space V, 1023503 (31 May 2017); doi: 10.1117/12.2277515

SPIE.

Event: SPIE Optics + Optoelectronics, 2017, Prague, Czech Republic

X-ray Lobster Eye All-sky Monitor for Rocket Experiment

V. Dániel[a], A. Inneman[b,c], L. Pína[b,c], V. Zadražil[a], T. Báča[c], V. Stehlíková[c], O. Nentvich[c], M. Urban[c], V. Maršíková[b,c], R. McEntaffer[d], J. Tutt[d], T. Schulz[d]
[a]Aerospace Research and Test Establishment, Prague, Czech Republic; [b]Rigaku Innovative Technologies Europe, Prague, Czech Republic; [c]Czech Technical University, Prague, Czech Republic; [d]Pennsylvania State University, Pennsylvania, USA

ABSTRACT

This paper presents a Lobster Eye (LE) X-ray telescope developed for the Water Recovery X-ray Rocket (WRX-R) experiment. The primary payload of the rocket experiment is a soft X-ray spectroscope developed by the Pennsylvania State University (PSU), USA. The Czech team participates by hard LE X-ray telescope as a secondary payload. The astrophysical objective of the rocket experiment is the Vela Supernova of size about 8deg x 8deg. In the center of the nebula is a neutron star with a strong magnetic field, roughly the mass of the Sun and a diameter of about 20 kilometers forming the Vela pulsar.

The primary objective of WRX-R is the spectral measurement of the outer part of the nebula in soft X-ray and FOV of 3.25deg x 3.25deg. The secondary objective (hard LE X-ray telescope) is the Vela neutron star observation. The hard LE telescope consists of two X-ray telescopes with the Timepix detector. First telescope uses 2D LE Schmidt optics (2D-LE-REX) with focal length over 1m and 4 Timepix detectors (2x2 matrix). The telescope FOV is 1.5deg x 1.5deg with spectral range from 3keV to 60keV. The second telescope uses 1D LE Schmidt optics (1D-LE-REX) with focal length of 25 cm and one Timepix detector. The telescope is made as a wide field with FOV 4.5deg x 3.5deg and spectral range from 3keV to 40keV. The rocket experiment serves as a technology demonstration mission for the payloads. The LE X-ray telescopes can be in the future used as all-sky monitor/surveyor. The astrophysical observation can cover the hard X-ray observation of astrophysical sources in time-domain, the GRBs surveying or the exploration of the gravitational wave sources.

Keywords: X-ray telescope, Lobster Eye, All-sky monitor

1. INTRODUCTION

All-sky photometric surveys have been performed at several missions. The first missions focusing on x-ray and gamma ray sky monitoring begins in the 70s with missions HEAO, followed by ROSAT satellite in the 80s with imaging all sky survey detecting over 100,000 X-ray sources between 0.1-2.4 keV. The first mission to observe the time variation of astronomical X-ray sources was **RXTE** (Rossi X-Ray Timing Explorer) (1996 – 2012) [12]. Observations from the RXTE have been used as evidence for the existence of the frame-dragging effect predicted by the theory of general relativity. From in orbit optical satellite we can name **CHANDRA** satellite (launched in 1999) optimized for high spatial resolution imaging and high resolution spectroscopy. In the same year the **XMM-Newton** with large collecting area was launched for simultaneous imaging and high resolution spectroscopy [6]. Both satellites have main telescope with Wolter type-1 optics, focal length 7.5 m and 10 m, 0.1–12 keV, with cryogenically cooled CCD. In the year 2002 the **INTEGRAL** satellite with coded mask telescope was launched with wavelengths 15 keV to 10 MeV (main)and 3 to 35 keV (JEM-X). The used 128 x 128 Cadmium-Telluride tiles backed by 64 x 64 plane of Cesium-Iodide tiles detector were shielded from background radiation by SPI ACS (Anti Coincidence Shield) consisting of a mask shield and a detector shield. The enormous area of the ACS that results makes it an instrument in its own. It has all-sky coverage and its sensitivity makes it a natural gamma-ray burst detector. All mentioned satellites could in long term serve as all-sky monitors and gave the first all-sky surveys, see Figure 1. For collecting the data for Figure 1 several years were needed.

*daniel@vzlu.cz; phone +420 725 380 564; www.vzlu.cz

EUV and X-ray Optics: Synergy between Laboratory and Space V, edited by René Hudec, Ladislav Pina, Proc. of SPIE Vol. 10235, 1023503 · © 2017 SPIE
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2277515

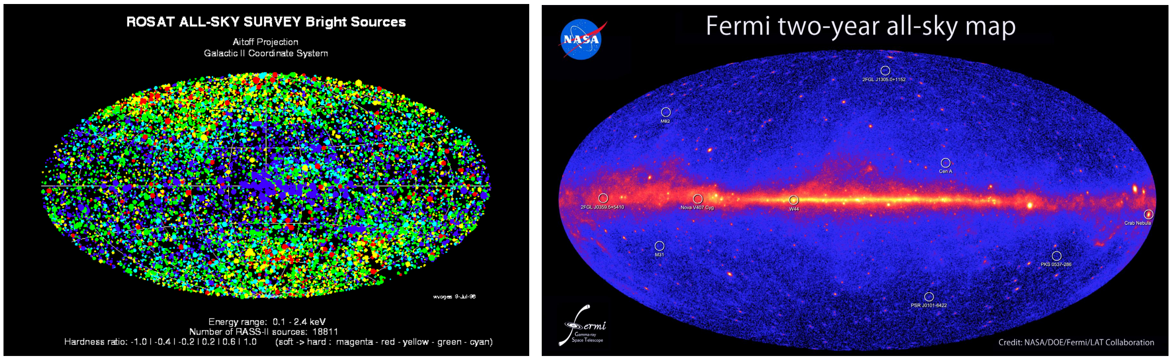

Figure 1. ROSAT all-sky survey for bright sources (left), Fermi (GLAST) all-sky survey map summing up two years observation, energies between 8 keV and 30 MeV (right)

In the year 2004 the **Swift** (Swift Gamma-Ray Burst Mission) satellite was launched with hard-X-ray monitor equiped by the BAT coded-mask imager. The BAT catalog is the product of the most sensitive all-sky survey in the hard X-ray band, with a detection sensitivity (4.8σ) of 2.2 × 10-11 erg cm-2 s-1 (1 mCrab) over most of the sky in the 14-195 keV band. The next mission in the hard X-ray band was **Fermi GLAST** (Gamma-ray Large Area Space Telescope) launched 2008. Fermi mission with Gamma-ray Burst Monitor (GBM) is sensitive to X-rays and gamma rays with energies between 8 keV and 30 MeV. There are also experiments on ISS. The Japanese all-sky experiment **MAXI** (2009) (Monitor of All-sky X-ray Image) acquires all-sky X-ray image using the Exposed Facility of the Japanese Experiment Module "Kibo." The summary of all-sky monitors is in the Table 1.

		FOV	Resolution	Energies	Energy resolution	Detector
RXTE	Shadow camera	6°×90°	3'×15'	1.5 – 3 keV 3 – 5 keV 5 – 12 keV	3 channels	Xenon proportional counter
Chandra	Wolter I	30'×30'	0.5''	0.1–10 keV	0.4 keV	CCD
XMM-Newton	Wolter I	30'×30'	4-15''	0.1–12 keV	0.1 keV	CCD
INTEGRAL	Coded mask	30°×30° 2°×2°	 4'	15 keV to 10 MeV 3 to 35 keV (JEM-X)		128 x 128 Cadmium-Telluride tiles 64 x 64 plane of Caesium-Iodide tiles
Swift	Coded mask (BAT) X-Ray Telescope (XRT)	50°×50° 23.6'×23.6'	17'	14-195 keV 0.2 - 10 keV	8 channels 0.2 keV	 CCD
GLAST		180°×180°	Several °	GBM 8 keV-1 MeV BGO 150 keV - 30 MeV	120 channels	Sodium iodide Bismuth germanate
MAXI	Gas Slit Camera (GSC)	1.5°×160°		2-4 keV 4-8 keV 8-16 keV	3 channels	CCD

Table 1 The summary of all-sky missions and payloads used for all-sky survey

For collecting the all-sky map sevaral years (XMM- Newton, Chandra) were needed down to several month (RWTE, Fermi, MAXI). The principally different detectors were used, enumation shadow cameras, slit cameras, coded mask and telescopes with optics. As a detector CCDs, Cadmium telluride, Caesium Iodide, Sodium Iodide Bismuth Germanate, Xenon proportional counter were used depending on energies.

2. TIME DOMAIN ALL-SKY MONITORING

The presented X-ray Lobster Eye All-sky Monitor is developed as a candidate for all-sky survey in time-domain observation. Larger facilities, both on the ground and in space are generally not operated in a time-domain mode (e.g. "observe the same object once every two days for 3 months"). X-ray astronomical sources cover the X-ray binaries of various subtypes, High-mass X-ray binaries (HMXBs), Low-mass X-ray binaries (LMXBs), X-ray transients (XTs) - subtype of HMXBs and LMXBs [10]. Many astronomical X-ray sources are soft and hard X-ray Transients (SXT/HXT) which are bursts of X-ray binary systems with accreting neutron stars or black hole. Like other high energy astronomical phenomena as Gamma-ray bursts, those SXT/HXT are just occasional (offten single) flares which mostly last hours or days. It is highly improbable that future all-sky surveyor could catch those sources accidentally. Similar X-ray spectral range to the presented X-ray detector have several space instruments.

2.1 Time-domain sources

Monitors of X-ray radiation play an important role in investigation of the processes operating on long timescales. The monitors onboard the NASA satellites RXTE (ASM - soft X-rays of 1.5-12 keV) and Swift (BAT observing in the 15-50 keV band) provided data for analysis of the evolution of the features which occurred on timescales of weeks in the very long (~600 d) outburst of the neutron star X-ray binaries. The cycle is present in some time segments only in the ASM band, while the intensity variations are always chaotic in the BAT band [12]. It is thus important to monitor X-ray sources over broad energy ranges. For observing such transient X-ray sources the wide-field monitoring of the sky is necessary (most transients are discovered only by the first detection of their outburst), outbursts are usually unpredictable – only their mean recurrence. The time (cycle-length) of outburst can be determined from a long (years to decades) series of observations. There are also (Quasi) persistent X-ray sources under astrophysics interests. The objects are often in the high state (luminous in X-rays), they transit between the high/low states (and fluctuations in the high state) and are usually fast (~days) and unpredictable. Some variations can be interpreted as Superorbital X-ray variations, caused by tilting and warping of the disk irradiated by a very luminous X-ray source. The timescale modulations are within the weeks and months [11].

2.2 Gravitational waves source survey

The gravitational waves are recently in the field of interest. The collision of two black holes leads to gravitational radiation which can be detected by LIGO/Virgo instrument. The LIGO/Virgo trigger reconstruction favours a binary black hole scenario. In this case, almost no detectable gamma-ray emission is expected, unless the binary is surrounded by a very dense gas cloud, and the emission caused by the enhancement of the accretion rate during the coalescence is directed towards the observer [9]. Also collapsars and binary mergers leading to the formation of a black hole plus an accretion disk have the potential to power the GRB fireball via the energy released from the accretion of the disk onto the newly formed BH [3] [14]. Also this formation can be detected by LIGO/Virgo instrument. The potential GRB can be detected by all-sky monitor or by presented LE rocket experiment instrument. The all-sky monitoring and instrument with wide FOV is necessary for searching and identification of such gravitational wave and GRB source.

2.3 Background radiation

The X-ray and gamma-ray background radiation for all-sky monitor on LEO consists of different sources. The main radiation "noise" in the range above 4 keV usually comes from the Van Allen radiation belts and solar proton events and solar energetic particles. These events will be filtered onboard by the algorithm filtering only one pixel events.

The other x-ray and gamma ray events can come from earth. The origin is in Terrestrial Gamma-ray Flashes (TGFs). TGFs are intense sources of gamma-rays associated with lightning bolt activity and thunderstorms. The sources of the terrestrial gamma-ray are the heavy tropical storms close to the equator. The activity of the storm takes part also above the storm and cannot be seen from the ground. For the space telescopes on LEO the TGFs make a kind of the background x-ray and gamma ray noise [4].

3. X-RAY LOBSTER EYE MONITOR

3.1 Mission

The described X-ray Lobster eye monitor will be launched on Water Recovery X-ray Rocket (WRX-R) experiment. It serves as the technology demonstration mission for the payloads. The primary payload of rocket experiment is the soft X-ray spectroscope prepared by the Pennsylvania State University (PSU), USA. The astrophysical objective of the rocket experiment is the Vela Supernova with size about 8deg x 8deg. The primary objective of WRX-R is the spectrum measurement of the upper part of the nebula in soft X-ray and FOV of 3.25deg x 3.25deg.

The Czech team participates by hard LE X-ray telescope as a secondary payload. The LE X-ray telescopes can be in future used as an all-sky monitor/surveys. With hard X-ray energy range it is suitable for Vela pulsar observation. The hard LE telescope consists of two X-ray telescopes with the Timepix detector. First telescope uses 2D LE Schmidt optics (2D-LE-REX) with focal length 1.3 m and 4 Timepix detectors (2x2 matrix). The telescope FOV is 1.5deg x 1.5deg with spectral range from 3 keV to 60 keV. Second telescope uses 1D LE Schmidt optics (1D-LE-REX) with focal length of 25cm and one Timepix detector [8]. The telescope is made as a wide field with FOV 4.5deg x 3.5deg and spectral range from 3 keV to 40 keV [2] [8].

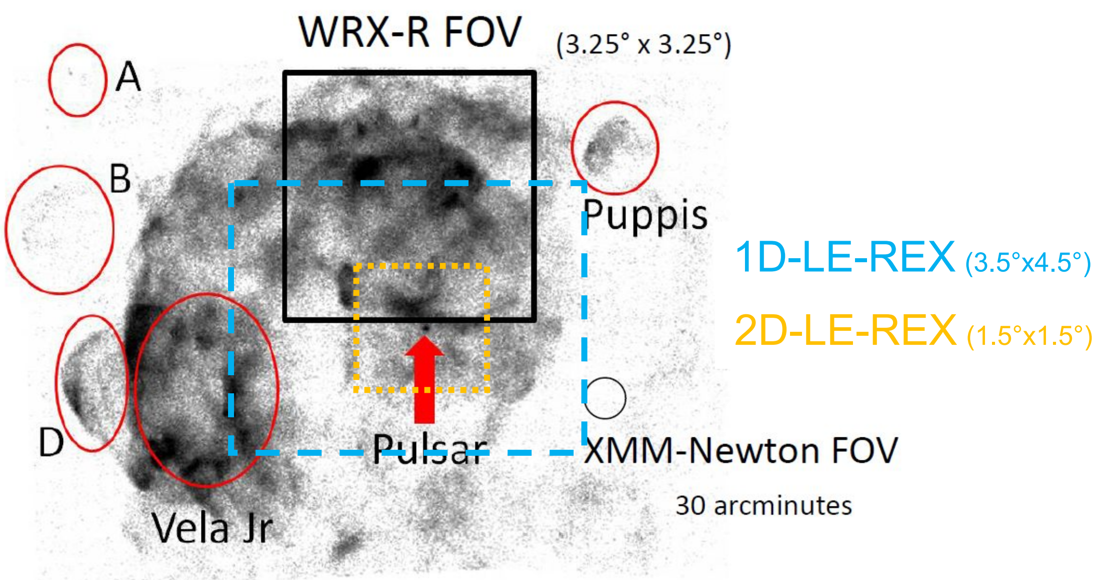

Figure 2. Vela supernova with vela pulsar in the center, The FOV of WRX-R, 1D-LE-REX and 2D-LE-REX.

3.2 Vela supernova

The astrophysical objective of the rocket experiment is the Vela Supernova with size about 8deg x 8deg. In the center of the nebula is a neutron star with a strong magnetic field, roughly the mass of the Sun and a diameter of about 20 kilometers forming the Vela pulsar. This Vela pulsar rotates 11 times per second. The observation of the Vela pulsar and its surroundings in hard X-ray was done by several missions. The Chandra X-Ray Observatory measures the spectrum of the pulsar in band 0.25–8.0 keV. The pulsar does not show statistically significant spectral lines. Thanks to the superb angular resolution of the Chandra telescope the pulsar was well investigated in the shape, rotation axis and its spectrum

[7].The measurement and evaluation in the similar energy spectrum as our 2D and 1D-LE-REX was done by hard (2.5-5keV) X-ray images of the Vela supernova remnant (SNR), resulting from observations with the University of Birmingham coded mask telescope flown on the Spacelab 2 mission in 1985 [16]. Using the results from the modeling as the most reliable estimate Willmore obtain a value of 9.4 x 10^{-11} erg cm^{-2} s^{-1} for the 4-25 keV flux. The observation was done also by Swift mission with comparable results. The measured spectrum and X-ray image is in Figure 3 [16].

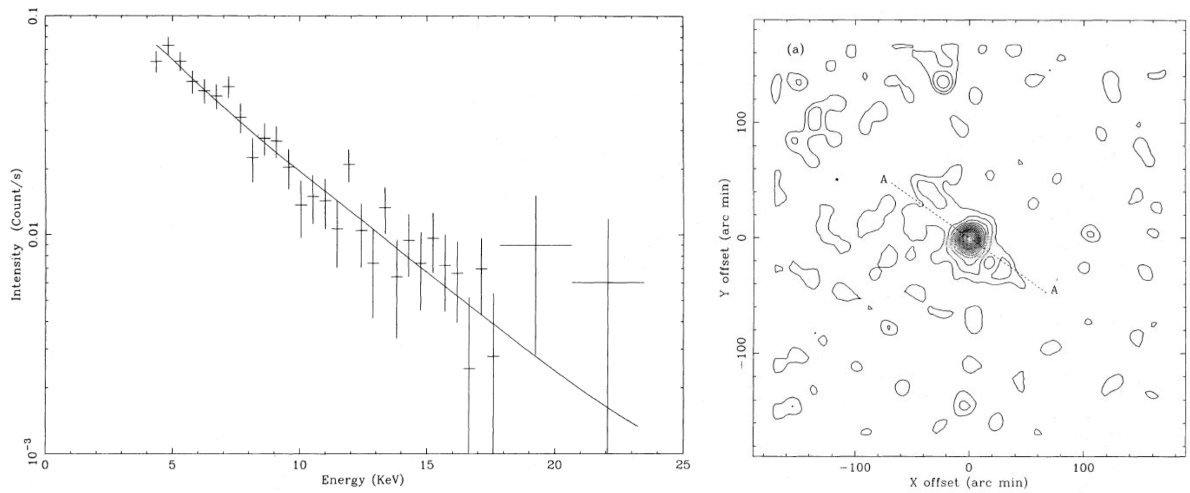

Figure 3. [16] Observed and fitted spectrum of the emission from the central 6 arcmin surrounding the pulsar (left), significance map of the Vela supernova remnant in the 2.5-10 keV energy range, after smoothing with a Gaussian filter of FWHM 13 arcmin. The map is centered on the pulsar with north at the top and east at the left. The contours are (1.5, 3, 5, 7, ...) σ. The line AA gives the orientation of the pulsar spin axis, determined from radio data (right).

According to the data form previous measurement [7] [16] the expected flux for the band 3-60 keV is 10 x 10^{-11} erg cm^{-2} s^{-1}. It gets approximately one photon per 3 second @10keV. For the expected observation time 15min it is 300 photons for all observation.

3.3 All-sky Monitor design

The X-ray Lobster eye monitor payload is 1.3 m long telescope with the RGB VIS camera with 10° FOV, soft X-ray 1D-LE-REX with FOV 4.5deg x 3.5deg and hard X-ray 2D-LE-REX with FOV 1.5deg x 1.5deg. The sketch of the LE-REX payload (Lobster Eye Rocket Experiment Payload) is on Figure 4.

As a detector, the Timepix detector with 300 µm of silicon was selected. There have been applications of Timepix sensor in space, namely onboard ISS [13] and PROBAV [5]. Such detector material allows capturing of photons in the range of 3 - 60 keV. Timepix is a hybrid semiconductor pixel detector with 256 × 256 pixels having 55 µm pitch. It does not require any special cooling besides removing its built up heat. USB Lite interface allows us to interface the Timepix by USB providing all necessary interface to the ASIC. The detector was developed in the frame of the Medipix2 Collaboration at the Institute of Experimental and Applied Physics (IEAP) of the CTU in Prague [15]. Maximum X-ray energy is limited by the Timepix detector (3-60 keV). Timepix can be used also for measurement of spectrum of astrophysical objects. For spectrum measurement the energy resolution is 3keV.

The 1D-LE-REX equivalent with VZLUSAT-1 LE optics corresponds to the low X-ray energy range of the highest gain of the optics in energy range 3-10 keV (50% efficiency @ 10keV) [1]. The VZLUSAT-1 miniaturized X-ray telescope of length 250 mm will be launched on nanosatellite VZLUSAT-1 which was developed for in orbit demonstration of such type of LE optics (Pina 2015).

2D-LE-REX optics is build up for this rocket experiment for hard X-ray energy band observation. The telescope is 2D created by two 1D sub-modules. The sub-module length is 150 mm. Each sub-module is suitable for low X-ray intensities and also harder X-rays energies 3 - 20 keV (50% efficiency @ 12keV). To get this parameters the focal length of the LE optics is 1300 mm. Optics is formed from glass foils with double side spattering by gold. Microroughness is lower than 0,5nm. Optics above 20keV behaves as a collimator (Soller slit), so that the gain is only 1 [8]. The LE of the same aperture area collects more photons per second than coded mask. It is necessary in miniaturization of the instrument for small satellites. According to ground experiment the 2D LE optics has field of view 1.5deg x 1.5deg with detector from 4 Timepix detectors (2x2 matrix). Measured angular resolution is 1 arcmin.

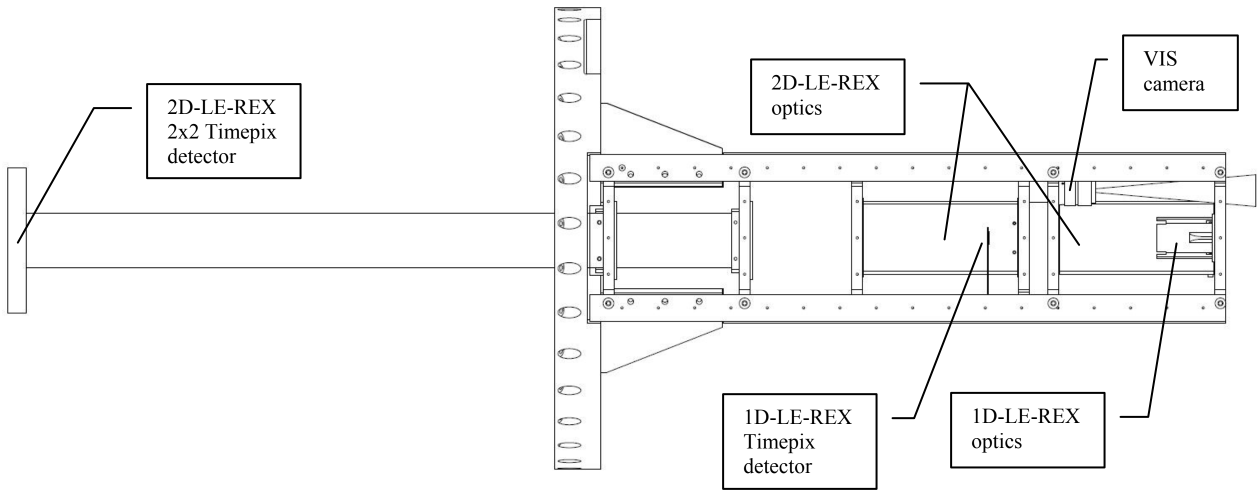

Figure 4. X-ray Lobster eye monitor for Water Recovery X-ray Rocket (WRX-R) experiment

4. GROUND EXPERIMENT

The ground experiment of the LE optics and detector was done in Pennsylvania State University. For the vacuum tunnel test the tiny Beta emitter Fe-55 source (energy 5,9 keV) was used. The source distance of 47 m lead to counted flux 0,1counts /cm2 s. In such test the background noise (background radiation forming picture noise) is bigger than the signal from the Fe-55 source. Because of that long time exposition of exposition time 985 minutes was done with picture filtering. For filtering the background noise the sequence of thousands of pictures was done and each was filtered separately for one pixel events. The final picture covers the sum of thousands of pictures.

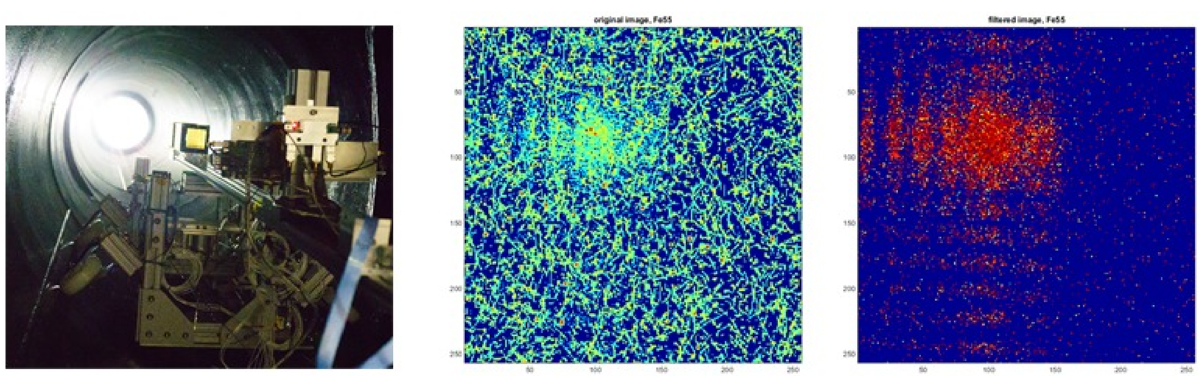

Figure 5. Inside the 47 m long vacuum chamber

5. SUMMARY

The X-ray Lobster eye all-sky monitor for rocket experiment is 1.3m long telescope with the RGB VIS camera, soft X-ray 1D telescope and hard X-ray 2D telescope. It will be launched as a secondary payload on Water Recovery X-ray Rocket experiment prepared by the Pennsylvania State University (PSU), USA. The astrophysical objective of the rocket experiment is the Vela pulsar and its surroundings. The payload covers the FOV of 4.5deg x 3.5deg by 1D telescope and FOV 1.5deg x 1.5deg by 2D telescope. The 2D telescope is suitable for soft X-ray energies and also for hard X-ray energies from 3 to 60 keV (50% efficiency of LE optics @ 12keV). The Vela pulsar is the X-ray source studied before by several missions. The aim of the presented payload on rocket experiment is the evaluation and demonstration of the LE Schmidt optics with Timepix detector for a future all-sky monitoring mission.

ACKNOWLEDGMENTS

The research was carried out within the Medipix Collaboration and has been supported by project TA04011295 of the Technology Agency of the Czech Republic and MSMT LH14039 of the Ministry of education youth and sports of Czech Republic.

REFERENCES

[1] T. Baca; M. Platkevic; J. Jakubek; A. Inneman; V. Stehlikova; M. Urban; O. Nentvich; M. Blazek; V. Daniel, "Miniaturized X-ray telescope for VZLUSAT-1 nanosatellite with Timepix detector, " JINST, Volume 11, October (2016).

[2] M. Blazek, P. Pata, A. Inneman, P. Skala, "Astronomical Tasks for Tests of X-Ray Optics in VZLUSAT-1 Nanosatellite," Advances in Astronomy, Article ID 3162892; https://doi.org/10.1155/2017/3162892 (2017).

[3] A. Corsi, "Gravitational waves and gamma-ray bursts," Proceedings IAU Symposium No. 279 (2012).

[4] V. Dániel; L. Pína; A. Inneman; V. Zadražil; T. Báča; et al., "Terrestrial gamma-ray flashes monitor demonstrator on CubeSat," Proc. SPIE 9978, doi:10.1117/12.2240299, (2016).

[5] Francois, M., et al. "The PROBA-V mission: the space segment." International Journal of Remote Sensing 35.7, 2548-2564 (2014).

[6] M. G. Kirsch ; U. G. Briel ; D. Burrows ; S. Campana ; G. Cusumano, et al. "Crab: the standard x-ray candle with all (modern) x-ray satellites," Proc. SPIE 5898, UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy XIV, 589803, doi:10.1117/12.616893; http://dx.doi.org/10.1117/12.616893 (2005).

[7] G. G. Pavlov, V. E. Zavlin, D. Sanwal, V. Burwitz, and G. P. Garmire, "The X-Ray Spectrum of the Vela Pulsar Resolved with the Chandra X-Ray Observatory," The Astrophysical Journal Letters, Volume 552 (2001).

[8] L. Pina, R. Hudec, A. Inneman, D. Cerna, J. Jakubek, L. Sieger, V. Dániel, W. Cash, L. Mikulickova, R. Pavlica, E. Belas, J. Polak, "X-ray monitoring for astrophysical applications on Cubesat," Proc. SPIE 9510, EUV and X-ray Optics: Synergy between Laboratory and Space IV, 951005, doi:10.1117/12.2185091 (2015).

[9] V. Savchenko, "INTEGRAL upper limits on gamma-ray emission associated with the gravitational wave event GW150914," Astrophysical Journal Letters, 820:L36 (5pp), doi:10.3847/2041-8205/820/2/L36 (2016).

[10] V. Šimon, "Echo outbursts in KS 1731–260," A&A 513, A71, DOI: 10.1051/0004-6361/200912022 (2010).

[11] V. Šimon; "Unstable cyclic modulation during the main outburst of KS 1731-260," New Astronomy 17, 697–704 (2012).

[12] V. Šimon, "Evolution of the complicated decaying branch of the very long outburst in XTE J1701-462," New Astronomy, Volume 37, Pages 26–34, DOI: 10.1016/j.newast.2014.11.005 (2015).

[13] Turecek, D., et al. "Small dosimeter based on Timepix device for International Space Station." Journal of Instrumentation 6.12, C12037 (2011).

[14] T. Vachaspati, "Gravitational Waves, Gamma Ray Bursts, and Black Stars," IJMPD Vol. 25, No. 12, 1644025, DOI: 10.1142/S0218271816440259 (2016).

[15] Vykydal, Z., et al., "USB Lite – Miniaturized readout interface for Medipix2 detector." Nuclear Instruments and Methods in Physics Research, S48-S49 (2011).

[16] A. P. Willmore, C. J. Eyles, G. K. Skinner and M. P. Watt, "Hard X-ray emission from the Vela supernova remnant," Mon. Not. R. astr. Soc. 254,139-145 (1992).