Spacecraft health and environmental monitoring from a CubeSat platform

Conference or Workshop Item

How to cite:

Burgon, Ross; Holland, Andrew; Harriss, Richard and Sheridan, Simon (2012). Spacecraft health and environmental monitoring from a CubeSat platform. In: UN/Japan Nano-Satellite Symposium, 10 Oct - 13 Oct 2012, Nagoya, Japan.

Version: Version of Record

Spacecraft Health and Environmental Monitoring from a CubeSat Platform

Ross BURGON[1)], Andrew HOLLAND[1)], Richard HARRISS[1)], Simon SHERIDAN[1)]
[1)] *Department of Physical Sciences, The Open University, Milton Keynes, UK*
r.burgon@open.ac.uk

The uncertainties in the outgassing/offgassing, dust/debris, and radiation environments within and surrounding spacecraft regularly lead to operational problems with technical, scientific and ultimately economically deleterious consequences. In this paper we present the outputs of a study into a small modular spacecraft health and environmental monitoring package deployed in a standard 3U CubeSat platform that will provide real time measurements of a spacecraft's immediate environment to inform operators and on-board systems of threats to spacecraft or payload "health" via a comprehensive and correlated dataset of many related environmental parameters. We also demonstrate a mission concept with this platform deployed in LEO orbit.

Key Words: Cubesat, Health, Environment, Monitoring, Lunar

1. Introduction

Major space missions spend many £M investigating effects such as the radiation damage on sensors (Gaia[1)], Euclid[2)], Hubble[3)] etc.), whilst surface contamination from spacecraft outgassing is a major concern for designers, particularly where cryogenic surfaces are used. There are many instances of contamination build-up affecting the efficiency of calibrated instruments (Chandra[4)]) and debris can degrade sub-systems such as solar panels (e.g. Hubble[5)]) and detectors (e.g. XMM[6)]).

The development of a compact state-of-the-art miniaturized spacecraft health and environment monitoring instrument would provide a new level of information which could inform the decisions of those responsible for spacecraft operation, improving lifetime of missions and quality of data return. In addition, this combined instrument could attract significant development funding e.g. from ESA, and be further commercialized and offered as a low-mass add-on to many more major missions in the future, with terrestrial exploitation opportunities.

At the Open University, the Centre for Electronic Imaging (CEI) has designed and built the Compact CMOS Camera Demonstrator (C3D)[7)] to fly as a payload on UKube-1[8)], the first mission in the UK Space Agency's CubeSat technology demonstration programme. C3D's aims are to improve the TRL of CMOS sensors for future missions, correlate the effects of space radiation with ground based testing and capture images of the Earth. C3D uses a powerful, in-house developed payload control computer to manage multiple experiments within the payload. It is envisaged that this could be utilised as a multi-payload controller for future CubeSat missions.

This paper summarises the outputs of a concept study that's objectives were:

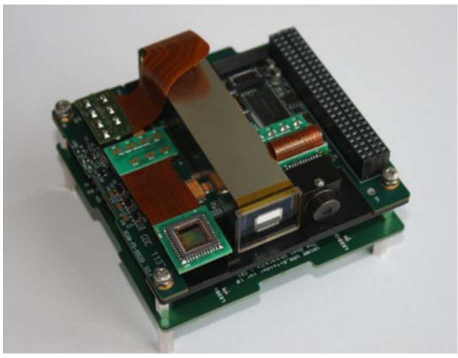

Fig. 1. The Compact CMOS Camera Demonstrator

- To assess the feasibility of demonstrating a miniaturised spacecraft health and environmental monitoring package on a CubeSat platform
- To produce workable designs of the instruments in the package
- To demonstrate that the UKube-1 C3D payload controller can be used to control the other instruments thereby providing evidence of a high state of readiness for future CubeSat opportunities

2. Instruments for Spacecraft Health and Environmental Monitoring

In this study, three main areas were investigated contributing to long-term detrimental effects to spacecraft and their sub-systems. These were:

- spacecraft outgassing
- radiation damage

- dust and micro-meteor particle damage

Instruments were conceptually designed that would record these effects within the CubeSat standard footprint of 10×10 cm and with the CubeSat mass and power constraints in mind.

2.1. Mass spectrometer and gas calibration unit

The proposed mass spectrometer is based on the Ptolemy ion trap mass spectrometer[9)] and consists of a set of 3 electrodes to which a radio frequency (RF) field is applied such that ions may be trapped in stable orbits within the internal cavity. By appropriate manipulation of the RF amplitude the ions may then be ejected in a controlled manner and in order of increasing mass-to-charge ratio from the cavity, into a suitably positioned detector. The output of the detector as function of time constitutes a mass spectrum and the technique is termed mass selective axial ejection. The mass-selective ejection technique typically affords unit mass resolution across an instrument's working range of 10 to 250 AMU.

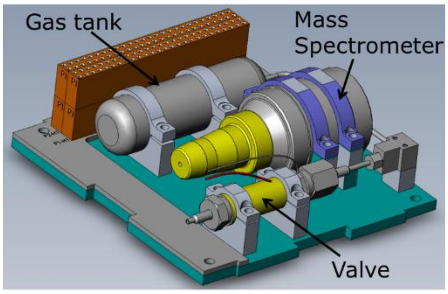

Fig. 2. The Mass spectrometer and gas calibration unit

Based on recent flight performance of the Ptolemy instrument during the Lutetia fly-by[10)] the device should be able to measure partial pressures of ~1x10^{-12} mbar. The use of the calibration gas unit will allow for the release of controlled amounts of benign reference gases for mass spectrometer calibration purposes, and uses a new type of valve which has been patented. In addition it will allow for the TRL raising of the gas system/valve technology ready for future opportunities, including micro propulsion systems.

2.3 Hyper-spectral imager technology demonstrator and radiation damage monitor

The C3D experiment is intended to measure the effects of radiation damage in e2v's new CMOS sensors. In addition, the instrument has the ability to measure the total ionising dose (TID) at the payload using a RADFET. Our aims in this stuft for this new instrument are twofold; to fly one of e2v's new CMOS imagers specifically designed for space applications, as a TRL-raising exercise, and to extend the space radiation monitoring function. The CIS107 CMOS sensor is currently under development at e2v as a sensor for future hyperspectral imaging instruments. The prototype sensor already exists, and the next generation device will be available within ~12 months. Being pin-compatible with the prototype, an instrument based on this sensor could fly the most up-to-date version of the sensor to enhance the TRL of this new technology, leading to take-up in future space instrumentation.

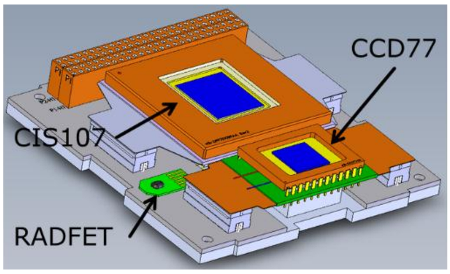

Fig. 2. Hyper-spectral Imager Technology Demonstrator and Radiation Damage Monitor

To extend the radiation environment monitoring function of the instrument, we would add a linear CCD which is capable of monitoring the received proton fluence, to complement the RADFET which measures ionising dose (TID). The original concept for this proton sensor, termed the Bulk Damage Monitor (BDM) was first explored over a decade ago, but never taken to a flight instrument. In selecting the most appropriate CCD (function, availability etc.) we identified the e2v CCD77 whose readout register can act as a linear CCD. Therefore in this experiment combination, the RADFET would enable monitoring of total ionising dose, whilst the linear CCD would provide a record of proton fluence. The inclusion of the CCD77 together with the CIS107 would enable a direct comparison of defect generation in space in CCD and CMOS imaging technologies.

2.3 Dust and particle monitor (DPM)

Several options exist for the monitoring of space dust and debris and an initial assessment was performed based on the plastic film, PVDF. However, this technology required the instrument to be permanently biased which placed a significant load on the CubeSat resources. We therefore subsequently investigated a dust monitor which could passively react to impacts, but could be read out periodically to give a record of impacts with a degree of temporal resolution (~10 minutes). Other studies have been conducted into systems which monitor pinholes in aluminised films but given the other technologies being considered for this CubeSat, we decided to explore the use of an aluminised film above an imaging sensor.

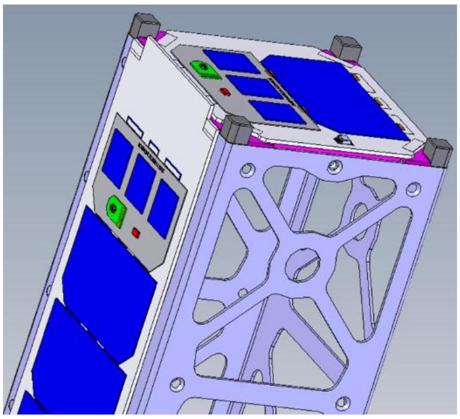

Fig. 3. The dust and particle monitor mounted on the CubeSat chassis

In this instance, we base lined the CIS107 which will be part of the radiation monitor package, and which could share resources with that experiment. We performed orbit modelling and placement of this sensor on the outside of the spacecraft would also deliver a high radiation dose of several hundred krad, which would provide a secondary benefit by demonstrating use of this technology in high radiation environments. We obtained agreement from e2v to have access to these sensors in die form, and therefore designed a dust sensor hybrid package which would have the same footprint as a solar cell, which could replace one of the spacecraft solar cells. To distinguish between dust/debris and micrometeorite populations, one dust sensor would be placed on the forward facing panel, and another on the top of the spacecraft. The sensors would be periodically turned-on in the daylight side and an image of the aluminised sensor taken. The increase in pinhole count would enable monitoring of the dust particles, whilst use of multiple sensors gives redundancy against any possible impact leading to catastrophic failure (a very low probability).

2.4 Multi-point distributed imaging

Based on heritage of the C3D imager on UKube-1 the multi-point distributed imaging package enables the capture of in-situ images of spacecraft components and sub-systems (e.g. deployables). We considered using up to 5 cameras deployed around the spacecraft up to 50cm away from the control electronics allowing cabling for deployment on full 3U CubeSat structures. Each camera (hosting an e2v EV76C560 CMOS imaging sensor) can capture variable resolution full-colour images up to 1280x1024 pixels in size and the on-board FPGA is capable of performing image processing and compression tasks. By placing the remote sensors facing out from the spacecraft structure, this payload could also be used as a star-tracker or limb sensor with the on-board FPGA calculating the attitude of the spacecraft for input to the attitude control computer.

3. C3D Payload Control Demonstration

The C3D payload controller provides the majority of the interface, control and data handling functions to the C3D instrument. The payload controller is designed around an Altera EP3C40 Cyclone III FPGA which implements a soft-core Nios II processor and supports 3 different types of storage; a flash based configuration device for storing the FPGA firmware configuration, a separate flash memory storage for storing the mission software and 16 MB of SDRAM which is the working memory for the instrument.

Part of this study involved demonstrating the potential of the C3D payload controller to be used as a multi-payload controller for future CubeSat missions. Of the 4 instruments conceptually introduced in section 2, two were at a development stage that allowed this demonstration in practice.

3.1 C3D payload controller with the Ptolemy mass spectrometer

For this study we have sucessfully been able to demonstrate the Ptolomy mass spectrometer being controlled by our FPGA electronics board emulating the C3D payload controller. The laboratory set-up is shown in Fig 4(a). The mass spectrometer sits within the vacuum chamber and it’s output shown on the display. Figure 4(b) shows the applied field (yellow) and spectrum (pink trace) of the system recorded on an oscilloscope with no gas present, corresponding to a partial pressure of 1×10^{-7} mbar. Figure 4(c) shows the spectra of a PFTBA reference gas at a partial pressure of 1×10^{-6} mbar. Characteristic mass peaks m/z 69, 101, 114, 119, 131 are seen. The FPGA electronics replace the lab MS electronics previously used to run the system. A development FPGA system (running the C3D payload controller firmware and custom software) was used instead of the C3D payload controller due to the lack of approporaite output connections on the latter, however this working system shows proof of concept that the C3D payload controller is able to run the Ptolomy mass spectrometer system (with plenty of overhead to manage additional payloads as well).

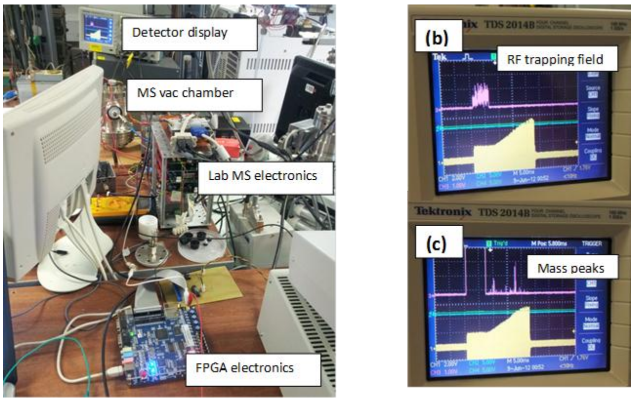

Fig. 4. Demonstration of the C3D payload controller running the Ptolemy mass spectrometer

3.2 C3D payload controller and the multi-point distributed imaging package

The C3D payload controller is designed to fit host three image sensors mounted on flexi connectors, with the nominal flexi length ~3cm. For this study we have successfully retrieved images from sensors mounted up to 30cm from the payload controller (Fig. 5).

Fig. 5. Demonstration of the C3D payload controller with an e2v EV76C560 CMOS imaging sensor on a 30cm flexi

Some image degradation was noticeable in the returned image at this flexi distance, however it should be possible to clean up this data return using a combination of impedance matching on the data lines of the flexi itself and/or slowing down the pixel rate through the flexi using the payload controller.

Whilst this demonstration work has yet to be finished, it appears feasible that the C3D payload controller would be able to support a multi-point distributed imaging package utilizing sensors on 30cm flexis. This cabling distance would allow the position of sensors almost anywhere within the 3U CubeSat structure assuming the centralized placement of the payload controller.

4. LEO Technology Demonstration Mission

The instruments introduced in Section 2, along with the C3D payload controller, form the basis of the spacecraft health and environmental monitoring package. When packaged together they form an integrated payload requiring a volume between 0.5-1U, a peak power-draw of ~2W and overall mass of ~660 g (inc. 20% margin). Whilst the ultimate aim for such a package would be integration into any spacecraft platform requiring the level of additional information the package could provide, a CubeSat mission was designed as part of the study that would act as a technology demonstration of the package and its performance capabilities.

4.1 Baseline Mission

The mission base-lined to demonstrate the spacecraft health and environmental monitoring package is a generalised version of the UKube-1 mission and summarized in Table 1.

Table 1. Baseline Mission Summary

Launcher	Any LEO/GTO launcher with PPOD compatibility
Lifetime	12 – 36 months
Orbit	300-1000km sun-synchronous orbit, >56° inclination, eclipse fraction 38%
Power	Deployable solar array generating 14-20 W, 2W min, 4.8W mean power draw, 20Whr battery
Communications	Data: 1Mbps S-band downlink, 7MB per orbit, TTC: 85bps UV transceiver, 60kB per orbit
Pointing	3-axis ±10° from orbit direction required, 1° achievable from sun sensors, horizon sensors, yaw RW, pitch MW and embedded magnetorquers

A schematic of the base-lined spacecraft is shown in Fig. 6. All the components required for the mission can comfortably fit within a standard 3U CubeSat chassis and there exists space, power and mass to support additional payloads.

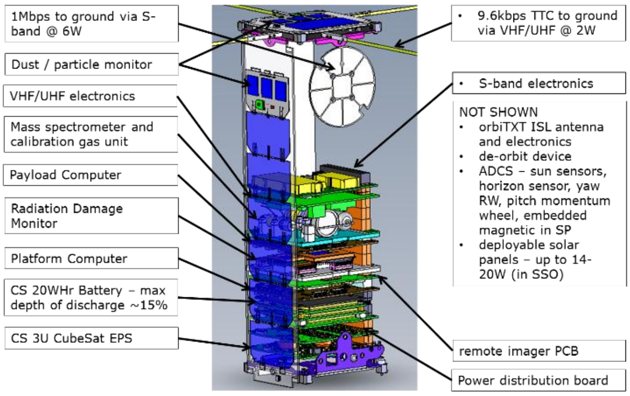

Fig. 6. Schematic of the baseline spacecraft health and environmental monitoring spacecraft

The mission itself can be very flexible since the primary payload (the spacecraft health and environmental monitoring package) does not necessitate any special orbital, power or communications requirements. The only mission requirement lies in attitude control where it is desirable for the dust and particle monitor (DPM) to point in the correct direction. The DPM positioned on the top face of the CubeSat stack needs to point in the direction the orbit and the DMP positioned on the side face of the spacecraft needs to point in the anti-nadir direction.

4.2 Additional Payloads

Free volume within the base-lined spacecraft allow for the inclusion of secondary payloads in addition to the spacecraft health and environmental monitoring package.

One option for an additional payload is orbitTX, an Inmarsat I-3/4 data relay for low data rate alerting or commanding. This S-Band inter-satellite link uses the Inmarsat communication network to provide near-100% orbit coverage in communications and is currently in the prototype stage at Clyde Space Ltd in the UK.

Another option for an additional payload would be for a de-orbit device. This payload would allow the mission to adapt to any launch opportunity by helping to ensure that the de-orbit requirements of 25 yrs could be easily met. There are plenty of concept CubeSat de-orbiting devices however the device base-lined for this mission involves the use of a highly reflective balloon11).

5. Conclusion

The uncertainties in the outgassing/offgassing, dust/debris, and radiation environments within and surrounding spacecraft regularly lead to operational problems with technical, scientific and ultimately economically deleterious consequences.

In this paper we presented the outputs of a study into a small modular spacecraft health and environmental monitoring package deployed in a standard 3U CubeSat platform. This package would provide real time measurements of a spacecraft's immediate environment to inform operators and on-board systems of threats to spacecraft or payload "health" via a comprehensive and correlated dataset of many related environmental parameters.

Results from preliminary investigations pairing the UKube-1 C3D payload controller to prototype modules of the spacecraft health and environmental monitoring package were also presented. This confirmed the suitability of the C3D payload controller as a generic multi-payload controller for future CubeSat applications.

Finally we demonstrated a mission concept with this platform deployed in LEO orbit.

Acknowledgments

The authors wish to acknowledge additional contributions to this study by Dr. Jason Gow and Matt Soman of the Open University and Steve Greenland of Clyde Space Ltd.

References

1. Seabroke, G., Holland, A., Burt, D. and Robbins, M. (2010). *Silvaco ATLAS model of ESA's Gaia satellite e2v CCD91-72 pixels*. Proceedings - SPIE the International Society for Optical Engineering, 7742(774214).
2. Gow, J. P. D., Murray, N., Holland, A., Hall, D. J., Cropper, M., Hopkinson, G. and Duvet, L. (2012). *Assessment of space proton radiation-induced charge transfer inefficiency in the CCD204 for the Euclid space observatory*. Journal of Instrumentation, 7(C01030).
3. Massey, R. (2010). *Charge transfer inefficiency in the Hubble Space Telescope since Servicing Mission 4 R. Massey Charge transfer inefficiency in HST since SM4*. Monthly Notices Of The Royal Astronomical Society: Letters, 409(1), L109-L113. doi:10.1111/j.1745-3933.2010.00959.x
4. O Dell, S. L., Swartz, D. A., Plucinsky, P. P., Freeman, M. A., Markevitch, M. L., Vikhlinin, A. A., & ... Morris, P. A. (2005). *Modeling contamination migration on the Chandra X-ray Observatory* [5898-40]. Proceedings - SPIE The International Society For Optical Engineering, 5898589813.
5. Moussi, A. A., Drolshagen, G. G., McDonnell, J. M., Mandeville, J. C., Kearsley, A. T., & Ludwig, H. H. (2005). *Hypervelocity impacts on HST solar arrays and the debris and meteoroids population*. Advances In Space Research, 35(7), 1243-1253. doi:10.1016/j.asr.2005.03.060
6. Kirsch, M. F., Abbey, A. A., Altieri, B. B., Baskill, D. D., Dennerl, K. K., van Dooren, J. J., & ... Haberl, F. F. (2005). *Health and cleanliness of the XMM-Newton science payload since launch* [5898-29]. Proceedings - SPIE The International Society For Optical Engineering, 589858980S.
7. Harriss, R. D.; Holland, A. D.; Barber, S. J.; Karout, S.; Burgon, R.; Dryer, B. J.; Murray, N. J.; Hall, D. J.; Smith, P. H.; Greig, T.; Tutt, J. H.; Endicott, J.; Jerram, P.; Morris, D.; Robbins, M.; Prevost, V. and Holland, K. (2011). *Compact CMOS camera demonstrator (C3D) for Ukube-1*. In: UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts V, 8 September 2011, San Diego.
8. UKSA, http://www.ukspaceagency.bis.gov.uk/19128.aspx (2011) - last accessed 14/08/2012.
9. Morse, A., Morgan, G., Andrews, D., Barber, S., Leese, M., Sheridan, S., Wright, I. and Pillinger, C. (2009). *Ptolemy - a GCMS to measure the chemical and stable isotopic composition of a comet*. In: Schulz, Rita and Boehnhardt, Hermann eds. Rosetta ESA's Mission to the Origin of the Solar System. Berlin/Heidleberg: Springer, pp. 669–718.
10. Andrews, D., Morse, A., Barber, S., Leese, M., Morgan, G., Sheridan, S., Pillinger, C. and Wright, I. (2012). *Ptolemy: operations at 21 Lutetia as part of the Rosetta mission and future implications*. In: 43rd Lunar and Planetary Science Conference, 19-23 March 2012, The Woodlands, TX, US.
11. Lücking, C., Colombo, C. and McInnes C.R. (2011) *A Passive De-orbiting Strategy for High Altitude CubeSat Missions using a Deployable Reflective Balloon*. In: 8th IAA Symposium on Small Satellites for Earth Observation Berlin, Germany, April 4 – 8, 2011.