Firmware development of a prototype Compton telescope for flight on a stratospheric balloon

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Introduction

Gamma-ray bursts are amongst the most luminous transients in the universe, yet the processes which drive these highly energetic objects are still poorly understood. Measurement of gamma-ray polarisation, when combined with spectroscopic and temporal measurements, may be one of the keys to unlocking the mystery behind these processes and the central engine which drives them.[1] Polarimetry measurements can also allow for a more complete understanding of other gamma-ray sources, such as pulsars and blazars.

A compact Compton Telescope (COMCUBE) is being developed to perform these measurements in the 100 keV to 1 MeV range, with a view to being deployed as a payload on 6U CubeSats deployed in a constellation. A scaled-down prototype detector is currently under development processed for flight on a high-altitude balloon in Q3 of this year.

Instrument Architecture

The COMCUBE instrument is composed of four distinct detectors which make up the 4U payload of a 6U CubeSat, shown in Figure 1. The prototype detector currently being developed is ¼ the size of the final version. The instrument is broken up into two interaction layers:

Primary interaction layer: 2 DSSDs, each developed separately by IJCLab and CEA. Interaction with DSSD leads to Compton scattering, with energy partially deposited.

Secondary interaction layer:
- D2 calorimeter (UCD) and side calorimeter (IJCLab).
- Captures scattered photons, allowing reconstruction of Compton interaction.

Data readout and experiment control are performed by a Zynq 7030 system on chip (SoC) from Xillinx, running a version of Linux. The SoC is contained within a TE0715-05 module which is mounted in a TE0703-06 carrier board, also from Trenz. The front-end electronics from each detector are interfaced with the programable logic (FPGA) of the Zynq chip via an interface board.

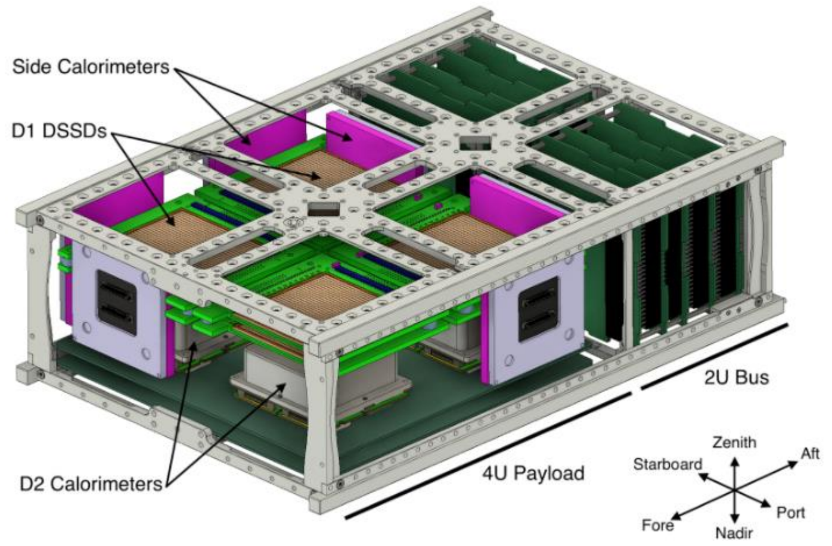

Figure 1: 3D model of full-scale COMCUBE instrument. The protype 1U instrument consists of ¼ the number of Scintillators and DSSDs.

D2 Calorimeter

The UCD D2 calorimeter (Figure 2) contains 4 GAGG Scintillator units from Advatech, each of which is composed of 16 separate crystals arranged in a 4 x 4 grid. Each unit is interfaced via a silicone optical pad to an array of 4x4 J-series SiPMs from OnSemi. The SiPMs are readout by an IDE3380 SIPHRA ASIC from IDEAS, with one SIPHRA per scintillator unit. This design builds upon that of GMOD, a CubeSat based gamma ray calorimeter developed by UCD.[2]

SIPHRA – Programmable Logic Interfaces

- SPI: Used for configuration of the SiPM readout, triggering and operational modes.
- Serial data TXD: Used to send raw ADC values from each SiPM, along with trigger information and temperature. Follows a non-standard 20-bit packet format, with one packet for each SiPM, a summed count packet and a temperature packet.
- Control lines: Reset, Error, external trigger.

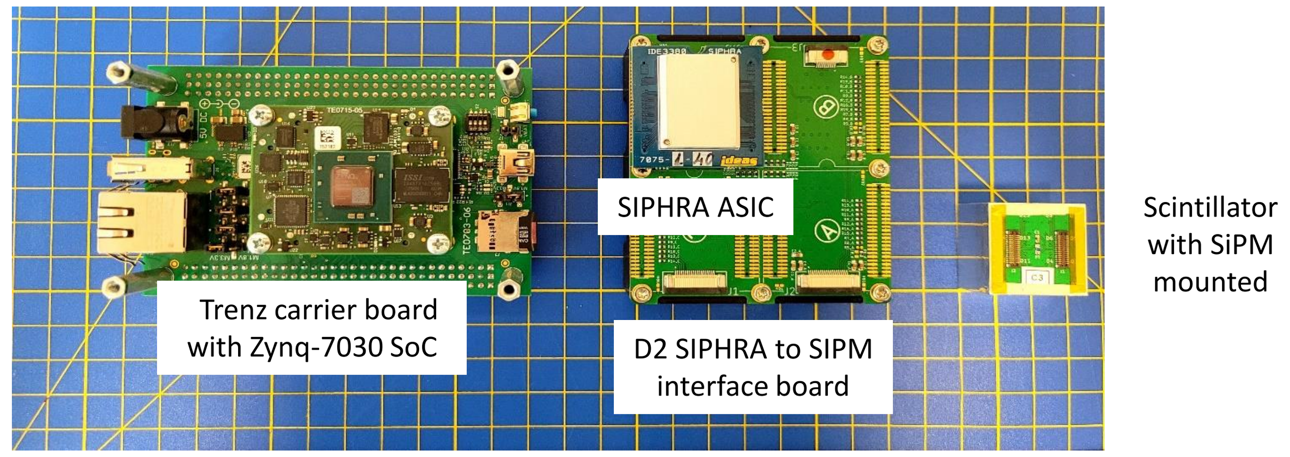

Figure 2: D2 Calorimeter hardware. For visibility, the interface board and cabling are not shown.

Programmable Logic Firmware

All programmable logic components are interfaced with the ARM-based Zynq processing system via the Advanced eXtensible Interface (AXI).[4] This is done via the Xillinx AXI-DMA IP for readout and Xillinx AXI GPIO IP for slow control and configuration. The block diagram for the data readout logic is shown in Figure 3.

Slow Control
- Decoding of SoC SPI controller to allow for configuration of 4 slaves.
- Configuration, reset and manual triggering of each SIPHRA ASIC.
- Generation of configurable 1 – 5 MHz SIPHRA input clock.
- Interception of SIPHRA temperature packet and readout to SoC.
- Monitoring of Error pin of each SIPHRA.

Readout Logic
- Synchronous serial 20-bit data receiver.
- 64-bit timestamping.
- Science Data packet generation and buffering.
- DMA to send science data to SoC memory.

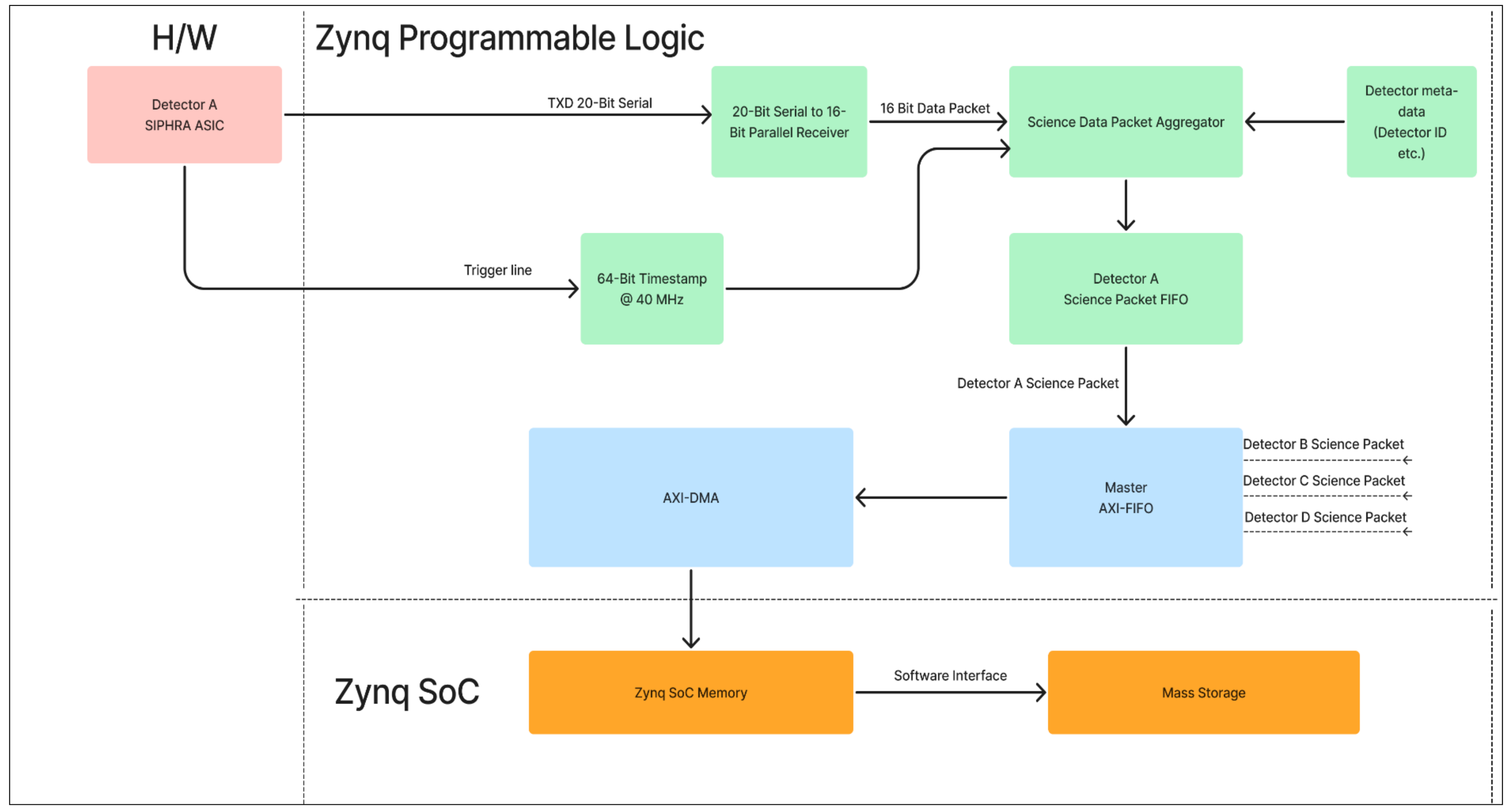

Figure 2: Detector readout Programmable logic block diagram.

Firmware – Software Interface

The SoC operating system is a custom version of Ubuntu with a kernel generated by the Xillinx Petalinux tool. This allows for the automatic inclusion of Xilinx Zynq 7030 specific drivers and interfaces and simplifies the development cycle.

UCD D2 Calorimeter Slow control interface:
- AXI-GPIO with the UIO driver.
- SPI mapped to Linux userspace with the SPIDEV driver.
- Python3 control software which utilises the MMAP and SPIDEV Python libraries.

UCD D2 Readout Logic interface:
- In-built Xillinx DMA driver for Linux.
- C application to bulk transfer experiment data to memory.
- High bandwidth transfer with low processor overhead

Software is easily iterated, and adaptable to different detector configurations. Allows future experiments to rapidly integrate SIPHRA based calorimeter.

Future Work

- The performance of the prototype instrument will be characterized over the duration of a stratospheric balloon flight during the upcoming CNES balloon campaign. This will estimate the instruments polarization sensitivity and overall performance.
- A recent proposal has reached the second round of the ESA call for ideas for "Innovative Mission Concepts Enabled by Swarms of CubeSats"
- It is expected that an improved instrument will be tested during a transatlantic balloon flight in 2024.

References

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Acknowledgements

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