This study presents a background estimation for the Cubesats Applied for MEasuring and LOcalising Transients (CAMELOT), which is a proposed fleet of nanosatellites for the all-sky monitoring and timing based localization of gamma-ray transients with precise localization capability at low Earth orbits. CAMELOT will allow to observe and precisely localize short gamma-ray bursts (GRBs) associated with kilonovae, long GRBs associated with core-collapse massive stars, magnetar outbursts, terrestrial gamma-ray flashes, and gamma-ray counterparts to gravitational wave sources. The fleet of at least nine 3U CubeSats is proposed to be equipped with large and thin CsI(Tl) scintillators read out by multi-pixel photon counters (MPPC). A careful study of the radiation environment in space is necessary to optimize the detector casing, estimate the duty cycle due to the crossing of the South Atlantic Anomaly and polar regions, and to minimize the effect of the radiation damage of MPPCs.

**KEYWORDS:**
instrumentation: detectors, gamma rays: bursts, X-rays: diffuse background, (ISM:) cosmic rays
1 | INTRODUCTION

Cubesats Applied for MEasuring and LOcalising Transients (CAMELOT), for details see Ohno et al. (2018); Pál et al. (2018); Torigoe et al. (2019); Řípa et al. (2018); Werner et al. (2018), is a future constellation of at least nine 3U CubeSats, which will be primarily monitoring and precisely and rapidly localizing gamma-ray bursts (GRBs), see Klebesadel, Strong, & Olson (1973); Kouveliotou, Wijers, & Woosley (2012); Vedrenne & Atteia (2009), over the whole sky. It will allow a regular detection of electromagnetic counterparts of gravitation wave sources similar to the breakthrough discovery of the neutron star merger GW170817 (Abbott et al., 2017) associated with a short GRB 170817A (Goldstein et al., 2017). This gamma-ray monitoring network will also allow to observe long GRBs associated with core-collapse massive stars, soft gamma repeaters (SGR) associated with magnetar outbursts (Kouveliotou et al., 1998; Mazets, Golentskii, Ilinskii, Aptekar, & Gurvan, 1979), and terrestrial gamma-ray flashes (TGF) produced by thunderstorms (Fishman et al., 1994).

The CAMELOT satellites (see Figure 1) will be equipped with two or four large and thin CsI(Tl) scintillators, 75 × 150 × 5 mm³ each, read out by Multi-Pixel Photon Counter (MPPC) silicon photomultipliers from Hamamatsu. The scintillators will be enclosed in Al or carbon fiber reinforced plastic (CFRP) support structure and will be placed on one or two of the long sides of the satellite with sensitivity in the range of ∼ 10⁻¹⁰⁻¹⁰⁰ keV.

The intended orbit configurations of the CAMELOT CubeSats are Low Earth Orbits (LEO) at altitude ∼ 500 – 600 km either with inclination of 53° or polar orbits with inclination around 97.6°. However, final decision will depend on the launch opportunities.

Here we briefly summarize our studies of the impact of the radiation environment in LEO on the CAMELOT satellites carried out to optimize the scintillator casing, estimate the duty cycle due to crossing of the South Atlantic Anomaly (SAA) and polar regions and to design radiation shielding to minimize the effect of the degradation of MPPCs due to the proton fluxes.

2 | BACKGROUND COMPONENTS

The aim of this work is to estimate the total background count rate due to the space environment in the part of the orbit ideal for gamma-ray transient observations, i.e. outside SAA and polar regions which contain high fluxes of geomagnetically trapped particles. Spectra of various background components are used as an input in the full Monte Carlo (MC) simulation applied in Geant4 (Agostinelli et al., 2003; Allison et al., 2016) together with the satellite’s mass model.

2.1 | Trapped particles

For the fluxes of the trapped e⁻ and p⁺ the AE9 and AP9 models (Ginet et al., 2013) implemented in ESA’s SPace EVironment Information System (SPENVIS) were used, respectively. AE9/AP9 are based on 33 satellite datasets from 1976 to 2011 developed by U.S. Air Force Research. The parameters of these models were set to MC mode with 100 runs and mean aggregate.

Averaged fluxes of e⁻ and p⁺ over three circular orbits (avoiding crossing SAA) at an altitude of 500 km outside SAA and polar regions with inclination i = 20° were simulated in SPENVIS. Figure 2 and Figure 3 show maps of trapped e⁻ and p⁺, respectively. The flux of trapped p⁺ outside SAA is negligible. The orbit averaged differential spectrum of trapped e⁻ is shown in Figure 4. The integral flux (E > 40 keV) is 2.0 cm⁻²s⁻¹.

2.2 | Cosmic X-ray background

The isotropic cosmic X-ray background (CXB), see Boldt (1981); Campana et al. (2013); Fabian (1985); Giacconi, Gursky, Paolini, & Rossi (1962); Mizuno et al. (2004), can originate from the summation of the emission of extragalactic sources (active galactic nuclei, quasi-stellar objects, supernovae Ia, galaxy clusters,
FIGURE 2 A map of the integral flux of geomagnetically trapped electrons at 500 km altitude according to the AE9 model (MC model, 50 % CL).

FIGURE 3 A map of the integral flux of geomagnetically trapped protons at 500 km altitude according to the AP9 model (MC model, 50 % CL).

2.3 Galactic cosmic rays

The spectra of primary particles of the galactic cosmic rays (GCR) used in the Geant4 simulations are described below and shown in Figure 4. For 500 km altitude the fluxes irradiate the satellite from the solid angle of 8.64 sr.

2.3.1 Primary H and He

For the spectra of the primary H and He we used the model ISO-15390[4], implemented in SPENVIS. ISO-15390 is the International Standard for estimating the radiation impact of galactic cosmic rays on hardware in space.

The averaged spectra were obtained for the same three orbits as described in Section 2.1 with following parameters: solar minimum activity (May 1996), magnetic shielding on, stormy magnetosphere, Stormer with eccentric dipole method and magnetic field moment unchanged.

The integral flux for H is $0.12 \text{ cm}^{-2} \text{s}^{-1} (E > 1 \text{ GeV})$ and for He it is $0.021 \text{ cm}^{-2} \text{s}^{-1} (E > 1 \text{ GeV/n})$.

2.3.2 Primary electrons and positrons

For the spectra of the primary $\text{e}^-$ and $\text{e}^+$ we used the model described by Mizuno et al. (2004) (see also references therein) for solar minimum (solar modulation potential $\Phi = 0.55 \text{ GV}$), 500 km altitude and for geomagnetic latitude $\theta_M = 20^\circ$.

The integral flux ($E > 1 \text{ GeV}$) for $\text{e}^-$ is $3 \times 10^{-3} \text{ cm}^{-2} \text{s}^{-1}$ and for $\text{e}^+$ it is $2.3 \times 10^{-4} \text{ cm}^{-2} \text{s}^{-1}$.

2.4 Secondary particles and radiation

Secondary (albedo) particles and radiation originates from the interaction of GCR with the Earth’s atmosphere (Jursa, 1985).

The fluxes used in the Geant4 simulations are described below and shown in Figure 4.

[4] www.iso.org/standard/37095.html
2.4.1 Secondary protons
For the secondary $p^+$ and for energy above 100 MeV we use the modeling by (Mizuno et al., 2004) based on the Alpha Magnetic Spectrometer (AMS) data (Alcaraz et al., 2000) from 380 km altitude for the geomagnetic latitude $17^\circ < \theta_M < 23^\circ$. For energy below 100 MeV we use the fit to MITA/NINA-2 data from 450 km altitude (Bidoli et al., 2002) for $1.0 \leq L$-shell $\leq 1.7$. For details see the LAT Technical Note LAT-TD-08316-03 of the Fermi satellite (Atwood et al., 2009).

There is only a small dependence of the flux on altitude (Bidoli et al., 2002; Zuccon et al., 2003) therefore it can be used as an approximation to the flux at 500 km. The same flux model is used for upward and downward component therefore the flux irradiates the satellite from the solid angle of $4\pi$ sr.

The integral flux ($\epsilon > 10$ MeV) is $0.037 \text{cm}^{-2}\text{s}^{-1}$.

2.4.2 Secondary electrons and positrons
For the secondary $e^-$ and $e^+$ and for energy above 100 MeV we use the modeling by (Mizuno et al., 2004) based on the AMS data (Alcaraz et al., 2000b) from 380 km altitude for the geomagnetic latitude $0^\circ < \theta_M < 17^\circ$. For energy below 100 MeV we use the fit to the Mir/MARIA-2 data from 400 km altitude (Voronov et al., 1991) for $1.0 \leq L$-shell $\leq 1.2$. For details see the LAT Technical Note LAT-TD-08316-01.

The same flux model is used for upward and downward component therefore the flux irradiates the satellite from the solid angle of $4\pi$ sr. The integral flux ($\epsilon > 20$ MeV) is $0.18 \text{cm}^{-2}\text{s}^{-1}$ for $e^-$ and $0.23 \text{cm}^{-2}\text{s}^{-1}$ for $e^+$.

2.4.3 Albedo X-rays
The spectrum of the albedo X-rays is taken from the Swift/BAT measurements for altitude of $\sim 550$ km and inclination $i = 20.6^\circ$ (Ajello et al., 2008). Concerning the altitude 500 km the flux would irradiate the satellite from the solid angle of 3.93 sr. The integral flux ($\epsilon > 10$ keV) is $2.0 \text{cm}^{-2}\text{s}^{-1}$.

2.4.4 Albedo neutrons
For the albedo neutrons we use the predictions of the QinetiQ Atmospheric Radiation Model (QARM), based on MC radiation transport code, as reported in the ESA document ECSS-E-ST-10-04C. The fluxes are scaled from 100 km to 500 km as described in the document and are for the cutoff rigidity of 5 GV. The integral flux ($\epsilon > 1$ eV) is $0.61 \text{cm}^{-2}\text{s}^{-1}$.

3 SHORT GRB SPECTRUM
The main goal of the CAMELOT mission is to detect and localize short GRBs, which are associated with mergers of neutron stars, and therefore strong sources of gravitational waves. Hence, the highest priority is to estimate the signal-to-noise ratio (SNR) expected from a typical short GRB.

The spectrum of a typical short GRB ($T_{90} < 2$ s) was constructed by taking the typical values of the spectral parameters: peak energy $E_{\text{peak}}$, low energy spectral slope $\alpha$ and high energy spectral slope $\beta$ of the Band function (Band et al., 1993) of short GRBs detected by Fermi/GBM from the distributions published by Nava, Ghirlanda, Ghisellini, & Celotti (2011). Then we tuned the normalization $A$ of the spectrum
to obtain the values of the integral flux in the range 10-1000 keV equal to the median peak fluxes \( F \) (ph cm\(^{-2}\)s\(^{-1}\)) of short GRBs observed by Fermi/GBM in the same energy range and calculated from the Fermi GBM Burst Catalog (FERMIGBST\cite{fermigbrst}, see D. Gruber et al. (2014); Naravana Bhat et al. (2016); von Kienlin et al. (2014).

The spectral parameters of a typical short GRB used in the Geant4 simulations are \( E_{\text{peak}} = 500 \) keV, \( \alpha = -0.5 \) and \( \beta = -2.3 \). The median peak flux and the spectral normalization for 1024 ms time scale around a GRB peak are \( F_{1024} = 2.00 \) ph cm\(^{-2}\)s\(^{-1}\) and \( A_{1024} = 7.8 \times 10^{-3} \) ph cm\(^{-2}\)s\(^{-1}\)keV\(^{-1}\), respectively.

### 4 Monte Carlo Simulations

Full Monte Carlo simulations including the satellite’s mass model in Geant4 is performed (see Figure\cite{fig:montecarlo}). Three different thicknesses of the Al casing, 1.0 mm, 1.5 mm and 2.0 mm are considered in the simulations to check the dependence of the count rates on the material thickness.

#### 4.1 Description of Geant4 simulations

In order to simulate the interaction of particles including gamma-rays from GRBs and background particles, a dedicated particle physics simulation was developed using Geant4 10.0.p4. In order to be as realistic as possible – to take into account the secondary particles created by the interaction of the primary particles and the material of the satellite too – a complex CAD model of the satellite was imported to the Geant4 simulation with CADMESH\cite{poole2012cadsim}. The “Physics List” used in the simulation was chosen to be a ModularPhysicsList that included elastic hadron scattering, all relevant physics for neutrons, electromagnetic processes and optical photon physics.

Individual (scintillation) photons with an optical wavelength were created by particles depositing energy inside the scintillator. These were tracked until they were either absorbed or detected by the SiPMs implemented in the simulation. The optical parameters of the scintillators were determined by a dedicated set of measurements. The most relevant optical parameters were attenuation length, the reflectivity of the enhanced specular reflector (ESR) tape that is planned to cover the CsI(Tl) scintillators and the photon detection efficiency of the SiPM. The optical parameters were fine tuned by matching the measured and simulated spectra.

#### 4.2 Simulation results

The detection count rates from the different components of the background obtained from the Geant4 simulations are presented in Table\cite{table:counts}. The dominant component is CXB followed by the albedo X-rays and secondary positrons.

The Geant4 simulation for a typical short GRB with the incident flux perpendicular to the scintillator and not passing through the satellite’s body gives detection count rates 135 cnt/s, 130 cnt/s and 125 cnt/s for Al scintillator casing thicknesses 1.0 mm, 1.5 mm and 2.0 mm, respectively. Assuming a trigger algorithm with a time window of 1 s then SNR = GRB counts / \( \sqrt{\text{background counts}} \) would be 4.3, 4.8 and 5.1 for the three Al casing thicknesses, respectively.

The detection count rates were obtained for only one CsI scintillator of size 75×150×5 mm\(^3\). Up to four CsI scintillators (two scintillators on two perpendicular sides) are planned for each CAMELOT 3U satellite.

### 5 Duty Cycle

As seen from Figure\cite{fig:map} the flux of trapped e\(^-\) can increase by several orders of magnitude in the polar regions or inside SAA compared to the flux near equator. The high increase of the background was also observed by the Lomonosov/BDRG\cite{svertilov2018} which is a gamma-ray transient detector sensitive in the energy range from 10 keV to 3 MeV. It consists of three modules of NaI(Tl) and CsI(Tl) scintillators covered by less than 1 mm thick Al window shield and read out by photomultiplier tubes. The instrument shows that background count rate can increase \( 50\times \) when passing SAA or polar regions.

Therefore we calculated the duty cycle for altitude 500 km and inclinations 53° and 97.6°, which are the inclinations considered in the feasibility study of CAMELOT\cite{werner2018}. We simulated 1000 circular orbits at 500 km altitude and calculated the fraction of the time the satellite spend in the area with high background flux of trapped e\(^-\) (> 1 cm\(^{-2}\)s\(^{-1}\)).

For the map of the integral fluxes of trapped e\(^-\) (\( E > 40 \) keV) we used the AE-8 MIN Update ESA-SEE1 model\cite{vampola1998}.

At 500 km altitude a satellite would spend 23% and 32% of the time in the regions of flux > 1 cm\(^{-2}\)s\(^{-1}\) of trapped e\(^-\) for inclinations 53° and 97.6°, respectively.

### 6 Expected Ionizing Dose in MPPC

It is considered to use Hamamatsu S14160-6050HS MPPCs for the detectors for CAMELOT. The proton beam irradiation

[https://heasarc.gsfc.nasa.gov/w3Browse/fermi/fermigbrst.html]
FIGURE 6 Expected annual ionizing dose in MPPCs due to fluxes from various sources as a function of the thickness of the lead shielding. The simulated orbits have altitude 500 km, inclinations of 53° (left) and 89.9° (right). The sources are: trapped p\(^+\) (blue squares), GCR H\(1+H2+He3+He4\) (yellow triangles), solar p\(^+\) (red crosses), secondary p\(^+\) (green circles).

TABLE 1 Detection background count rate (cnt/s) for one CsI(Tl) scintillator of size 75 × 150 × 5 mm\(^3\) as a function of the Al casing thickness obtained from the Geant4 simulations.

| Casing (mm) | CXB | Albedo | Secondary particles | GCR | Trapped | Total |
|------------|-----|--------|---------------------|-----|---------|-------|
|            | X-ray | p\(^+\) | n | e\(^-\) | e\(^+\) | H | He | e\(^-\) | e\(^+\) |       |       |
| 1.0        | 703 | 175 | 17 | 6.0 | 21 | 58 | 16 | 6.9 | 0.15 | 0.07 | 1.2 | 1007  |
| 1.5        | 425 | 179 | 19 | 4.8 | 20 | 63 | 19 | 6.9 | 0.16 | 0.33 | 1.2 | 738   |
| 2.0        | 324 | 164 | 18 | 5.1 | 21 | 63 | 19 | 7.0 | 0.15 | 0.33 | 1.2 | 622   |

tests at W-MAST (Wakasa-wan, Japan) facility performed by the CAMELOT team reveal that the MPPCs degrade when irradiated by 200 MeV p\(^+\). Therefore it is necessary to estimate the expected total ionizing dose at (LEO) and design a protective cover shielding MPPCs to decrease the total dose due to p\(^+\).

We used Multi-Layered Shielding Simulation (MULASSIS) implemented in SPENVIS to calculate ionization dose in a Si sphere shielded by Al and Pb. A simple spherical geometry with source flux isotropically incident over 4\(\pi\) rad was used for approximation.

The following proton sources are used in the simulation: trapped p\(^+\) AP9 model (MC mode, 50% CL, 100 runs, 30 days of orbit simulation with 60 s sampling); solar p\(^+\) ESP-PSYCHIC (Xapsos, Stauffer, Jordan, Barth, & Mewaldt, 2007) model implemented in SPENVIS (50% CL, magnetic shielding on, stormy magnetosphere, Störmer with eccentric dipole method, magnetic field moment unchanged); GCR p\(^+\) ISO 15390 model (same parameter setting as described in Section 2.3.1); for secondary p\(^+\) we use the same model as described in Section 2.3.1.

The expected annual doses for inclinations 53° and 89.9° are shown in Table 2 and in Figure 6. The irradiation tests at W-MAST facility suggest that the considered MPPCs can be used for the CAMELOT mission when a proper shielding is applied. For a 1U CubeSat demonstration mission GRBAlpha we consider to use 2.5 mm of Pb + 1.0 mm of Al.

7 | CONCLUSIONS

We studied the expected background for the CAMELOT mission and detectability of short GRBs. It was shown that with at least one large scintillator short GRBs with a typical peak flux can be detected. Future work will include, for example, a study of the background activation due to the radioactive decay of elements of the detector and the satellite’s body generated when passing SAA. Also other transients, beside the short GRBs, such as long GRBs, SGRs, TGFs should be considered. The expected annual doses allow to use the planned MPPCs for the CAMELOT mission when a proper shielding against protons is applied.
TABLE 2  Expected ionizing dose (rad/year) in MPPCs for altitude 500 km as for different shielding.

| Shielding thickness (mm) | Trapped $p^+$ | Solar $p^+$ | H1 | H2 | He3 | He4 | Secondary $p^+$ | Total |
|-------------------------|--------------|-------------|----|----|-----|-----|----------------|-------|
| no shielding            | 1108         | 41          | 0.8| 0.9| 0.4 | 0.4 | 0.2            | 1152  |
| Al 1.0                  | 223          | 1.2         | 0.9| 1.1| 0.5 | 0.5 | 0.2            | 227   |
| Pb 1.0 + Al 1.0         | 132          | 0.3         | 1.1| 1.4| 0.5 | 0.5 | 0.2            | 136   |
| Pb 1.5 + Al 1.0         | 117          | 0.2         | 1.2| 1.5| 0.5 | 0.5 | 0.2            | 121   |
| Pb 2.0 + Al 1.0         | 106          | 0.2         | 1.2| 1.6| 0.5 | 0.5 | 0.2            | 110   |
| Pb 2.5 + Al 1.0         | 95           | 0.2         | 1.3| 1.7| 0.5 | 0.6 | 0.2            | 99    |
| Pb 3.0 + Al 1.0         | 86           | 0.1         | 1.3| 1.8| 0.6 | 0.6 | 0.2            | 90    |
| Inclination 53°         |              |             |    |    |     |     |                |       |
| no shielding            | 773          | 1262        | 1.6| 1.8| 0.8 | 0.8 | 0.2            | 2040  |
| Al 1.0                  | 153          | 36          | 1.7| 2.0| 0.8 | 0.8 | 0.2            | 194   |
| Pb 1.0 + Al 1.0         | 92           | 10          | 2.0| 2.4| 0.8 | 0.9 | 0.2            | 108   |
| Pb 1.5 + Al 1.0         | 80           | 6.7         | 2.1| 2.6| 0.9 | 0.9 | 0.2            | 94    |
| Pb 2.0 + Al 1.0         | 72           | 4.8         | 2.1| 2.6| 0.9 | 0.9 | 0.2            | 83    |
| Pb 2.5 + Al 1.0         | 66           | 3.5         | 2.2| 2.7| 0.9 | 0.9 | 0.2            | 76    |
| Pb 3.0 + Al 1.0         | 59           | 2.6         | 2.3| 2.9| 0.9 | 0.9 | 0.2            | 69    |
| Inclination 89.9°        |              |             |    |    |     |     |                |       |

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Conflict of interest

The authors declare no potential conflict of interests.

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