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Simulation and analysis of the LUCID experiment in the Low Earth Orbit radiation environment

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Abstract. The Langton Ultimate Cosmic ray Intensity Detector (LUCID) experiment is a satellite-based device that will use five Timepix hybrid silicon pixel detectors to make measurements of the radiation environment at an altitude of approximately 635 km, i.e. in Low Earth Orbit (LEO). The experiment is due to launch aboard Surrey Satellite Technology Limited's (SSTL's) TechDemoSat-1 in 2014. The Timepix detectors, developed by the Medipix Collaboration, are arranged to form the five sides of a cube enclosed by a 0.7 mm thick aluminium "dome", and will be operated in Time-over-Threshold mode to allow the flux, energy and directionality of incident ionising radiation to be measured. To estimate the anticipated data rates with respect to these measurements, the LUCID experiment has been modelled using the GEANT4 software framework. As an input to these simulations, SPENVIS, ESA's Space Environment information system, was used to obtain the estimated flux of trapped protons and electrons in TechDemoSat-1's orbit with NASA's AP-8 and AE-8 models. A web portal, LUCIDITY, was developeded to allow school students from the LUCID Collaboration to manage SPENVIS flux spectra and GEANT4 input cards. The initial results reported here confirm that the LUCID's data transmission allowance is sufficient, and further work applying the techniques to more specific space radiation environments with a more sophisticated simulation is proposed.

1. Introduction

1.1. A brief history of LUCID

The Langton Ultimate Cosmic ray Intensity Detector (LUCID) is a student-designed experiment that will use technology developed by the Medipix Collaboration[1] to make measurements of the radiation environment in Low Earth Orbit (LEO). Upon returning from a school trip to CERN in 2007, a group of student scientists from the Simon Langton Grammar School for Boys in Canterbury, Kent, were inspired enter a satellite experiment design competition using the detector technology they had worked with while visiting the Medipix Collaboration laboratories at CERN. The competition, run by Surrey Satellite Technology Limited (SSTL) and the British National Space Centre[2], required entrants to design a scientific experiment to be installed and launched aboard the technology demonstration platform TechDemoSat-1. Six Langton students entered with a design that featured a number of Medipix-based detectors to make measurements of ionising radiation in space.

[1] See http://medipix.web.cern.ch for more information.
[2] The British National Space Centre has since become the UK Space Agency.

The cost of the final design exceeded the budget imposed by the competition, but further funding was secured and the Langton Ultimate Cosmic ray Intensity Detector (LUCID) was subsequently constructed by SSTL engineers. It has since been commissioned for space operations and is ready for launch in early 2014. Data from LUCID will be shared with school students and teachers from the UK and beyond through the CERN@school programme, which has been supported by a Science in Society Large Award from the UK Science and Technology Facilities Council (STFC).

1.2. The Timepix detector
The LUCID experiment is built around five Timepix hybrid silicon pixel detectors [1]. Developed by the Medipix Collaboration, these feature a 300 μm thick silicon sensor bump-bonded to a Timepix readout chip. 256×256 pixels of pitch 55 μm provide $65,536$ readout channels from the 1.98 cm^2 sensor element. In Time-over-Threshold (ToT) mode, the length of time that a pixels readout current registers a charge over a preset threshold can be measured. This time (the number of ADC counts, x, multiplied by the Timepix clock period, usually 0.1 μs), is related to the energy, E, incident on the sensor by:

$$E = ax + b - \frac{c}{t - x} \tag{1}$$

where a, b, c, and t are the calibration constants that must be determined for each pixel. A robust calibration methodology that can be used to extract energy measurements from the Timepix detector has been demonstrated in [2], and calibration data for LUCID has been obtained with the help of the IEAP at the Czech Technical University, Prague. The ToT count values can also be used to visualise the ionising radiation measured by the detector. Values that represent a charge above a preset threshold can mapped to colour values to form pixel images. Different types of radiation leave different patterns in the silicon, and so by analysing these patterns particles can be identified (to an extent).

1.3. The LUCID experiment and TechDemoSat-1
As the original LUCID student team realised, the capabilities of the Timepix detector outlined above are well suited to measuring interesting properties of the space radiation environment. Indeed, NASA has already deployed five Timepix detectors on the International Space Station (ISS) for dosimetry purposes [3]. LUCID, however, will be the first experiment to use the technology in open space. By doing so, it is hoped that new insights into particle directionality, identity, energy, and fluence in Low Earth Orbit can be gleaned. Phenomena such as the South Atlantic Anomaly (SAA), the outer electron belts at the poles, extra-galactic cosmic rays and the Forbrush Decrease may also be investigated.

The investigation of these environments is afforded by the orbit characteristics of LUCID's host satellite, TechDemoSat-1. Billed as an "in-orbit test facility", it has been built by SSTL with support from the UK Technology Strategy Board to take a number of scientific payloads into LEO. At the time of writing, the satellite is due to launch from Baikonur Cosmodrome aboard a Soyuz 2b launch vehicle. It will follow an orbit described by the parameters listed in table 1, and in doing so it will encounter many sources of ionising radiation. It is the goal of this work to establish the estimated data rates expected due to the dominant sources of charged particles – namely trapped protons and electrons – and establish a procedure for investigating other radiation environments.

2. Modelling LUCID and the LEO radiation environment
Simulations of LUCID and the LEO radiation environment were carried out using GEANT4 [4; 5]. A GEANT4 application, `SimLUCID`, was developed to model the transport of source particles

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Parameter	Value
Altitude	635 km
Type	Sun-synchronous
Inclination	98.4°
LTDN	0900
LTDN drift	~ 7 min. / month

Table 1. TechDemoSat-1's orbit parameters (as of October 2013). LTDN is the "LatiTude of the Descending Node".

through the key components of the LUCID experiment and estimate the rate of data collected by its Timepix detectors for a given type of source particle. The default GEANT4 physics settings were used.

2.1. Detector geometry and construction

While SSTL's CAD file representation of LUCID was available, a simplified geometry capturing the key components of the LUCID experiment was used in the `SimLUCID` application. This is shown in figure 1; a detailed description is provided in the accompanying caption. The whole geometry has been placed within a 50 mm hemisphere that serves two purposes: by creating source particles on the hemisphere's surface, the resultant flux calculations are simplified (see section 3.2); and the hemisphere itself is defined as a sensitive "pseudo detector" that can provide a cross-check on the properties of the source particles.

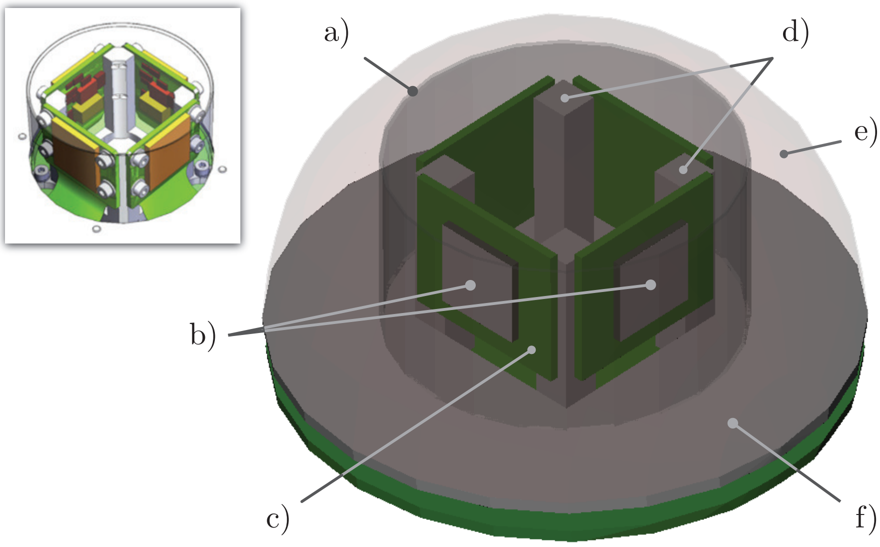

Figure 1. The LUCID experiment as modelled in the `SimLUCID GEANT4` application. As described in the text, a simplified geometry has been used that incorporates the major components of the apparatus, namely: a) the aluminium protective "dome" (a closed cylinder with wall thickness 0.7 mm); b) the Timepix detectors (two shown, with five in total including one mounted horizontally in the base); c) the PCB mounts for the Timepix detectors; d) support posts; e) the 50 mm hemisphere where source particles are created, and; f) LUCID's main aluminium covering plate. *Inset*: the Timepix detector arrangement in SSTL's original CAD model for comparison.

The quantity of interest for each run is the number of hit pixels per source particle, n_h, observed in each detector. To obtain an estimate of this, the Timepix detectors as modelled in the simulation were set to be "sensitive detectors". Hits registered in the silicon sensor regions above the Timepix detection threshold (4 keV) were segmented by pixel, and the number of pixels hit in each detector was recorded as an output of the simulation. The average number of hits pixels per source particle, $\bar{n}_h$, could then be calculated for a given source particle type by averaging over total number of runs.

2.2. The radiation environment

Information about the dominant source of charged particles in TechDemoSat-1's orbit – trapped protons and electrons – was obtained using SPENVIS, the European Space Agency's (ESA's) Space Environment Information System [6]. TechDemoSat-1's orbital parameters (table 1) were used in combination with the AP-8 [7] and AE-8 [8] models to produce estimates of the average flux of protons $\mathrm{d}\Phi_p/\mathrm{d}E$ and electrons $\mathrm{d}\Phi_e/\mathrm{d}E$ (respectively) at maximum solar activity, binned by energy. The differential flux spectra calculated for TechDemoSat-1's initial orbit are shown in figure 2.

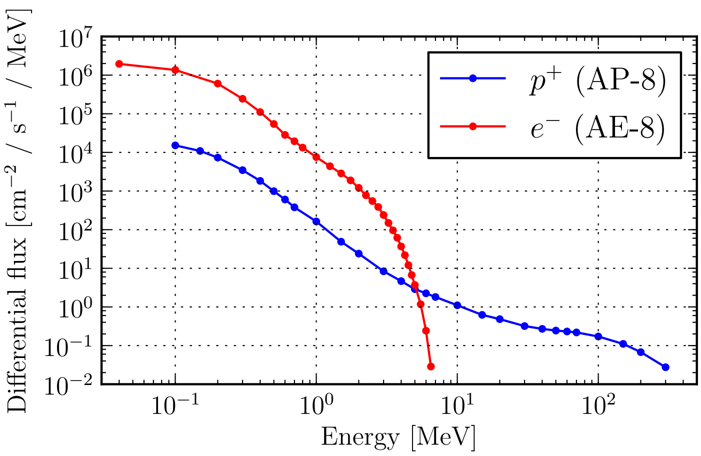

Figure 2. Differential flux spectra for trapped protons and electrons in TechDemoSat's initial orbit (see table 1), as estimated by SPENVIS [6] using the AP-8 [7] and AE-8 [8] models.

2.3. Simulation management

The source particles for each simulation run were defined using the GEANT4 General Particle Source (GPS) system. Particles were created on the surface of the 50 mm hemisphere surrounding LUCID's detectors and assigned a direction based on a cosine distribution, as appropriate for a (hemi)sphere in an isotropic source environment (as is the assumed scenario in this work). The particle energy was sampled from a uniform distribution corresponding to the SPENVIS flux spectrum energy bin in question.

In order to manage the GEANT4 input macros associated with each type of radiation environment and energy bin, a web portal was developed for use by students working on the project. LUCIDITY, The LUCID Interactive Test sYstem, is a web application powered by Ruby on Rails with a MySQL backend that takes advantage of the Hobo collection of Ruby gems and plug-in modules for the rapid development of web appplications. Hosted on an Amazon Web Services (AWS) virtual server running Ubuntu 12.04 and deployed using Phusion Passenger/Apache and the AWS Simple Storage Service (S3), LUCIDITY allows users to import SPENVIS spectra files, process them, download the resultant GEANT4 simulation macros, and manage the simulation results.

3. Results and discussion

3.1. Trapped radiation: protons and electrons

Simulations corresponding to the proton and electron flux spectra of figure 2 were performed using `SimLUCID`, with 10,000 events run for each energy bin. The resultant $\bar{n}_h$ values are plotted in the top half of figure 3 for protons (left) and electrons (right) observed in all five Timepix detectors. As one might expect, low energy particles are shielded by the aluminium dome structure with a peak in the number of hit pixels per source particle $\bar{n}_h$ occuring at 100 MeV (1 MeV) for protons (electrons). Beyond these peaks, a gradual fall-off is observed as fewer high energy particle interact with the silicon.

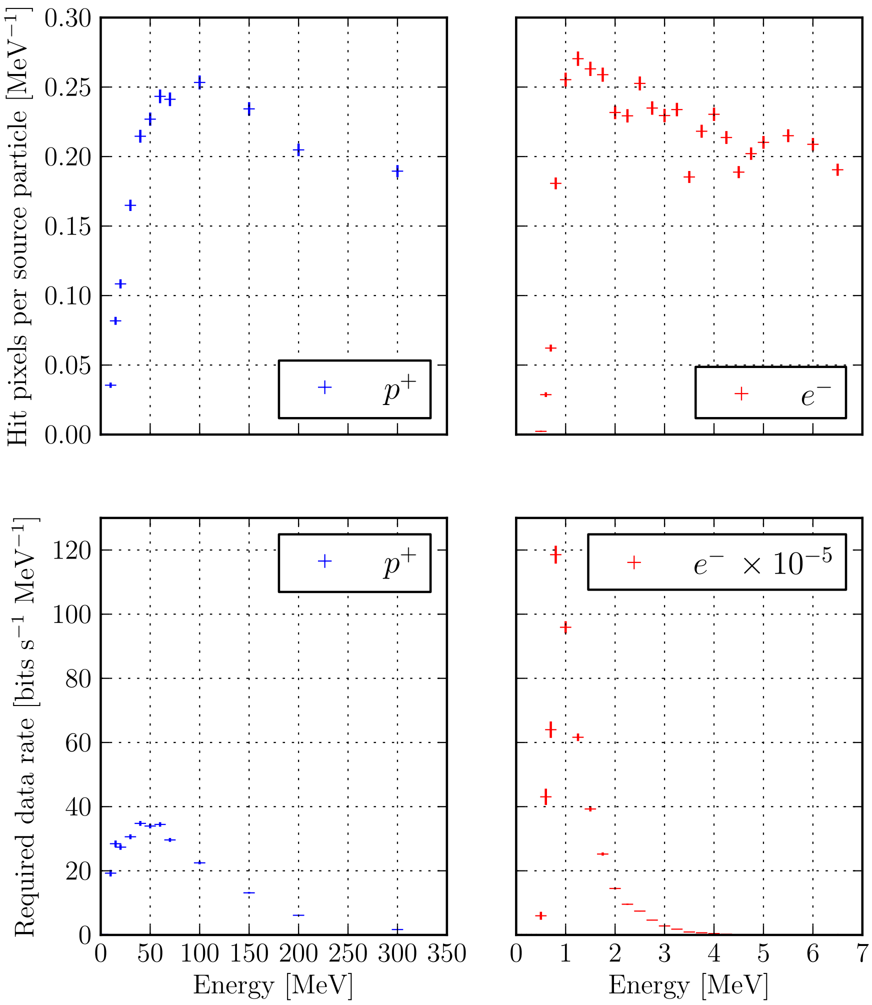

Figure 3. *Top*: Hit pixels per source particle $\bar{n}_h$ for trapped protons (*left*) and electrons (*right*) in TechDemoSat-1's orbit. *Bottom*: required data rate due to trapped protons (*left*) and electrons (*right*) in TechDemoSat-1's orbit. Note that the electron data rate plot has been scaled down by a factor of 10^5 to enable a qualitative comparison with the corresponding proton values. The error bars plotted are statistical; the factor 2 error quoted for the AP-8 and AE-8 models is not represented in the plots shown here.

3.2. Implications for required data rates

The estimated differential bit rate due to a particle source i, $\frac{\mathrm{d}R_i}{\mathrm{d}E}$, may be calculated using

$$\frac{\mathrm{d}R_i}{\mathrm{d}E} = \frac{1}{2}\,\pi\, r^2 \;\cdot \bar{n}_h \;\cdot B \;\cdot \frac{\mathrm{d}\Phi_i}{\mathrm{d}E}, \tag{2}$$

where E is the energy of the particle, r is the radius of the hemisphere surrounding the detector[3], $\bar{n}_h$ is the number of hit pixels per source particle, and B is the bits per pixel, which for the Timepix detector is 16[4]. The resultant values for the trapped protons (electrons) are plotted in the bottom left (right) of figure 3. Note that in these plots the electron data rates have been scaled down by a factor of 10^5 to allow a qualitative comparison with the proton rates. While the $\bar{n}_h$ values are similar for protons and electrons, the estimated electron flux is several orders magnitude larger than that of the trapped protons. Summing over all energy bins, the required data storage/transmission rates are

$$\begin{array}{lcccccl} R_p & = & (& 5.30 & \pm & 0.04 &) \quad \mathrm{kbs}^{-1} \\ R_e & = & (& 1.01 & \pm & 0.01 &) \quad \mathrm{Mbs}^{-1} \end{array}$$

for trapped protons and electrons (respectively). A completely filled frame corresponds to $65,536 \times 16 \sim 1\,\mathrm{Mb}$, so the combined bit rate of $\sim 1\,\mathrm{Mbs}^{-1}$ from all five detectors suggests that a fifth of all pixels will be hit per second. LUCID will operate with a shutter speed (frame rate) of 4 Hz, and so the typical frame occupancy (hit pixels per frame) will be about 5 %. Given that LUCID is capable of tramsmitting data at a rate of $20\,\mathrm{Mbs}^{-1}$, with 2 GB of onboard storage, even with the factor of 2 errors suggested by the AP-8 and AE-8 flux models it would appear that LUCID will be able to cope with the trapped proton and electrons in TechDemoSat-1's orbit.

3.3. Future work

Having established that LUCID can handle the data rates produced by trapped protons and electrons in LEO, the following areas of investigation suggest themselves:

- Examining the expected data rates in specific regions of interest in TechDemoSat-1's orbit, such as the polar regions (where outer belt electrons come into effect) and the South Atlantic Anomaly;
- Enhancing the `SimLUCID` application to incorporate digitisation of the particle hits in the sensitive detectors, and model more of the LUCID experiment and TechDemoSat-1.

Such simulations are likely to be more computationally intensive than those performed with the version of `SimLUCID` used here. It is therefore anticipated that the UK Grid for Particle Physics, GridPP, could be used by student members of the LUCID Collaboration to perform these studies before LUCID launches in 2014.

4. Summary and conclusions

It has been established that the LUCID experiment will ba able to cope with the demands imposed on its data transmission capabilities by the trapped protons and electrons in TechDemoSat-1's orbit. In order to do this, LUCID and its five Timepix detectors were modelled using `SimLUCID`, a purpose-built GEANT4 application. SPENVIS was used to obtain input flux

[3] The factor $1/2\,\pi\, r^2$ models a hemisphere moving through an isotropic particle source where incident particles have a cosine distribution - see section 2.1.
[4] 14 bits are used to represent the ToT value, with 2 bits for overhead.

values for the trapped proton and electrons expected in TechDemoSat-1's orbit, and a web portal, LUCIDITY, was created to manage the simulation input parameters and results for members of the LUCID Collaboration. Having created this simulation framework, further work has been suggested that will refine the understanding of what LUCID could see when it launches and begins operations in 2014.

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