Compact CMOS Camera Demonstrator (C3D) for Ukube-1

R. D. Harriss[a], A. D. Holland[a], S. J. Barber[a], S. Karout[a], R. Burgon[a], B. J. Dryer[a], N. J. Murray[a], D. J. Hall[a], P. H. Smith[a], T. Grieg[a], J.H. Tutt[a], J. Endicott[b], P. Jerram[b], D. Morris[b], M. Robbins[b], V. Prevost[b], K. Holland[c]

[a]Department of Physical Sciences, Open University, Milton Keynes, UK;

[b]e2v technologies, Chelmsford, UK;

[c]XCAM Ltd., Northampton, UK;

The Open University, in collaboration with e2v technologies and XCAM Ltd, have been selected to fly an EO (Earth Observation) technology demonstrator and in-orbit radiation damage characterisation instrument on board the UK Space Agency's UKube-1 pilot Cubesat programme. Cubesat payloads offer a unique opportunity to rapidly build and fly space hardware for minimal cost, providing easy access to the space environment. Based around the e2v 1.3 MPixel 0.18 micron process eye-on-Si CMOS devices, the instrument consists of a radiation characterisation imager as well as a narrow field imager (NFI) and a wide field imager (WFI). The narrow and wide field imagers are expected to achieve resolutions of 25 m and 350 m respectively from a 650 km orbit, providing sufficient swathe width to view the southern UK with the WFI and London with the NFI. The radiation characterisation experiment has been designed to verify and reinforce ground based testing that has been conducted on the e2v eye-on-Si family of devices and includes TEC temperature control circuitry as well as RADFET in-orbit dosimetry. Of particular interest are SEU and SEL effects. The novel instrument design allows for a wide range of capabilities within highly constrained mass, power and space budgets providing a model for future use on similarly constrained missions, such as planetary rovers. Scheduled for launch in December 2011, this 1 year low cost programme should not only provide valuable data and outreach opportunities but also help to prove flight heritage for future missions.

Keywords: Cubesat, CMOS, UKube-1, Earth Observation, radiation damage, SEE, single event effects, CIS, EV76C560

1. INTRODUCTION

Cubesats are a potentially revolutionary concept which could change the way the wider community accesses the space environment. Evolving out of the successful OPAL microsatellite launched by Stanford University in February 2000[1], the Cubesat concept aims to increase access to space by taking advantage of recent advances in miniaturisation, reducing the size, and therefore cost, of launching hardware into low Earth orbit[2]. The recently formed UK Space Agency (UKSA) has aspirations to start an annual Cubesat program with the aim of developing the UK's space capabilities and technology at a relatively low cost. Announced in December 2010, UKube-1 is the pilot mission in this Cubesat program with the original intention being to launch 3 payloads into LEO by the end of 2011.

The Open University was selected to fly its Compact CMOS Camera Demonstrator (C3D) technology demonstrator payload on board UKube-1. It is based around a 0.18 micron Complementary Metal Oxide Semiconductor (CMOS) Imaging Sensor manufactured by e2v technologies[3]. CMOS Imaging Sensors (CIS) are a relatively recent advance in the field of semiconductor imagers. Offering significant advantages over the more established Charge Coupled Device (CCD) in terms of power consumption, read out speed and inherent radiation hardness, their wide spread use in scientific applications has, until recently, been limited by lower noise performance[4]. Consequently the flight heritage of CIS is relatively poor, especially for European

Further author information: (Send correspondence to Richard D. Harriss)
Richard D. Harriss: E-mail: r.harriss@open.ac.uk, Telephone +44 (0)1908 332 769

manufactured high grade scientific devices. It is therefore important to establish heritage and flight credentials of this less mature yet important type of imaging device.

C3D will use the e2v 1.3 MPixel EOS EV76C560 CIS, which are part of the e2v family of 'eye on Si' chips. These devices, originally designed for medical and industrial purposes, are highly integrated imaging sensors, providing all the required circuitry for image capture and digital readout on one single integrated circuit. The EV76C560 uses a simple Serial Peripheral Interface (SPI) communications protocol for command, requiring only one additional reference clock, and outputs 10 bit digital data with a frame rate of over 60 frames per second. The power consumption is under 300 mW [5]. C3D aims to not only increase the Technology Readiness Level (TRL) of this type of device, but hopes to characterise the radiation performance of these devices as well as capture images of the Earth's surface.

This paper outlines the design and testing of the C3D payload. The progress to date is presented, including the key design considerations, and the expected mission aims and performance are discussed.

2. UKUBE-1

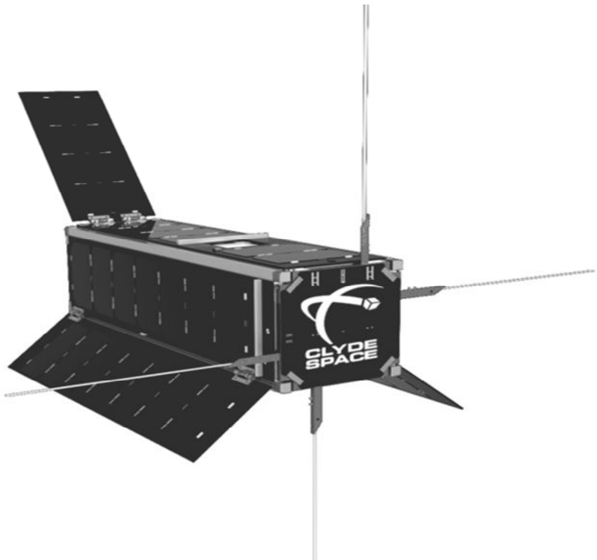

Figure 1: Artists impression of UKube-1 (source: ClydeSpace)

2.1 Mission Summary

UKube-1 is a fully autonomous space craft with its own power, telemetry, computing and pointing systems. The space craft is a 3 cube Cubesat based around the standardised PC-104 system. The space craft was commissioned by the newly formed UKSA with the primary aim of demonstrating and improving UK technology in the real space environment, whilst offering invaluable opportunities for outreach and training. The space craft platform itself is being developed by ClydeSpace Ltd, a small space start-up company (based in Glasgow, UK) who primarily develop components for small nano and pico satellites. The original call for 3 payloads from the British space community was re-evaluated a few months into the project and there are now four payloads being provided by various groups from around the UK[6].

Astrium are providing the Janus payload which aims to demonstrate the concept of using Single Event Upsets in solid state RAM as a random number generator. Bath University are developing a payload called TopCat which will map the top side ionosphere using GPS signals. The UK Students for the Exploitation and Development of Space (UKSEDS) are developing a concept called the IQEA MyPocketQUB 440 which is aimed at increasing access to the space environment for students whilst providing outreach opportunities to schools and universities across the UK. The last payload, which this paper focuses on, is being developed by the Open University[7].

2.2 UKube-1 Design Overview

UKube-1, like all Cubesats, occupies a foot print of 100 mm x 100 mm. As a 3U Cubesat UKube-1 is approximately 320 mm in length. The main spacecraft structure is provided by the 3 cube Cubesat space frame manufactured by Pumpkin, which is an off the shelf Cubesat component conforming to the PC-104 format. The space craft is constructed from a series of vertically stacked boards which all fit within this outer frame. Corner posts constructed from M3 hex bolt spacers between each board are attached to the frame and provide much of the support to the separate PCB cards which make up the space craft. The original intention was for each of the three payloads to occupy approximately 36 mm of the total height, however with the increased payload capacity the height envelope of each payload has been customised to suite its particular design[6]. Figure 2 shows a CAD drawing of the UKube-1 structure.

The electrical interfaces on the PC-104 design are standardised and are provided by two 52 pin connectors attached to each board. When the boards are stacked on top of each other these connectors are all connected, forming a spine which is the main bus for the space craft. I2C communications protocols provide the primary payload interface with an additional 1MHz SPI bus adding a high speed data return bus. The payloads are provided with 4 switchable power lines which can provide an average continuous power to each payload of 400 mW with a peak power of 2000 mW.[6]

Data return is provided by both a UV whip monopole antenna (primary) and an S band (secondary) antenna. Mass data storage is provided by the platform for the payloads which can store up to 250 GBs of data ready for telemetering to the ground. The ground segment is being provided by RAL Space UK. Each payload is allocated only 100 Kbits per orbit, which for an imaging system is the key limiting factor. However, the actual data return may be much higher if the secondary S band antenna is successfully brought online which offers a much higher telemetry rate[6]. Data compression is provided by the platform; however C3D will be implementing its own data compression specific to image data.

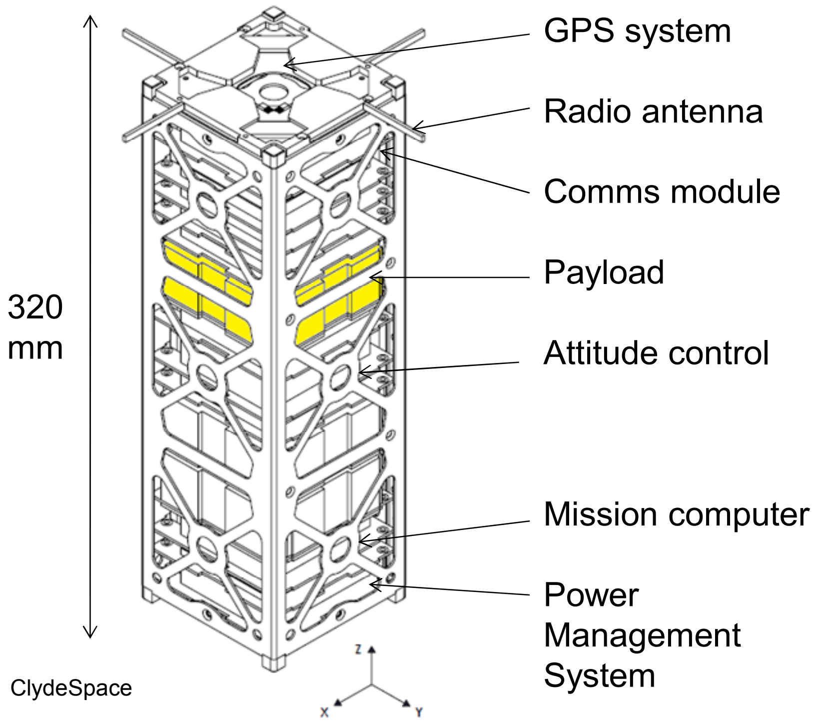

Figure 2: UKube-1 structure showing the outer Pumpkin space frame. A single instrument payload slot is highlighted (source: ClydeSpace[6]).

The space craft is intended to be put into an orbit of 650 km with a 97° inclination. The orbital period is approximately 90 minutes. Originally night operations are not envisaged with only daytime payload activity initially being allowed. Reaction wheels are provided by UKube-1 as the primary pointing control with a stability error of 3 degrees in the Z axis Thompson Roll of the spacecraft. There are also secondary magnetorquers installed, which can potentially offer much greater pointing accuracy[6]. Pointing control will allow imaging operations to be aimed at specific locations with the imager read out being fast enough to prevent significant image smearing.

3. C3D OVERVIEW

3.1 Payload Aims

C3D is primarily a technology demonstration payload whose main aim is to increase the TRL of the EV76C560 CIS through successfully demonstrating their use in space. Not only will this directly raise the TRL of the EV76C560 sensors but will also have an impact on the TRL of similar devices built with the same process. The secondary payload aims are to characterise the response of these sensors to space radiation. The characterisation of the effects of space radiation on imaging sensors is one of the crucial components to flight qualifying them. There is also an invaluable opportunity to use this dedicated radiation damage experiment to calibrate ground based testing with real in orbit data. The third payload aim is to capture images of the Earth. Although this is the lowest priority science goal it provides arguably the most rewarding return in terms of PR and outreach. There are also many potential future applications for relatively high resolution imaging in a small cost effective instrument.

3.2 Design Overview

In order to meet its science aims C3D is comprised of three separate EV76C560 CIS, each fulfilling a specific purpose. Not only does this offer optimisation for each task but the multiple sensors provide some redundancy against both sensor failure and against certain space craft failure scenarios, such as a loss of pointing. The Narrow Field Imager (NFI) CIS provides the sensor to the NFI system, which is the high resolution custom built camera for Earth Observation (EO). The second EO sensor is the Wide Field Imager (WFI) CIS which provides lower resolution wide angle imaging through the use of a Commercial Off The Shelf (COTS) lens. The third sensor is the radiation damage monitor (RDM) which is an optically dark, temperature controlled sensor for studying the effects of space radiation. The sensors themselves are all mounted on flex rigid circuits.

C3D is designed around a Field Programmable Gate Array (FPGA) payload controller being developed by XCAM Ltd. The payload controller provides functions such as the platform interface, command and control to the payload and data handling capabilities. In addition to the payload controller and the 3 sensors there is a second set of electronics called the Experiment Support System (ESS) which provides housekeeping functionality such as temperature control and dosimetry.

The payload controller and the ESS exist as two separate cards which are mounted one above the other. The sensors are connected to the payload controller directly by their flex rigid circuitry. The boards are supported by an aluminium chassis which also mounts the various optical components. The optics are sandwiched between the payload controller and the ESS cards and are faced in the nadir direction of the space craft. Figure 3 outlines an overview of the C3D instrument.

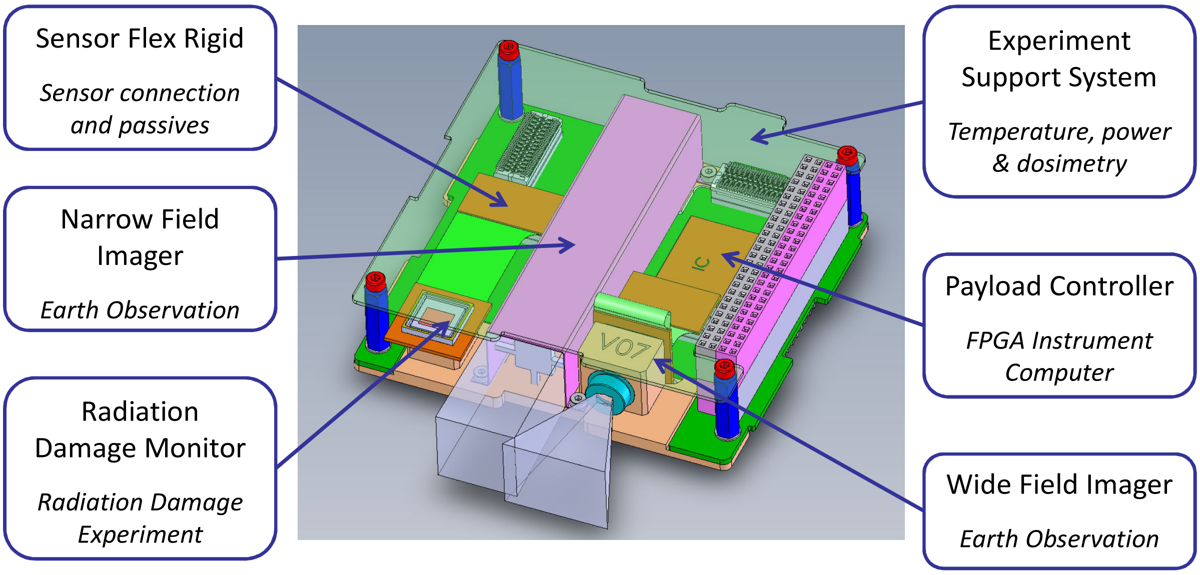

Figure 3: C3D instrument overview.

4. e2v EV76C560 CMOS IMAGING SENSORS

The EV76C560 CIS is a highly integrated CMOS sensor manufactured by e2v Grenoble. The sensors are part of the e2v 'eye-on-si' family of chips which are intended for industrial and medical purposes. The EV76C560 is a 1.3 MPixel chip with 5.5 micron pixels. The pixel is a 5T design, although it can operate in a 4T mode. The chip requires only power, a single clock and an SPI interface and produces 10 bit digital data out. The EV76C560 sensors which are being used in C3D are colour imagers using an RGGB Bayer filter, although black and white versions are available.

The sensor is a highly digitised CIS. The raw pixel outputs are initially fed into a 10 bit column ADC which is then digitally processed inside the sensor. After processing the data is buffered internally before being outputted in parallel with separate frame and line synchronisation signals. The sensors are capable of achieving a pixel rate of 100 MHz which corresponds to 60 frames per second. The sensor also includes the capability to define multiple Regions Of Interest (ROI), each with separate imaging parameters. These separate ROIs can also be binned on chip further minimising the amount of off chip processing required.

The EV76C560 CIS use only 3.3 V and 1.8 V power lines with the IO standards being 1V8CMOS. At the standard 100 MHz pixel rate the EV76C560 CIS uses approximately 200 mW of power. However at the 10 MHz pixel rate which C3D is operating at, this drops considerably to around 35 mW.

5. MECHANICAL DESIGN

The mechanical structure of C3D is provided by a black anodised aluminium chassis at the base of the instrument onto which the payload controller card is mounted directly. The chassis is then attached to the main UKube-1 structure via the four UKube-1 corner posts, but is electrically and thermally isolated from the rest of the UKube-1 structure. The ESS card sits at the top face of the C3D instrument and is fixed to the chassis via 4 corner posts which also form part of the UKube-1 overall mechanical support. The ESS and the payload controller are electrically attached via a flex rigid circuit.

The chassis not only provides mechanical support to the PCBs but also provides a mounting point for the optical systems. The Wide Field Imager optics housing is machined as part of the chassis providing a light tight and dust tight enclosure for the sensors and WFI lens assembly. The housing is threaded allowing an off the shelf stock lens to be used for the WFI with its focus being adjusted by screwing the lens into or out of the housing. The lens is then screwed and glued into place to fix it in position.

The two Narrow Field Imager mirrors are mounted directly onto the chassis. The primary M1 mirror, with the NFI CIS attached to its rear surface is fixed in place. The secondary M2 mirror is moveable along the optical axis allowing the focus to be adjusted. This optics system requires more precise alignment than the WFI and as such custom Ground Support Equipment (GSE) is also being manufactured to focus and align this optics system.

The RDM is also mounted to the chassis, although not directly. The RDM is temperature controlled via a Thermo Electric Cooler (TEC) and as such the sensor is mounted on to the TEC with the entire assembly then sitting directly on the chassis. The TEC is designed to heat the sensor to enhance the effects of dark current. In order to do this it draws heat from the chassis effectively 'pumping' it into the CIS. This makes the chassis an important part of the C3D thermal control system.

6. ELECTRONICS DESIGN

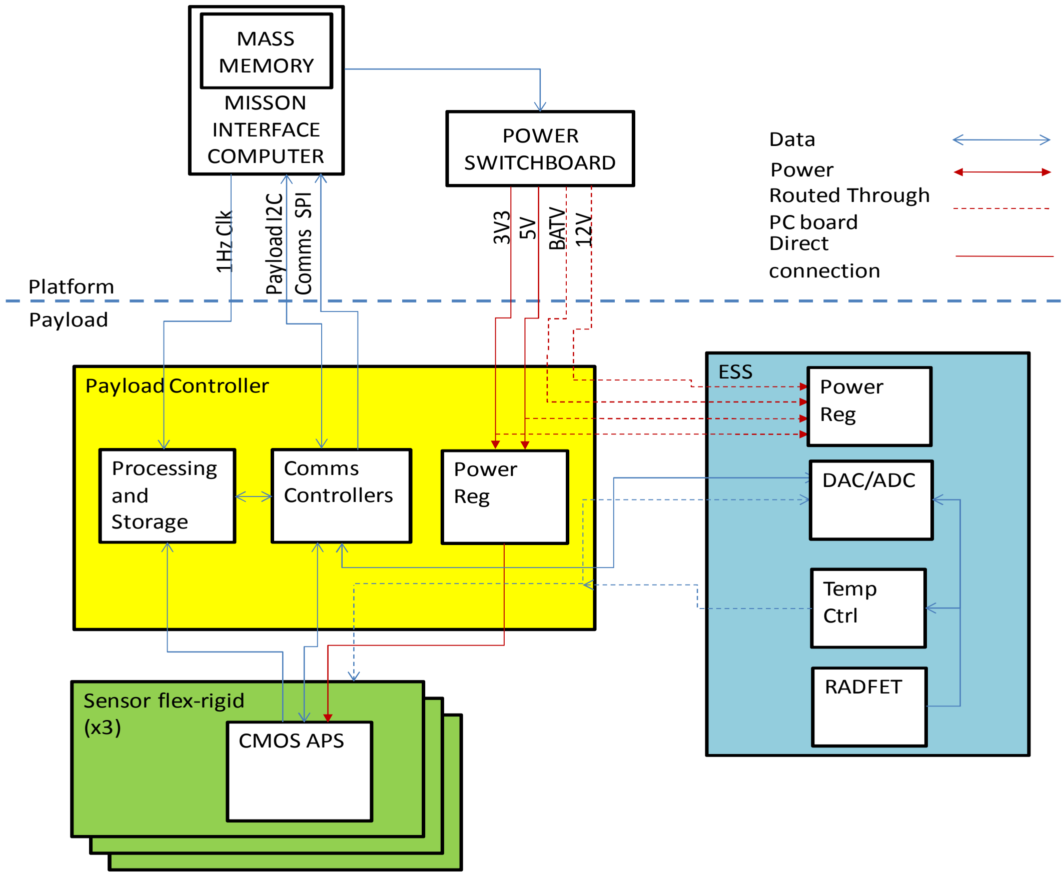

Figure 4: C3D electronics system concept

6.1 Payload Controller

The payload controller provides the majority of the interface, control and data handling functions to the instrument. The payload controller is designed around an Altera EP3C40 Cyclone III FPGA which implements a soft-core Nios II processor. The payload controller provides 3 different types of storage to support the mission. There is an flash based configuration device for storing the FPGA firmware configuration. There is also flash memory storage for storing the mission software. The last piece of memory is provided by 16 MB of SDRAM which is the working memory for the instrument, storing all data prior to uploading data packets to the space craft ready for telemetry.

Due to the low cost, rapid build nature of this Cubesat program all components that have been used are COTS components. This does offer some challenges in terms of radiation hardness. Where possible components have been selected to minimise the radiation effects, such as the choice of RAM over flash for the working memory. However, none of the components are themselves designed to be radiation hard. This has led to some limits on what can feasibly be studied by C3D. In particular it would be very hard to identify Single Event Upsets in the CIS as the upset could very likely be due to the RAM or FPGA. The instrument will be put through a Total Ionising Dose (TID) test campaign prior to launch which should help to identify any significant problems. Also the operations cycle, and in particular the data limit, mean that C3D will not be on for the majority of its operational life which should help to reduce the radiation effects.

6.2 Experiment Support System (ESS)

The ESS provides all the additional electronics which C3D requires that is not directly related to the FPGA or the imaging sensors. This is primarily housekeeping functionality. The ESS board also provides its own power switching and control.

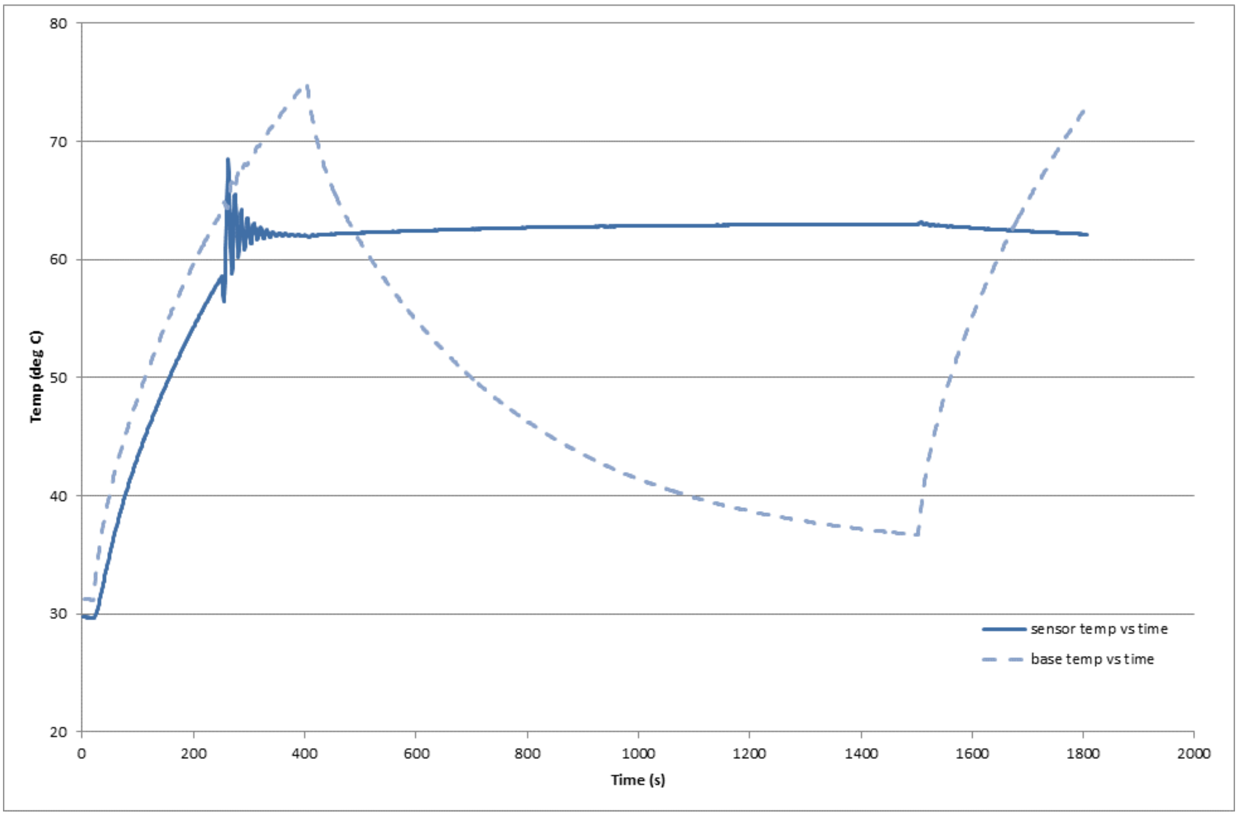

Figure 5: This graph outlines testing on the thermal control system under vacuum. The TEC and sensor were mounted on a metal base whose temperature was varied by 40° over 30 minutes. The thermal control system was activated approximately 5 minutes into the cycle and managed to maintain the set point to within half a degree. The real UKube-1 thermal cycle is not as severe and varies over 90 minutes rather than 30. As such the achieved thermal stability will likely be better than outlined here.

The first task which the ESS provides is thermal control and monitoring. The ESS uses an off the shelf Maxim Integrated Circuits TEC controller Integrated Circuit (IC) to drive and control a small low power single stage TEC. This IC includes not only a TEC driver but also a Proportional-Integrative-Derivate (PID) controller tailored specifically to the Bode response of the TEC. The TEC is then thermally coupled to the RDM and is capable of both cooling and heating. Thermal feedback is provided to the ESS TEC driver through a Negative Temperature Coefficient (NTC) thermistor. Temperature monitoring is also provided to a number of key elements by PRTs placed around C3D. These PRTs are then fed into ADCs which are accessed by the FPGA. Figure 5 outlines some preliminary testing on the prototype instrument system of the thermal control system under vacuum.

The second function of the ESS is to provide dosimetry information for the radiation damage experiment. The dosimeter for C3D is based around REM RFT 300 RADFETs[8]. The C3D dosimeter design will allow measurements of the order of a single Rad. One RADFET is being used directly by C3D, with 2 others are being provided by C3D to the platform to help study the dose rate in Cubesats. Some initial work has been done on testing and calibrating the RADFET dosimeter, however an in depth calibration must still be completed which takes into account temperature effects. Figure 6 outlines the initial testing on the RADFET dosimeter out to 20 Krads using the ESTEC Co-60 source.

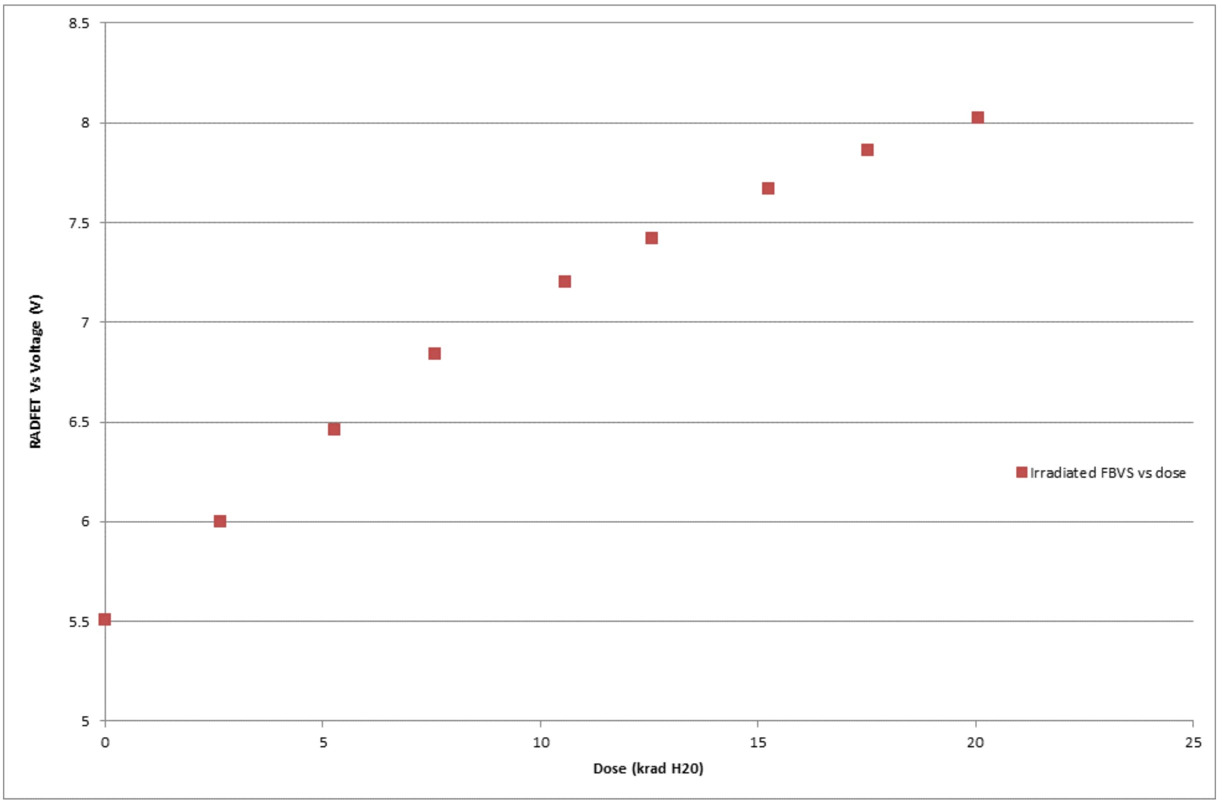

Figure 6: RADFET Flat Band Voltage Shift (FBVS) measured as a function of dose.

7. RADIATION DAMAGE EXPERIMENT

7.1 Dark Current

Dark current is a noise source common to all semiconductor imagers caused by thermal excitation of conduction charges across the bandgap. All silicon imaging sensors suffer increases in dark current during operation in space and in CCD and CMOS imagers this can particularly manifest itself as an increase in bright pixels, some fraction of which also flicker. The increase in dark current can significantly degrade the image quality, especially with longer integration times or with faint light sources.

The RDM on-board C3D is optically dark so will only integrate dark current. Images taken with this sensor should show bright pixels which are characteristic of CIS after irradiation. Figure 6 shows an example image of an EV76C454 imager which has been exposed to two different levels of proton irradiation. The longer the CIS is in space the higher the dose and the more pronounced this effect will become. The thermal control system for the RDM should enhance any bright pixels by heating the sensor so that the rate of dark current generation is higher. This will allow dark current effects to be studied even at relatively low doses.

A ground based radiation test programme is planned to irradiate the EV76C560 to 3 years UKube-1 dose which will allow the space effects to be compared to those seen on the ground. This will likely be completed after instrument delivery but prior to launch.

7.2 Single Event Latchup

Single Event Latchups (SEL) are a potentially catastrophic failure mode for CMOS technologies. SELs are caused by the deposition of large amounts of energy in the bulk silicon by the transition of high energy heavy ions through the device. This energy causes the creation of parasitic transistors within the bulk silicon which create un-regulated conduction loops. If not monitored or controlled these latchup events can not only leave the CMOS devices un-responsive but can ultimately lead to an irreversible failure.

C3D is designed to monitor SEL events as UKube-1 transits through the radiation belts present in LEO. As the instrument moves through its orbit it is bombarded by heavy ions which will cause the RDM CIS to latchup. The power supply of this sensor is being constantly monitored. If the power consumption moves significantly away from the mean then the sensor is probed to see if it is still operational. If the CIS is un-responsive then the sensor is reset and the event is recorded as a latchup event and the data is telemetered back to the ground.

7.3 Additional Modes

The RDM will also be used to measure the energy spectrum of the radiation present at various parts of the orbit. Through the logging of multiple frames of data, a histogram of the energy spectrum in that location can be built up and transmitted back to the ground.

8. EARTH OBSERVATION

8.1 Image quality

The Earth observation instrument has the largest potential for data generation, however due to the limited payload bandwidth which has been allocated image quality and optimising the image return is very important. C3D incorporates a number of strategies to maximise the image return quality from orbit.

The space craft orbit results in a ground speed of nearly 27,000 kph. This means that in order to avoid significant smearing of the image exposure times on the NFI must be less than 0.2 ms. The minimum integration time with the C3D camera set up is around 17 µs. Based on flux modelling of the required integration times for good exposure control we are estimating we will require approximately 100 µs with the NFI. This indicates that smearing should not be significant.

C3D will implement image compression based upon JPEG-LS algorithms. This should offer a 60% reduction in data for EO type data and a 30% reduction for dark image data. This should help to maximise the data return. In addition C3D will be implementing thumb-nailing of images to allow selection on the ground of the best images. With the baseline data rate and image compression we are expecting a download rate of 1 image every 4 days. This corresponds to around 90 images per year. However if the S band antenna is successfully brought online this could significantly increase.

The last factor affecting image quality is the pointing control error of the spacecraft with the primary reaction wheels which is 3^o or almost 35 km on the ground. This would make targeted imaging difficult. However the pointing knowledge is much better. As such we have are planning on using a system where the spacecraft triggers the image capture at the appropriate moment. There is also a secondary pointing control system based around magnetorquers which potentially offer much better pointing control. Pointing errors in the WFI are less significant.

8.2 NFI

A cost/performance study was conducted for 3 telescope designs: bi-conic, Newtonian and Cassegrain. The bi-conic design was preferred based on its performance however it was de-selected due to the cost of manufacturing. The Cassegrain design was ultimately selected due to its longer focal length plus ease of integration. The NFI Cassegrain telescope has a field of view of 2^o with an effective area of 18 mm x 18 mm and a focal length of around 90 mm. The expected GSD performance of the NFI is close to 25 m per pixel, which is pixel limited rather than diffraction limited. The swathe width is around 300 km. Figure 7 shows a representative NFI image of the UK.

Figure 7: NFI representative image of the UK (Source: NASA)

8.3 WFI

The WFI uses a stock lens with a field of view of 40^{o} and a focal length of around 5 mm. This translates to a GSD of 300 m per pixel and a swath width of 600 km. Figure 8 shows a representative WFI image of the Isle of Wight, UK.

Figure 8: WFI representative image of the Isle of Wight, UK (Source: Google Earth)

9. CONCLUSIONS

Cubesats offer a unique opportunity to construct and launch tech demonstration payloads into LEO. Raising the TRL of imagers usually requires their use on a primary instrument at great expense and also often with a long development time. Cubesat missions allow new instrument technologies to be rapidly flown in a low risk and low cost way.

Radiation damage studies can also now be carried out in orbit for costs comparable to conventional ground based radiation test campaigns. A conventional ground based testing programme has an associated cost of the order of a Cubesat instrument so future radiation test campaigns could be done in LEO. This allows both a raising of TRL and also radiation qualification in the real environment in one mission. The major drawback is that you lose experimental control and encounter greater uncertainty.

The EO aims on this mission, despite being modest, represent one of the most ambitious designs so far in Cubesats in terms of resolution and performance. Typical Cubesat imagers are off the shelf webcam type technologies and do not use bespoke optics and sensors. The applications for low cost Cubesat imagers are many, from disaster relief and mapping to climate change and forecasting applications. Although we do not have any specific goals for our EO images we do feel that future iterations of this technology could be put to use on specific tasks. As part of this we have ambitions for Ukube-2+ which include flying a larger optic and possibly more advanced imaging technology with the aim of better resolution.

REFERENCES

[1] Heidt H. et al., "CubeSat: A new Generation of Picosatellite for Education and Industry Low-Cost Space Experimentation", *14th Annual/USU Conference on Small Satellites*, (2000).

[2] Puig-Suari, J. et al., "Development of the standard CubeSat deployer and a CubeSat class PicoSatellite", *Aerospace Conference, 2001, IEEE Proceedings.,* **Vol 1**, 1/347 – 1/353, (2001).

[3] Holland A. D., Harriss R. D. et al, "OU e2v Demonstrator CMOS Imager for UKube-1", *UKube-1 Payload Proposal*, (2010)

[4] Janesick j. et al., "Fundamental performance differences between CMOS and CCD imagers; Part I", *Proc. SPIE,* **Vol. 6276**, pp. 62760M, (2006)

[5] e2v EV76C560 datasheet, 1005A, (2009)

[6] UKube Payload Interface Requirement Specification, UKUBE.RS.001 ISS04, **Issue 4**, (2011)

[7] UKSA, http://www.ukspaceagency.bis.gov.uk/19128.aspx, (2011)

[8] REM Oxford RFT-300-CC10G1Datasheet, rft0888CC10-dat0B, **Issue B**, (2009)