A BALLOON BORNE 3D CZT SPECTRO-IMAGER PROTOTYPE FOR HARD X-RAYS MEASUREMENTS.

Ezio Caroli, Natalia Auricchio, John B. Stephen(1)
Stefano Del Sordo, Paolo Nogara, Giuseppe Sottile(2)
Andrea Zappettini, Silvia Zanettini(3)
Leonardo Abbene, Fabio Principato(4)
Nicola Zambelli, Giacomo Benassi(5)

(1) INAF/OAS of Bologna, Via Gobetti 101, I-40129, Bologna (Italy), e-mail: ezio.caroli@inaf.it
(2) INAF/IASF of Palermo, Via Ugo la Malfa, 153, I-90146 Palermo (Italy), e-mail: stefano.delsordo@inaf.it
(3) CNR/IMEM of Parma, Parco Area delle Scienze 37/A, I-43124 Parma (Italy), e-mail: andrea.zappettini@imem.cnr.it
(4) DIFC, Univ. of Palermo, Viale delle Scienze, I-90128, Palermo (Italy), e-mail: leonardo.abbene@unipa.it
(5) Due2lab S.r.l., Via Paolo Borsellino 2, I-42019 Scandiano (RE) (Italy) e-mail: zambelli@due2lab.com

ABSTRACT

A new generation of telescopes for hard X- and soft γ-rays astrophysics (10-1000 keV) requires the development of high performance detectors allowing high efficiency and high quality measurements in spectroscopy, timing, imaging and, last but not least, in polarimetry. With this target, our group is developing imaging spectrometers based on CZT sensors sensitive to the position in three dimensions (3D CZT sensor). Herein, we will first describe the ongoing developments and the performance we expect to obtain from the prototype and then the information we could obtain from its implementation on a stratospheric balloon together with the characteristics of the balloon payload by specifying the required resources required in terms of volumes, weights, power and telemetry.

1. INTRODUCTION

For the development of next generation of hard X- and soft γ-rays astronomy space instruments, the main requirements can be identified in the followings: (a) a two–order of magnitude increase in sensitivity with fine angular resolution, in the energy band up to several hundreds of keV (600-700 keV) is required to solve several still open hot scientific issues; (b) polarimetry shall become a "standard" observational mode of cosmic ray sources in this energy regime to fully understand the emission mechanism of several sources classes. To fulfil these requirements two different observational approaches are possible, requiring two type of instruments: (i) high sensitivity narrow field instruments: e.g. telescopes implementing new high energy focussing techniques (such as broad-band Laue lenses) [1]; (b) Wide field instrument able to observe simultaneously a large fraction of the sky [2].
The development of such type of high-energy telescopes, impose challenging requirements to detectors to be used. In particular: (a) high modularity and compactness to allow their suitable for a large variety of satellite class (from medium to micro/nano-satellite) in different mission scenarios (e.g. single or cluster type); (b) high operational dynamics (i.e. large energy band) and high performance in term of efficiency, spectroscopy, imaging and timing as well as polarimetry. This new generation of hard X/γ-rays detectors shall exploit high detection efficiency, (>80% at 500 keV), fine spectroscopy (1% FWHM at 511 keV), fine spatial resolution (<0.5 mm) in three dimension, good timing resolution (<1 μs), and finally reliable scattering polarimetry capability simultaneously with spectroscopy, imaging and timing.
Spectro-imager that could fulfil contemporarily all the above requirements can be realized using CZT spectrometers units highly segmented to offer fine three-dimensional spatial resolution, referred in the following as 3D CZT sensor [3]. Such type of spectro-imager can allow further important advantages, such good capabilities in the rejection of environmental and instrumental background, uniform response over the sensitive volume by means of signal compensation techniques, fine spectroscopy also for multiple events (hit signals come from a small sensitive voxel), and high efficiency scattering polarimetry in high energy astrophysics above 80/100 keV [4] .
Since a decade, our group is involved in the development of high performance spectro-imager based on a particular configuration of 3D CZT sensor. In the following section, we report first on the current development with a summary of achieved results and finally we outline a small payload for a stratospheric balloon experiment based on such type of device devoted to test both technical implemented solutions and achievable performance in a pseudo spatial environment.

2. 3D CZT SPECTRO-IMAGER SENSOR

Our approach for the realisation of high performance 3D CZT sensors is mainly based on the following ideas: (a) Planar Transverse Field (PTF) irradiation configuration [5], (b) Anode with a drift strip configuration [6], and (c) Cathode segmented in strip orthogonally to the anode ones. Furthermore, we apply a new signals readout scheme, that imply to use together with signals from cathode and collecting anode strips also the grouped drift strip induced signals.

The PTF configuration allow increasing the thickness (i.e. efficiency) for photon absorption up to 40 mm (today is standard 20 mm). The adopted electrode configuration together with the signal readout scheme, allow to obtain a high "virtual" segmentation of the sensor detection volume (e.g. 30000 voxels, for a spatial resolution of 0.4 mm in each direction) with few (25/30) electronics readout channels.

Tests at laboratory and ESRF (Grenoble, France) demonstrated that a 3D sensor built using a 20×20×5 mm^3 CZT crystal, with the above-described electrode configuration and signal readout type, can achieve contemporarily fine 3D imaging capability and fine spectroscopic performance [7].

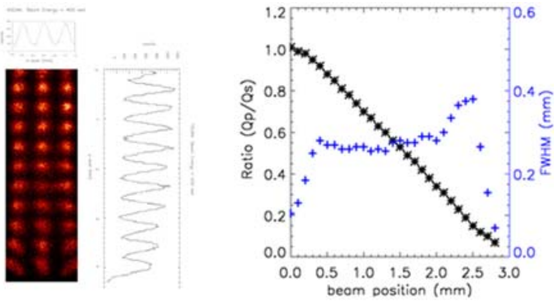


Figure 1. (left) spatial resolution in the photon impinging sensor surface; (right) the relation between the ratio of cathode (Qp) and anode signal (Qs) vs the beam position (black), the spatial resolution in the same direction (blue)

Fig. 1(left) show the image of the collimated beam (0.05 mm in diameter) on the 3D CZT sensor surface where the beam itself imping with the profile in the two orthogonal directions (*x* and *y*). As example, the spatial resolution achieved in these measurements at 400 keV in the three directions were respectively *x*=0.15 mm, *y*=0.26 mm, while across the cathode strip, *z*=0.65 mm. On Fig. 1(right) is shown the almost linear relation between the ratio of cathode and anode signal with respect to beam position across the two electrodes planes. This relation allow reconstruct the beam position along the charge collecting field direction, and from this knowledge to compensate the signals for trapping and therefore improve the spectroscopy.

The measurements confirmed that, together with the end spatial resolution in three dimensions, this type of sensor exhibits excellent spectroscopic performance after signal compensation allowed by the reconstruction of the 3D interaction position.

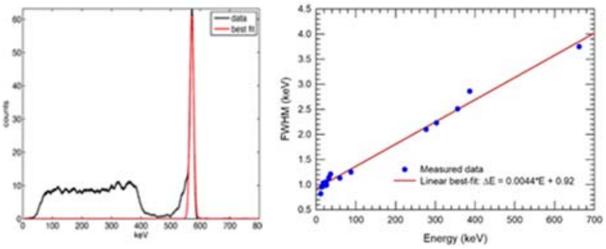


Figure 2. Measured spectroscopic performance of a 3D CZT sensor prototype using signal compensation: (left) spectrum at 580 keV; (right) energy resolution (FWHM) vs beam energy.

As an example, Fig. 2(left) shows the spectrum obtained with a 580 keV beam. Fig. 2(right) plots the relation between the measured energy resolution and the photon energy in the range between 100 and 700 keV, showing that this sensor type can achieve 0.6 % at 661.6 keV.

2.1. CZT spectro-imager as scattering polarimeter

Segmented detectors are able to operate as scattering polarimeter, relying on the asymmetry exhibited by the Klein-Nishima Compton scattering cross section with respect to the azimuth angle. For such type of measurement, this detector are quite efficient, because each pixel/voxel acts contemporary as scattering and detection element, and can perform at the same time spectroscopy, imaging and timing.

The quality of the scattering polarimetry response strongly depend on the detector segmentation level (i.e. the 2/3D spatial resolution) and on their spectroscopic performance. Fig. 3(left) represents the scattering map (i.e. the azimuth distribution of scattering angle for Compton events), and Fig. 3(right) shows the derived modulation curve obtained at ESRF (Grenoble, France) with a Caliste module [8] based on a 1 mm thick CdTe Schottky 16×16 pixels detector with fine pitch (0.625 mm).

The modulation curve (in blue) obtained by the right map exhibits a modulation factor Q=~0.78 that is very close to the value of 0.9 expected by the Klein-Nishima Compton scattering theory for linearly polarized (red) photons. This performance is in fact equivalent to one achievable with a 3D CZT spectro-imager, selecting events which scatter at angles close to 90° (i.e. with the same z coordinate of the two hits) [9].

In perspective, 3D spectro-imagers will offer better polarimetric performance because their improved scattering efficiency, due to higher thickness, and the possibility to perform more event selection type, as well as to decrease background by means of Compton kinematics reconstruction.

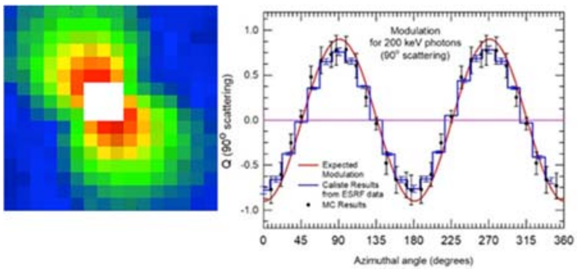


Figure 3. (left) Scattering maps at 200 keV and with the polarisation plane 30° inclined with respect to the detector axes measured with the Caliste module. (right) The modulation curve (blue) obtained from the left scattering map compared with the one from compton scattering theory for polarized photons.

3. CURRENT DEVELOPMENTS

In the framework of a R&D project funded in 2018 by the Italian Space Agency (ASI) through INAF, our collaboration is currently developing a complete detection system based on a 3D CZT spectro-imager module with its own charge sensitive preamplifier (CSP) front end electronics readout by a multichannel digital systems based on high speed digitizers and FPGA.

The digital processing approach will guarantee a large flexibility of the detection system to different operative condition. The detector performance can be tuned to the observational targets and space mission contest, without requiring a change in its hardware.

Figure 4. One of Redlen CZT used for 3D spectro-imager module; (left) anode side (48 stripes) and (right) cathode one (10 cathode stripes).

The 3D CZT spectro-imager module will be made of 4 3D CZT realized on single spectroscopic graded Redlen crystals of 19.6×19.6×6 mm^3. On one of the crystal large face, the anode side, there are (Fig. 4 left) 48 strips with 0.15 mm gap (12 anode strips, 36 drift strips). The anode strips have 1.2 mm pitch. Between each anode's strips, there are three drift strips. On the opposite crystal face, the cathode (Fig. 4 right) is made by 10 strips with 2 mm pitch orthogonally oriented with respect to the anode ones.

The realization of the 3D CZT drift-strip sensor units is extremely challenging for two reasons: a) the segmentation of cathode and anode requires a double patterning process on both sides of the CZT crystal; 2) the surface leakage current between the anode stripes must be drastically reduced by using special surface passivation techniques. After a delicate polishing of the CZT surfaces, a 100 nm gold film is deposited by wet-chemical electroless technique. The stripes on both cathode and anode are patterned using a standard photolithography process. Due to the small gap between strips in the anode side, was mandatory to reduce drastically the surface leakage current in order to provide the correct sensor polarisation. We have implemented a passivation process that is an improved version of a technique developed for previous projects that rely on the deposition of a thin insulating film of Al_2O_3 between the strips. After this process, the average leakage current value is around 5.-6. nA, with a satisfying homogeneity over the whole anode surface. The dark current between one anode stripe and cathodes increases linearly with potential and it is around 6-7 nA at 500V.

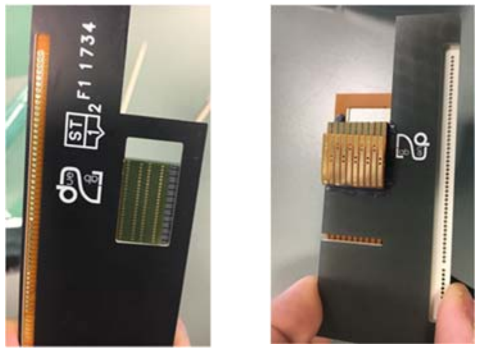


Figure 5. The 3D CZT unit mounted and bonded to the support interface with the AFEE board: (left) anode side; (right) cathode side.

Each 3D CZT sensor will be bonded on a board that provide both the electrical and mechanical interface for final module packaging and connection to the CSP front-end electronics. Fig. 5 show a first prototype. The board consists of five superimposed layers of different materials (Roger, Kapton and FR4) rolled together. The 3D CZT sensor will be bonded to Au lines on Kapton film.

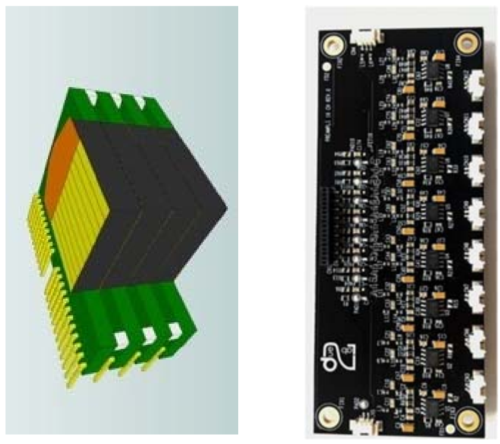


Figure 6. (left) The detector module: four CZT 3D sensors packaged together. The photon entrance window is the top black side; (right) the hybrid charge sensitive preamplifier board with 16 channels.

Four of these 3D CZT boards will be packed together to build an almost cubic detection module with a sensitive volume of about 8 cm^3 that will have the configuration shown in Fig. 6 (left). The detector module electrodes are analogically readout by seven 16 CSP hybrid board (Fig. 6 right) for a total of 100 active channels (25 for each CZT sensor). The CSP boards implement a custom designed low noise and low power consumption preamplifier circuit developed in the framework of the project. Each 16 CSP boards require 1.4 Watt on the single 5 V power supply. The 3D CZT sensors are biased with a HV between 150 and 500 V, that can be tuned to obtain the best performance.
The 100 pre-amplified signals are to the Digital Pulse Processing (DPP) system, that directly digitize and sample the detector output signals and process them by means of custom algorithms implemented in the it's FPGA. Using this readout type, the original information on the event that generated the signal is fully preserved. The DPP system, based on two pipelined shaping steps (a fast and a slow), will allow an easy implementation of custom designed filters and procedure to handle detected events (Fig. 7).

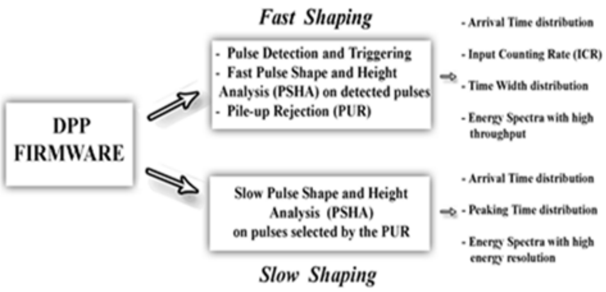


Figure 7. The main operations and output data of the DPP system under development.

This approach has already demonstrated his efficiency and reliability allowing to achieve very high timing (few ns) resolution even with quite intrinsically slow detector such as CZT spectrometers [10]. Moreover, the DPP approach allows the easy implementation of: (i) bi-parametric techniques for signal compensation (e.g. shaping time/energy, fast/slow, cathode/anode signals ratio), (ii) sub-pixel spatial resolution techniques, and efficient techniques of charge sharing handling with coincidence time windows down to 10 ns (i.e. good for Compton event handling and polarimetry).
The DPP will based on two units of a device currently under realisation by the CAEN (Viareggio, Italy) company. Each unit will be equipped with fast digitizers (125 MHz) and an open Xlinx FPGA able to handle 64 channels with a power consumption of 30 Watt.

4. THE BALLOON EXPERIMENT

A balloon flight opportunity for this detection system will be very important to integrate the information obtained at ground facilities (like ESRF for photons, INFN/LNL for charged particles). In particular, to assess the reliability of some technological solution we implemented in the 3D CZT spectro-imager module, and furthermore to verify the flexibility and reliability of the digital approach in a pseudo space environment.
Based on the detection system under development, a payload configuration will be studied in the next months to assess the feasibility of a proposal submission to the HEMERA second call, which will be issued on September 2019, for a flight in 2021 [11]. This opportunity is fully compatible with the development schedule of our detection system, which foresee its final delivery in spring 2020. This date will leave enough time to implement the arrangements to make the prototype compatible with a balloon payload, in particular to develop mechanical and electrical interfaces with the subsystems and services (e.g. power supplies and TLM) of the gondola, as well as the on board data storage subsystem.
The currently available launch sites in the HEMERA project framework, are currently at very high latitude, implying operate our detector system in a rather "dirty" environment. In fact, this represents a good situation to perform several interesting tests and measurements.
First, a flight on this type of environment could allow the reliability verification of the 3D CZT sensors passivation, bonding, and packaging, as well as the custom CSP FEE designed electronics behaviour. Furthermore, by measuring the background spectrum, we can test our capability using the digital readout approach of both to discriminate different types of particles from the signals features and to reconstruct the unknown angular distribution of incoming photons by using the Compton kinematics and the 3D spatial sensitivity of the detector.
Finally, a balloon experiment will allow assessing the flexibility of the readout digital approach to change the observational mode of the detection system during the flight, uploading different filters and event handling logic in the firmware of the FPGA on-board to the DPP system, or even simply by changing filter and logic setting parameters.
The balloon payload will be constituted by four main subsystems: (i) the detection system made by the 4 CZT sensors module plus its CSP Front End Electronics); (ii) the Data Handling system made by the DPP unit, that provide the required real-time signal acquisition, coincidence and trigger logics; (iii) the on board storage and telemetry unit, providing the mass memory for on-board data storage and the interface with the gondola TLM system; (iv) the power unit that provide the bias of all the payload subsystems using the gondola main power lines. The expected main resources, in terms of dimensions, weight and power budget, required by these four payload subsystems are summarized in Table 1.
With respect to the final configuration of the 3D CZT spectro-imager detection system, that foresee the readout and handling of 100 channels using two DPP 64-channels units, we think to perform a small de-scope reducing the

number of channels to be digitally readout in order to use on board only a CAEN 64 channels digitizer.

Table 1. 3D CZT Payload required resources

Subsystems	*Sizes (cm)*	*Weight (kg)*	*Power (W)*
CZT module+FEE	35×28×15	3.0	3.0
Data Handling	30×50×25	5.0	30.0
On-board storage + TLM unit	30×25×5	3.0	5.0
Power unit	30×25×5	4.0	7.0
Totals	40×50×40 *footprint*	15.00	45.0

This reduction does not affect the significance of the achievable measurements. This cut of 36 channels of the current detection system configuration will be the one of the main targets of the study we intend to perform in the next few months for the preparation of an HEMERA proposal. A possible solution that can be easily implemented without affecting the configuration of the detection system (3D CZT module plus FEE) is to digitally readout only 5 over the 10 cathode strips and only the central 8 over 12 collecting anodes for CZT each sensors. This means a reduction of the original sensitive volume of the CZT module. The 36 missing channels can be used, for example, to realize an embedded A/C system using the same CZT material.

We foresee to transmit to ground only few scientific information (e.g. channel count rates) together with health HK's information and parameters, requiring a continuous telemetry downlink that can be evaluated in less than 1-1.5 kbits/s. The largest part of the scientific data will be stored on a SSD mass memory on board. Assuming a maximum rate of 1000 counts over the entire volume in the operation range (10-1000 keV), the real-time acquisition by the DPP system will produce ~1 MB/s. Therefore, a 128 GB solid-state disk would allow to store more than 35 hours of data.

Given to the objectives expected for this payload, there are no particular constraints of trajectory and/or latitude and not even in the pointing requirements. Moreover, the payload, for its weight, dimensions, and required power budget can be embarked on a platform together with other experiments.

5. CONCLUSIONS

The possibility of performing a balloon experiment with the described detector prototype will allow us to obtain interesting results and information otherwise impossible to obtain in ground laboratories.

In particular, we would highlight again, that stratospheric balloon experiments represent an extremely important stage in research and development of new space instrumentation for high-energy astronomy. Balloon experiments can act as pathfinders in the development and optimization of new satellite missions.

In general, we recognise that these kinds of experiments offer three main challenging opportunities:

1. Reliability verification in pseudo-spatial conditions of both technological solution and instruments operations, essential for the implementation of new space mission;
2. Scientific values always inherent, even in pure "technological" experiments. The stratospheric in- flight conditions allow to obtain scientific information on detector performance in different observational and background conditions.
3. The training of young researchers. Balloon experiments, due to the intrinsic prototypal nature of payloads and to their short development times, represent an excellent bench for the training of young researchers and technologists.

Table 2. Mission outline and constraints. Some of the more relevant mission requirements in the HEMERA calls. (*) A long duration (days) will be preferred for our purpose, (+) 10% variation/stability would be ideal.

Balloon type	ZPB
Preferred launch site	No preference
Launch period and flights condition constraints	No preference
Float altitude	3 mbar (35/40 km)
Float duration	$\geq$ 6h (*)
Altitude stability/variation	No constraints (+)
Azimuth pointing of the payload gondola	Not required
External power during countdown	Required
Down-link of data, continuous or burst	1000-1500 bits/s continuous
Up-link of data/commands, continuous or burst	1000 bits/s burst
Maximum recovery time after landing of experiment	10 days
Experiment sensitivity to landing/impact forces	Yes (crash protection needed)
Experiment sensitivity to temperature	Yes (thermal insulation needed)

6. ACKNOWLEDGEMENTS

The undergoing development and the derived recent results shown herein have been obtained thanks to a project funded by the Italian Space Agency in the framework of the "Studies for future scientific missions" call under the ASI-INAF agreement n. 2017-14-H.0.

7. REFERENCES

1. Virgilli, E., Valsan, V., Frontera, F., et al. (2017). Expected performances of a Laue lens made with bent crystals. *J. of Astronomical Telescopes, Instruments and Systems (JATIS)*, **3**(4), 044001. DOI: 10.1117/1.JATIS.3.4.044001

2. Moiseev, A., for the AMEGO Collaboration. (2019). All-sky Medium-Energy Gamma-ray Observatory (AMEGO). *Proc. of the 36th International Cosmic Ray Conference (Madison, WI July 24-Aug 1, 2019)*, **PoS(ICRC2019)**, 583.

3. Caroli, E.; Auricchio, N.; Budtz-Jorgensen, C., et al. (2008). A three-dimensional CZT detector as a focal plane prototype for a Laue Lens telescope. *Proc. SPIE on Space Telescopes and Instrumentation 2008: Ultraviolet to Gamma Ray*, **7011**,70113G. DOI: 10.1117/12.790558.

4. Caroli, E., Moita, M,, Curado da Silva, R.M., et al. (2018). Hard X-ray and Soft Gamma Ray Polarimetry with CdTe/CZT Spectro-Imager. *Galaxies*, **6**(3), 69. DOI: 10.3390/galaxies6030069.

5. Casali, F., Bollini, D., Chirco, P., et al. (1992). Characterization of small CdTe detectors to be used for linear and matrix arrays. *IEEE Trans. on Nucl. Sci.*, **39**(4), 598-604. DOI: 10.1109/23.159672.

6. Gostilo, V., Budtz-Jorgensen, C., Kuvvetli, I. (2002). The development of drift-strip detectors based on CdZnTe. *IEEE Trans. on Nucl. Sci.*, **49**(5), 2530-2534. DOI: 10.1109/TNS.2002.803857.

7. Kuvvetli, I.; Budtz-Jørgensen, C.; Zappettini, A., et al. (2014). A 3D CZT high resolution detector for X- and gamma-ray astronomy. *Proc. SPIE on High Energy, Optical, and Infrared Detectors for Astronomy VI*, **9154**, 91540X. DOI: 10.1117/12.2055119.

8. Limousin, O., Lugiez, F., Gevin, O., et al. (2011). Caliste 256: A CdTe imaging spectrometer for space science with a 580 μm pixel pitch. *Nucl. Instr. and Meth. in Phys. Res.*, **A647**(1), 46-54. DOI: 10.1016/j.nima.2011.05.011.

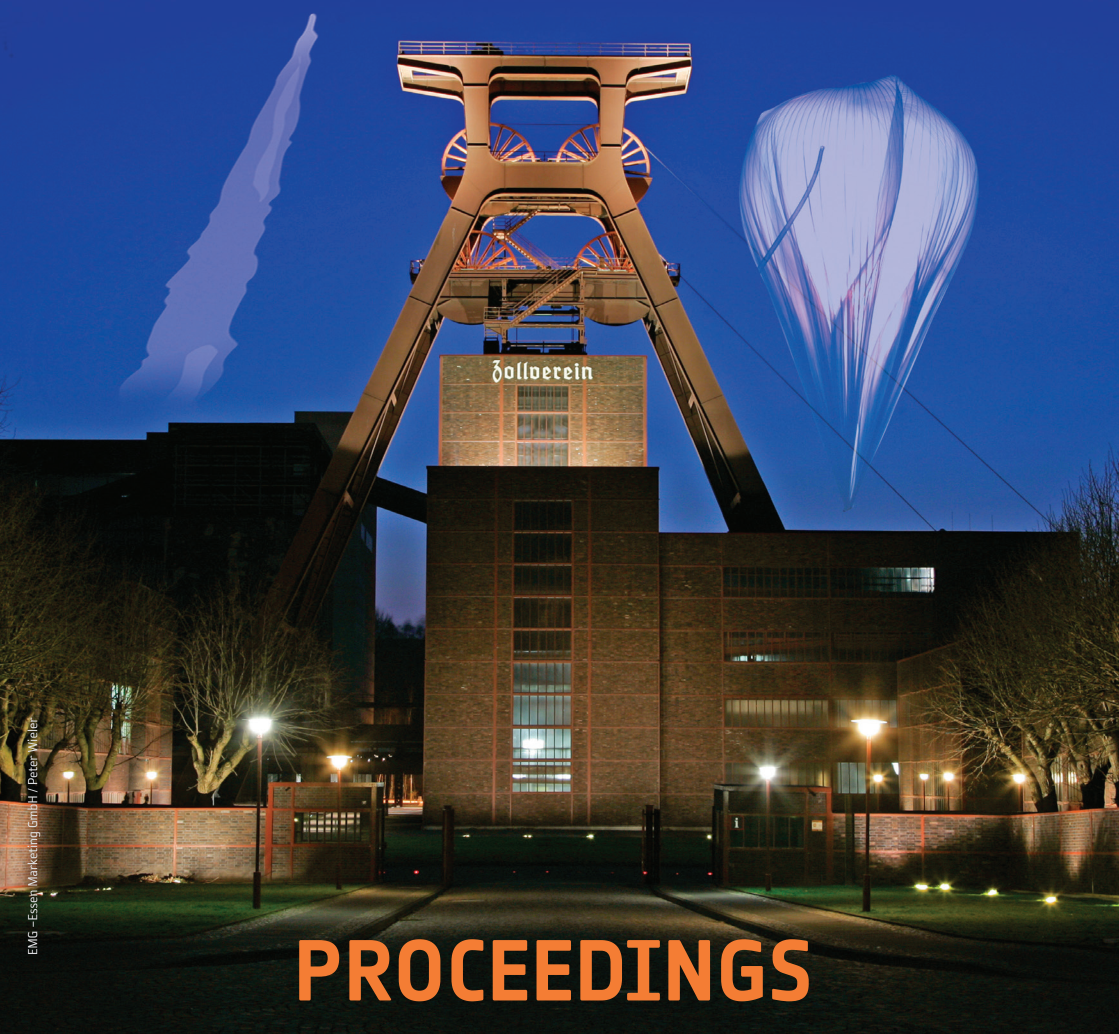
9. Antier, S., Ferrando, P., Limousin, O, et al. (2015). Hard X-ray polarimetry with Caliste, a high performance CdTe based imaging spectrometer. *Experimental Astronomy*, **39**(2), 233-258. DOI; 10.1007/s10686-015-9442-5

10. Abbene, L., Gerardi, and Principato, F. (2013). Real time digital pulse processing for X-ray and gamma ray semiconductor detectors. *Nucl. Inst. and Meth. in Phys. Res.*, **A730**, 124-128. DOI: 10.1016/j.nima.2013.04.053.

11. HEMERA home page: www.hemera-h2020.eu/

24th ESA Symposium on European
ROCKET & BALLOON
programmes and related research

16-20 June 2019 · Essen · Germany



PROCEEDINGS

DLR

esa
European Space Agency

ISSN 0379-6566

SP-742
ISBN 978-92-9221-307-7

October 2019

24TH ESA SYMPOSIUM ON EUROPEAN ROCKET AND BALLOON PROGRAMMES AND RELATED RESEARCH

16-20 June 2019

Essen - Germany

Organised by:
European Space Agency (ESA)
Andøya Space Center (ASC)
Centre National d'Etude Spatiales (CNES)
Deutschen Zentrums für Luft- und Raumfahrt (DLR)
Swedish Space Corporation (SSC)
Hochschule Luzern (HSLU)