IAC-14-B4.2.9

DEVELOPMENT AND IN ORBIT TESTING OF AN X RAY DETECTOR WITHIN A 2U CUBESAT

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A CdZnTe based semiconductor X-ray detector (XRD) and its associated readout electronics is developed by the Space Systems Design Laboratory of Istanbul Technical University and High Energy Astrophysics Detector Laboratory of Sabanci University along with an SME partner. The detector will utilize 30 orthogonal cross strip electrodes (and 3 steering electrodes in between anodes) whose geometry is optimized by an extensive set of simulations and energy resolution measurements. The signals will be read by RENA 3b ASIC controlled by MSP 430 microcontroller. The system will have its own battery and will be turned on intermittently due to power constraints. CdZnTe based X-ray detectors have been utilized in space, but they are either pixellated (NuStar), or they consist of many individual crystal pieces (BAT in Swift satellite). The aim of the XRD is to show that large volume crystals with orthogonal strips are viable alternatives, especially for small satellite systems with medium energy resolution requirement. XRD will also characterize the hard X-ray background in 20-200 keV at low Earth orbit conditions as a function of altitude. Due to power and telemetry constraints, the individual events will be corrected for hole trapping on-board, histogrammed, and only the X-ray spectra will be transmitted to the ground station along with a small set of raw data for diagnostic purposes.

The XRD is planned to travel into space, as a secondary science mission, on board BeEaglesat which is a 2U CubeSat developed as one of the possible double (2U) CubeSats for the QB50 project. QB50 is a European Framework 7 (FP7) project carried out by a number of international organizations led by the von Karman Institute of Belgium. Its main scientific objective is to study in situ the temporal and spatial variations of a number of key constituents and parameters in the lower thermosphere with a network of about 50 double and triple CubeSats, separated by few hundred kilometers and carrying a determined set of sensors.

I. INTRODUCTION

Currently, nano and micro size spacecrafts constitute an important part of satellite development, around 50% in 2013[1]. Most of them follow the CubeSat standard [2]. Current CubeSat developers are not just academic institutions but also important industry and top space agencies including NASA of USA, ESA of Europe and CSA of Canada. CubeSat studies include many novel missions which will be of great help in developing new technology for lighter, stronger and capable spacecraft and reusable launch systems, for creating a living civilization in earth orbits and then in the solar system. Several important projects are proposed and supported by various space agencies and framework programs for increased use of CubeSat capability. Such a project is QB50 which is a European Framework 7 (FP7) program project carried out by a number of international organizations led by the von Karman Institute of Belgium (VKI). QB50 has the scientific objective to study in situ the temporal and spatial variations of a number of key constituents and parameters in the lower thermosphere with a network of about 40 double CubeSats and about 10 triple CubeSats, separated by few hundred kilometers and carrying a determined set of sensors (www.qb50.eu).

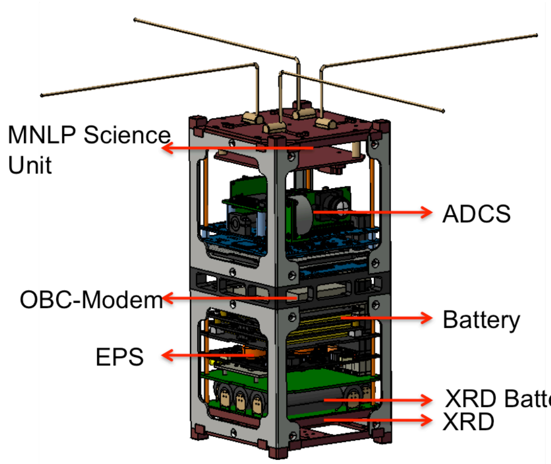

Fig. 1: BeEagleSat drawing and major subsystems.

One of the possible 40 double (2U) CubeSats is the BeEagleSat2 jointly realized by Istanbul Technical University (ITU) and Turkish Air Force Academy (TurAFA) of Turkey. Sabancı University (SU) of Turkey is contributing to the project by providing a novel X-Ray detector. The project is also supported by HAVELSAN of Turkey and microSMEs Ertek Space and Gumush Space, spin off companies of ITU Space Engineering. BeEagleSat is employing the Sensor Set #3 consists of "Multi Needle Langmuir Probe and Thermistors", provided by the QB50 management. The BeEagleSat will also use the QB50 ADCS system [3] which is also provided by the QB50 project. A COTS electrical power system (EPS) is selected. The rest of the systems are developed in house based on the mass, volume, link and pointing requirements of the QB50 (www.qb50.eu). Technical drawing of the BeEagleSat is shown in Figure 1.

The BeEagleSat will carry an X-ray detector (XRD) as a secondary science payload. The X-ray detector system consists of an orthogonal strip CdZnTe crystal (II.I), an application specific integrated circuit (RENA-3b ASIC) for readout, control electronics (II.II), electrical power system, associated coupling circuits, and its own batteries (II.III). In this paper, we will also discuss the early vibration tests for mechanical design (II.IV), the control algorithms and software (II.V), and on ground calibration plans (II.VI).

II. X-RAY DETECTOR ON BEEAGLESAT

CdZnTe based hard X-ray detectors have been well utilized in space observatories, e.g. coded-mask instrument Swift-BAT [4], and X-ray CCD on NuSTAR [5]. BAT consists of 32,768 individual 4 x 4 x 2 mm crystals whereas NuSTAR CCD has 4 pixellated 21 x 21 x 2 mm crystals with a pitch of ~0.6 mm. This means that the BAT readout electronics have 32,768 channels, and the NuSTAR readout electronics have 4096 channels.

Smaller CdZnTe systems have been tried on two CubeSats: AAUSat-2 [6], and The Cosmic X-Ray Background Nanosat, CXBN [7]. While these CubeSats have been launched successfully, neither of the science payloads was able to send scientific data to ground. For AAUSat-2 several pixels are joined together for a single channel readout, where as CXBN utilizes 16 x 32 grid with 600 x 600 µm pixels and two on board calibration sources. The thickness of the crystal is 5mm because it is intended to measure mostly gamma-rays.

BeEagleSat XRD also utilizes a relatively thick CdZnTe crystal (2.5 mm), with the main difference of having orthogonal strips for position resolution on the detector. With 15 anode and 15 orthogonal cathodes, the crystal is segmented into 225 pixels using only 30 readout channels. Having low number of electrical readout channels with orthogonal strip configuration is advantageous for small satellite systems due to power and space constraints. Their disadvantage compared to pixellated detectors would be worse energy resolution and higher minimum detectable energy. At the operating range of the XRD, 20-200 keV, the astrophysical processes produce continuum spectra and having a medium energy resolution would not affect the objective of the mission, which is mainly technology demonstration; to show that the ASIC and the CdZnTe crystal detector will work at low Earth orbit. As a bonus, the XRD will measure the hard X-ray background at a range of altitudes at low Earth orbit of the BeEagleSat.

In the following subsections, we give a detailed description of the XRD.

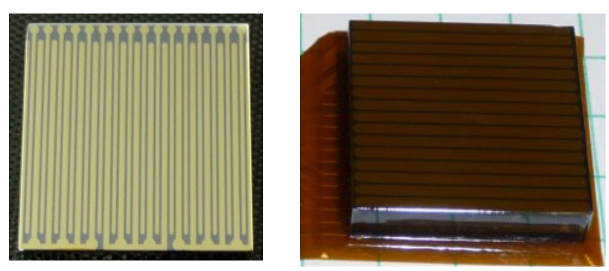

Fig. 2: Left: Anode and steering electrode pattern (1.2 mm pitch) on a 20 x 20 x 5 mm REDLEN crystal. Due2Lab crystal will have a similar pattern, with 1 mm pitch and 15 anodes. Right: Cathode strips overlaid on a REDLEN CdZnTe crystal. Due2Lab crystal will have a similar cathode pattern.

II.I CdZnTe crystal with orthogonal strip configuration

Currently, two different CdZnTe crystals are being prepared for the XRD: at Due2Lab* in Parma, Italy which we plan to use, and at Middle East Technical University in Ankara, Turkey as an alternative.

Due2Lab crystal has dimensions of 15 x 15 mm and has a thickness of 2.5 mm. Gold strips will be deposited on both sides of the detector orthogonally. The side that faces the PCB has 15 anode strips that are 0.25 mm wide and kept at ground potential. There are 3 sets of steering electrodes (also 0.25 mm wide) between the anode strips. They are kept at a lower potential to steer electrons towards the anodes, and their presence also enhances energy resolution due to small pixel effect [8, 9]. A similar electrode design can be seen in Fig. 2.

The anodes will be attached to the pads on the board with conductive epoxy (see Figure 3, inside the white box "CdZnTe crystal"). Then the crystal will be glued to the board using a space qualified insulating epoxy for structural integrity and damping vibrations (see II.IV). On the opposite side, there will be 15 orthogonal cathode strips that are 0.8 mm wide and will be kept at -250V. The cathode signals and high voltage will be transmitted using gold wires from the crystal to the board. Both the anodes and the cathodes are AC coupled to the RENA ASIC through coupling capacitors.

The pitch for both the anodes and the cathodes is 1 mm. For the given pitch, the optimum widths for anode and the steering electrodes were determined through extensive simulations and measurements at Sabanci University High Energy Astrophysics Laboratory (SU-HEALAB) such that they provide the optimal performance in terms of charge collection and sharing, energy resolution and noise due to leakage currents. Crystals with similar electrode designs have also been tested using RENA 3b readout system at the lab.

* www.due2lab.com/detectors.html

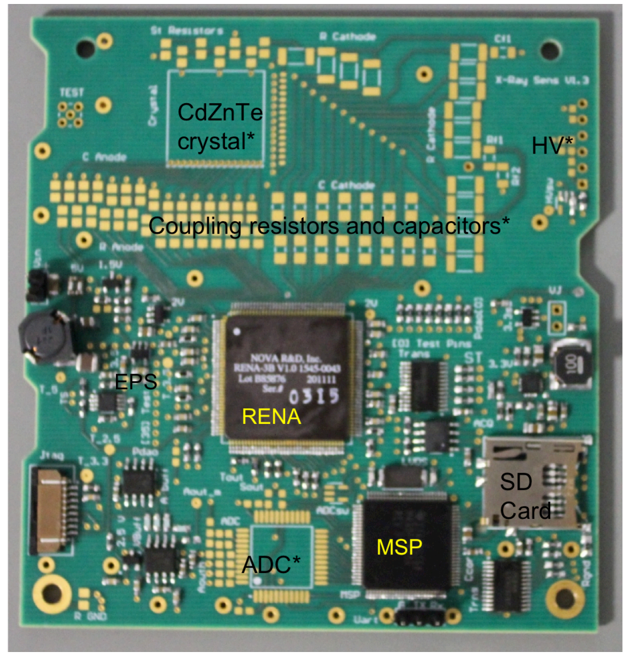

Fig. 3: Picture of the engineering model as the electrical tests being conducted. Some important components are shown on the picture. * indicates that the component has not been soldered (or glued) yet.

The alternative CdZnTe crystal is from REDLEN that has dimensions of 20 x 20 x 5 mm. We are collaborating with the Middle East Technical University Physics Department for the preparation of this crystal to gain knowledge and experience in CdZnTe preparation in Turkey. For this crystal, the orthogonal strip geometry and techniques to attach the crystal to the board are similar to the Due2Lab crystal. Due to larger crystal size we plan to use 16 anode strips that are 0.3 mm wide and steering electrodes that are 0.4 mm wide. There are 16 orthogonal cathode strips that are 1 mm wide. The pitch is 1.2 mm for both the anodes and the cathodes. In Figure 2 a picture of a similar REDLEN crystal is shown, the pattern is as described in this work. While the crystal in Figure 2 is 5 mm, we will trim the REDLEN crystal to 2.5 mm to use in our system.

Before preparing the REDLEN crystal, we tested crystal cutting, polishing, chemical etching and contact deposition capabilities with the crystals grown at METU. The results are encouraging (see II.IV), however, problems have been encountered especially with electrode deposition. This is possibly due to existing surface impurities after chemical etching. More tests are required before the REDLEN crystal prepared at METU can be seriously considered as an alternative for the XRD system.

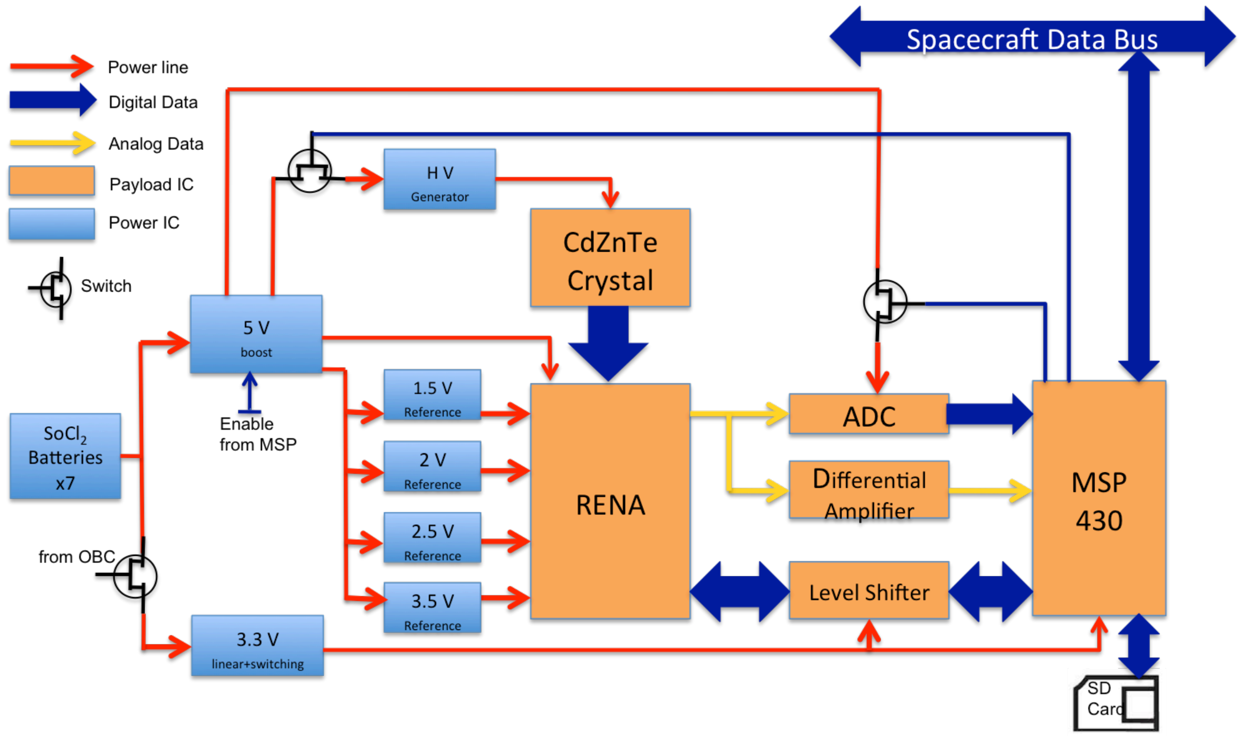

Fig. 4: Electrical block diagram and data flow diagram of the XRD. 3.3V is enabled by the on board computer (OBD) of BeEagleSAT. MSP enables 5V to turn the rest of the system on. MSP can also turn on/off the HV generator and the ADC for power considerations.

II.II Readout circuitry

All the anode and cathode signals will be read with the help of a single RENA-3b ASIC (see Figure 3). RENA-3b is a low-noise, 36-channel, self-trigger, self-resetting charge sensitive amplifier/shaper integrated circuit, which is commercially available [10]. Thanks to its low power consumption of <6 mW per channel and use of submicron CMOS process for fabrication, it is well suited for small satellite applications.

RENA chip is programmed and controlled by a MSP 430 Microcontroller. Each channel can be individually configured for polarity, threshold, gain and shaping time. Once programmed, signals exceeding the thresholds trigger the system. The list of triggered channels are sent to MSP 430, and then the MSP sequentially reads the analog outputs of triggered channels waiting at the peak & hold circuitry. The analog outputs can be read either through a 14 bit analog-to-digital converter (ADC), or directly at the ADC of the MSP with a resolution of 12 bits. Due to high power demands of the ADC and also the extra noise it presents to the system, the current plan is to use the MSP ADC and accepting a loss of digital resolution which is unimportant compared to the inherent noise of the crystal.

II.III Electrical power system

The EPS of the XRD is independent of the spacecraft EPS and the power will be supplied by 7 non-rechargeable Li-SOCl2 batteries from SAFT [11]. To save power, the system will be turned on intermittently at different altitudes for maximum scientific gain. The electrical block diagram can be seen in Fig. 4. On board computer (OBC) of the BeEagleSAT can turn on and off the 3.3V regulator. 3.3V powers the MSP which enables 5V. RENA requires 4 reference voltages to operate, 1.5V, 2V, 2.5V and 3.5V and also 5V for power. Enabling 5V from the MSP therefore turns on the RENA system. MSP also controls the operation of the high voltage (HV) generator, it is turned on only during data taking mode. Finally ADC is also turned on only when necessary (II.V).

Tests conducted at SU-HEALAB showed that RENA and CdZnTe crystal pair works as expected when 100V per mm of crystal thickness is applied. Higher potentials sometimes produce breakdowns and high levels of noise, and lower potentials worsen the energy resolution due to incomplete charge collection. Therefore the XRD requires a HV source that can deliver negative potentials up to -300V. In house circuits we designed and tested showed unacceptable noise levels therefore we decided

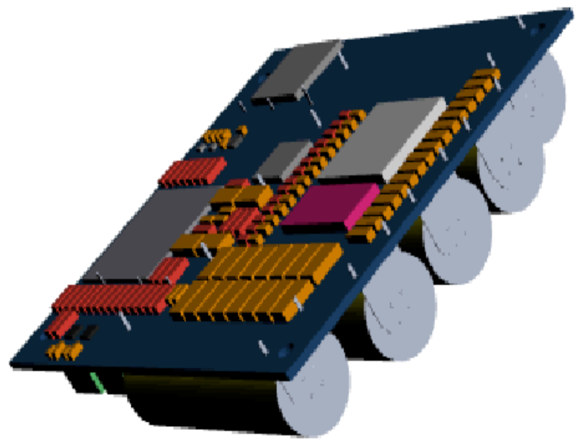

Fig. 5: CAD Drawing of the XRD.

to use a COTS HV source. Tests done with the UltraVolt US series show that it provides a steady voltage with very low ripple (<40 mV @ -300V) and performed well in thermal vacuum tests.

Based on efficiencies of the power circuits we use, the batteries will last for a total of 100 hours of operation. For all power sources, prototypes were designed, produced and tested for noise, stability. All prototypes went through thermal-vacuum tests. For all prototypes, ripple was less than 20mV peak to peak.

II.IV Mechanical design and early vibration tests

The XRD board has been designed and produced as 6 layer PCB board from TG 175 material (engineering module picture can be seen in Figure 3). Batteries will be attached to one side of the board. For stability and spacing reasons the batteries will be placed as close to the surface as possible, soldered and then covered with 3M insulating epoxy for further stability and vibration damping (see Figure 5 for a CAD drawing of the system, and Figure 6 showing batteries soldered and attached for the early vibration test). The presence of batteries resulted in placing almost all of the components on one side of the PCB board as shown in Figure 3.

Since the CdZnTe crystal is sensitive to optical light, the entire board will be enclosed in an aluminium cover with 1.5 mm thickness. This cover will provide additional stiffness, as well as electromagnetic noise protection from the rest of the spacecraft. The thickness is reduced to 0.5 mm over the crystal to allow X-rays greater than 20 keV to enter the crystal. The crystal will face +Z direction, opposite to ram velocity. The placement of the XRD within the spacecraft can be seen in Fig. 1.

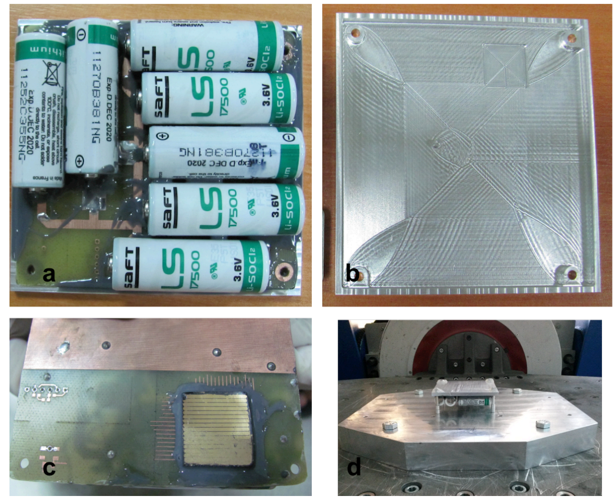

Fig. 6: Vibration test pictures. a) Batteries soldered and glued to the board, picture taken after the vibration test. b) Aluminum cover. c) CdZnTe crystal glued to the board. Picture taken after the vibration test. The defects on the electrodes were present before the test. d) Mechanical replica on vibration table.

To ensure structural stability we prepared a mechanical replica of only the critical parts, which are the board with holes for the attachment of batteries (Figure 6, a), batteries (Figure 6, a), a CdZnTe crystal grown at Middle East Technical University (Figure 6, c), and the aluminium cover (Figure 6, b). We prepared the system as it would be prepared for the actual XRD; we soldered, and then glued the batteries, glued to mock CdZnTe crystal onto the board, soldered electrical parts at the side of batteries (to make sure that they stay intact with the batteries), and then screwed and glued the aluminum cover. We then placed the system to thermo-vacuum chamber and observed that there were no changes in the shape of batteries and other components and the system remained intact. We then applied vibration tests to the mock mechanical XRD without the external structure of the spacecraft (See Figure 6, d showing mock mechanical system on vibration testbed). Since the spacecraft structure will further damp vibrations, this test can be considered as the worst-case scenario. After 2 dimensional vibration tests, all components remained intact there was no damage to the crystal, and batteries continued to operate as expected.

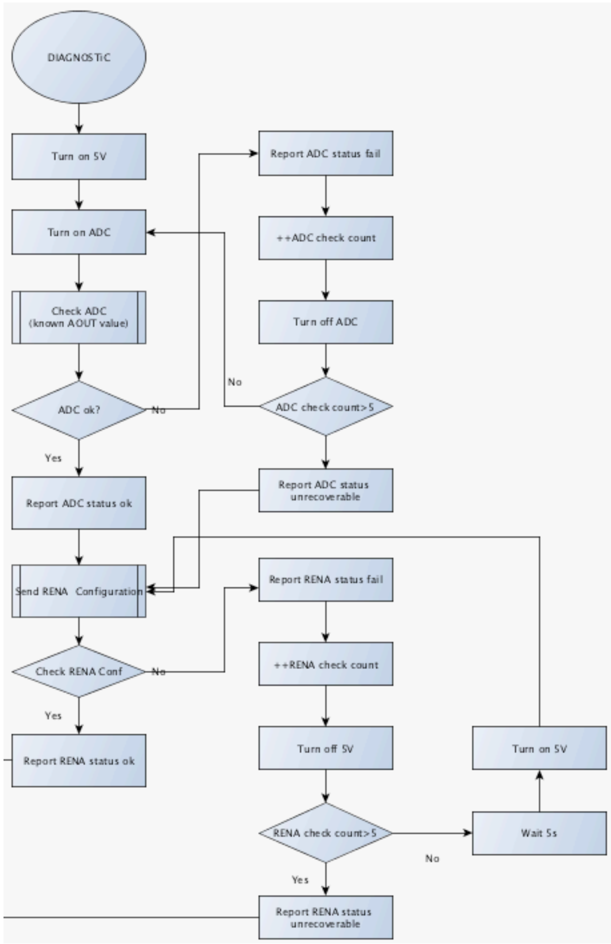

Fig. 7: Flow diagram for the DIAGNOSTIC mode of the XRD.

II.V Control and software

XRD currently has five operation modes, "IDLE/SAFE MODE", "DIAGNOSTIC", "DATA TAKING" and "POST PROCESS", and "DATA TRANSFER". In the IDLE/SAFE MODE all power circuits are disabled (except 3.3 V that powers the MSP). An interrupt from the OBC wakes the MSP 430, and depending on the interrupt, the system goes into one of the modes mentioned above.

In the DIAGNOSTIC mode, checks will be applied to ensure healthy operation of the readout circuit. The flowchart of the mode is given in Figure 7. In the DIAGNOSTIC mode, first ADC is checked. If it does not provide expected values, it will be turned on and off 5 times. If ADC does not work the problem is reported in a log file in the SD card. As noted earlier, the ADC may not be used at all in XRD, but the current version of the software includes modes and operations related to the ADC

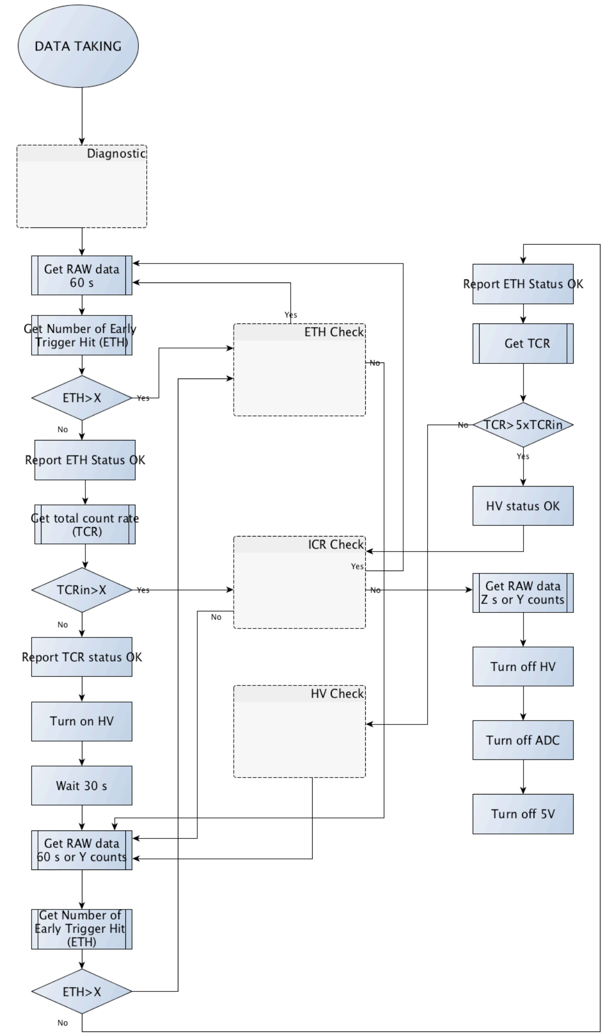

Fig. 8: Flow diagram for the DATA TAKING mode of the XRD. Details of Early Trigger Hit, Individual Count Rate and HV check are not shown here, but described in text.

in case direct readout with MSP internal ADC fails. After ADC diagnosis, the RENA configuration is sent. Using the RENA chip test outputs, MSP checks if the configuration has been sent successfully. If the check fails 5V is turned off which resets RENA. If the configuration cannot be send successfully 5 times in a row, a log is written in the SD card and the system goes into the IDLE/SAFE mode.

The main mode of operation is "DATA TAKING" mode. This mode initially repeats the DIAGNOSTIC mode to make sure that the RENA and the ADC works as expected. The flow diagram of the DATA TAKING mode is provided in Figure 8. Based on the experience of working with RENA ASIC, two additional checks are built in the software to make sure that the system is not dominated by noise. If the threshold of an individual channel is set too low (or for some reason that particular channel get very noisy) the system repeatedly triggers before the analog output values are read by the MSP. These type of events are called Early Trigger Hits (ETH), and if not dealt, would stall the operation of RENA. If ETH rate is high, the thresholds are increased, the RENA is reset by disabling 5V, and ETH is checked again for a maximum of five time. Each case is logged.

Similarly, sometime the threshold remains in a "gray region" such that ETH does not happen but the threshold is so low that the system is triggered only over one or more channels repeatedly by noise. An algorithm is developed (Individual Count Rate Check, ICR Check) to check the frequency of triggers from each channel and correcting the thresholds for the channels that create repeated hits by noise.

Once RENA passes these checks, the HV is turned on. Turning on the HV must result in significant more triggers compared to HV off case. If this is not the case, HV is turned on and off for a maximum of five times (and RENA is reset at the same time). If the count rate is still low, a log is written and the system goes into IDLE/SAFE mode. If HV operates successfully, the ETH check and noise trigger check must be done one more time because turning on HV may increase noise.

After all tests, system takes a pre-determined amount of time or hits, whichever comes first, and writes the raw data to the SD card. The raw data consists of anode and cathode strips that are hit for each trigger, and the signal on each strip. Assuming we use the 12 bit MSP ADC, the channel and multiple hit information result in a total of 19 bits per event. Under normal conditions, mostly a single anode and 2 cathodes should trigger for a single X-ray photon. For Compton scattering events number of strips that get a signal can go up to 4. Therefore a single X-ray can occupy 19 bits to 68 bits.

In the POST PROCESSING mode, raw data is converted into spectrum. This step is necessary due to limited telemetry available to XRD as the main science instrument of the QB50 will take most of the packets. So instead of sending the entire raw data, we first calibrate the channels and apply a depth correction (see section II.VI). Afterwards, calibrated event data is histogrammed in 1 keV bins to create a spectrum. The telemetry packets include log files of the operation, binned spectrum and a sample of raw data for diagnostic on ground.

When the spacecraft is ready for telemetry, another interrupt will be sent from the OBC, which will put MSP in "DATA TRANSFER" mode. The details of this mode are being discussed by the OBC Team.

II.VI Ground calibration

To be able to convert ADC signals from each channel to energy values in keV, a channel to energy calibration table must be created on ground. Since CdZnTe detectors are heavily affected by hole trapping, the resulting signals will be interaction depth dependent, interactions away from the cathodes will be affected more severely by hole trapping and will produce smaller signals [9]. For events that induce charges on cathodes and anodes at the same time (most of the events should be in this category), it is possible to correct for the depth effect by first estimating the depth of interaction from the cathode signal to anode signal ratio, and then apply this correction to the anode signals to obtain full signal. This is a well know technique, and depth correction tables for each channels can be obtained during on ground calibration work. After the crystal is attached to the board, this calibration process will be done at SU-HEALAB using radioactive calibration sources. Depth correction and channel-energy conversion tables will be loaded to the SD Card, and the MSP software will use these tables to apply corrections and conversions to create energy spectra.

III. Conclusion

A 2U CubeSat is being developed by ITU, TurAFA, and SU which will be a part of the QB50 Network and will hose sensor Set 3 of QB50. Moreover, a local X-Ray detector system will be space qualified. A successful demonstration of cross-strip CdZnTe detectors in space could lead to scientific X-ray imager systems on small satellites. Students, through hands-on work, have been developing the necessary skills and experience to succeed in the space industry. Overall, the QB50 project will provide an outstanding intercultural experience and a global network of students and engineers with the possibility of exchange and cooperation programs.

IV. Acknowledgments

The X-Ray detector part of this work has been supported by TUBITAK Grant 108T595 and Sabancı University Internal Research Grant IACF-13-01107. Emrah Kalemci thanks Prof. Raşit Turan and Mr. Yasin Ergunt for preparation of the crystal at METU.

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