MR-AVI-0068 Radiation Survival Summary

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Document History Log

Status (Baseline / Revision / Canceled)	Document Revision	Effective Date	Description
Baseline	1	01/18/2021	Initial release
Revision	1.1	02/12/2021	Added specifics and results of tests
Revision	1.2	02/21/2021	Updated content throughout - CDR version
Revision	1.3	4/22/2021	Updated for Delta CDR

Revision	Release Notes	Author(s)	Release Date
A	Bringing this document into compliance with the MoonRanger standard process for labeling revisions with letters. No content changes.	Chuck Whittaker	5/25/2021

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Definition of abbreviations

TID	Total Ionizing Dose
COTS	Commercial Off The Shelf
ISIS	Innovative Systems in Space
OBC	On Board Computer
NSS	Neutron Spectrometer System
DPM	Data Processor Module
DSNE	Design Specification for Natural Environments
SPE	Solar Particle Events
GCR	Galactic Cosmic Rays
LEO	Low Earth Orbit
HEO	High Earth Orbit
GPIO	General Purpose Input Output
DUT	Device Under Test

Introduction

MoonRanger's radiation viability is achieved via **component selection, shielding, short mission duration, testing, error correction and monitoring**. Some components, including power management, primary and watchdog computers, accelerometer, and intelligent battery are selected for radiation tolerance, prior rad testing, or space heritage. Shielding is utilised for critical components that lack space heritage and boards developed by the program. MoonRanger takes advantage of the low total dose and relatively low probability of damage by high-energy particle hits resulting from short mission duration of 6-9 days in transit and less than 15 days on the lunar surface. The highest radiation dose rate occurs in transit through the Van Allen Belts, which is predicted to take 3-4 hours during which avionics is powered down. Our testing has irradiated critical components to 4x mission TID and greater exposures are planned. Independent testing determined that the central computer survives a multiple of the predicted high energy and TID exposure. The central computer has built-in error correction. Load current is monitored for latch-up detection and subsequent reset for recovery.

This report includes the following:

1. The avionic components, devices and boards are listed and categorized as space heritage, rad tolerant, prior rad tested, COTS and developed in-house. The untested COTS and in-house developments are designated for TID testing.
2. Components that are shielded are listed and their shielding is described.
3. The means for monitoring load current to detect latch-up are described.
4. The intrinsic reliability features of the central computer are described.
5. Summary of methodology and results from in-house dose testing to date are that are more fully presented in the accompanying radiation test report.
6. Results from the extensive independent proton SEE and ^{60}Co dose testing that determines viability of the central computer are presented.

Avionic Components

MoonRanger's computer, cameras and interface board have been tested so far in a powered state to 4 krad dose without adverse effects. During mission these components are expected to experience <0.5 krad in an unpowered state during transit and <0.5 krad in a powered state when on the lunar surface. Additional testing is on-going.

MoonRanger's central computer has been independently tested by JHU APL to survive 45 krad TID in unpowered state and 10 krad when powered. Additionally, the proton testing determined >= 90% probability of survival with an average of 4 resets in a flux analogous to a 6 month moon mission.

The MSP430 microcontroller used throughout the MoonRanger's avionics system comes from a family of microcontrollers with extensive flight heritage. MSP430 based systems have flown on many cubesats including BasicLEO, RAX-1, RAX-2, and LMRSat. In addition, the ferroelectric program memory is immune to radiation effects.

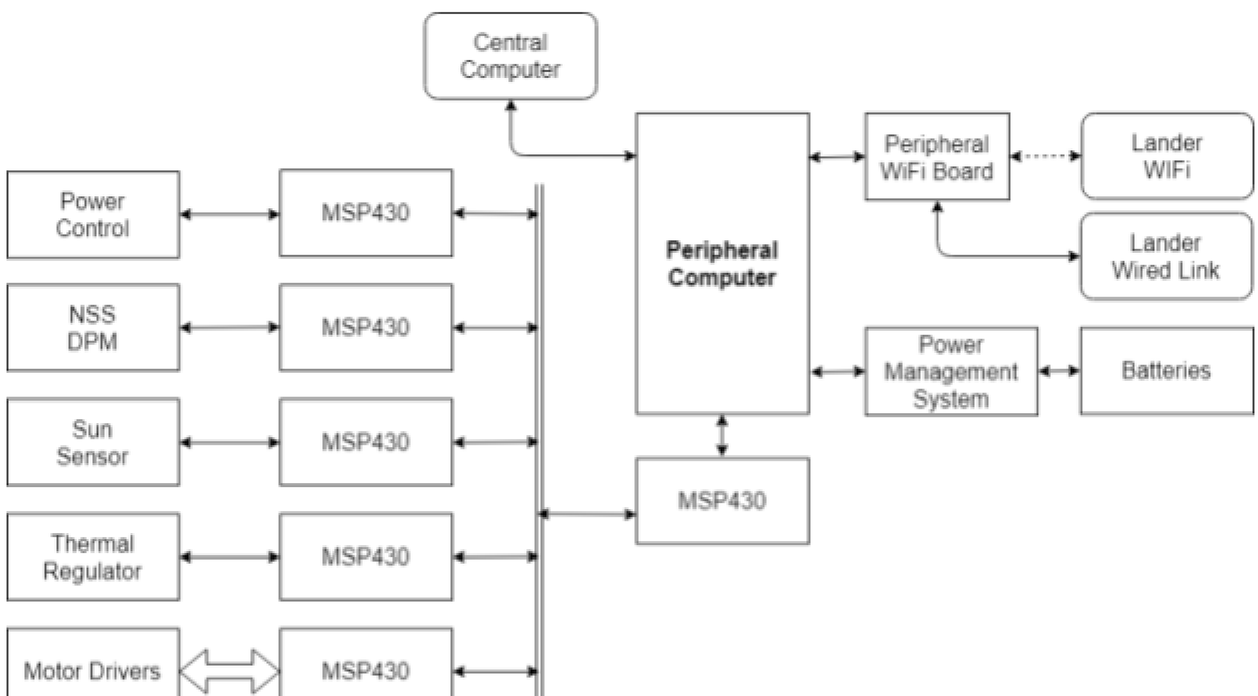

Figure 1 - MoonRanger System Architecture - Low Level

Component description	Heritage	TID testing
Power Management System (EPSM)	Space heritage (CubeSat heritage)	No testing feasible due to budget
Batteries (CubeSat Kit™ Battery Module 2 (BM 2))	Space heritage (CubeSat heritage)	No testing feasible due to budget
IMU (Sensonor - STM300)	Space heritage (CubeSat space qualified, heritage up to 5 krad)	No testing required
SunSensor (SolarMEMS nano-SSOC-D60)	Space heritage (Heritage TID 30 krad, p+ 300 krad 6 MEv)	No testing
Peripheral computer (ISIS On-board Computer ARM9)	Space heritage (CubeSat space heritage)	Testing as feasible
DCDC Converters (Crane Interpoint SMRT2815S)	Space heritage (Rad hardened)	No testing required
Central computer (NVIDIA TX2i GPGPU on ConnecTech Spacely carrier)	COTS	TID testing required
Camera module (Leopard Imaging - LI-IMX274-MIPI)	COTS	TID testing required
WiFi module - Central (Doodle Labs - NM-DB-2U)	COTS	TID testing required
WiFi - Peripheral (Custom board with TI CC3200)	In-house development with select COTS	TID testing required
Power Control and Thermal Regulation subsystem (Custom board with MSP430)	In-house development with select space qualified COTS	TID testing required
Motor controller (Custom board with with MSP430)	In-house development with select rad hardened COTS	TID testing required

Table 1 - Component list with TID information

Shielding

Shielding is added to key electronic components. The table below gives rationale and shielding description for key components.

Component	Shielded?	Rationale & Description
Central Computer, carrier board & WiFi module	Yes	Critical component - Unit still functional after experiencing TID equivalent to unit in space with shielding
Peripheral computer	Yes	2.5mm aluminum shell; Rad shield doubles as thermal strapping
Power Management System (EPSM)	Yes	2.5mm aluminum shell; Rad shield doubles as thermal strapping
WiFi - Peripheral	Yes	2.5mm aluminum shell used; Custom board with no flight heritage
Power Control and Thermal Regulation subsystem	Yes	2.5mm aluminum shell used; Custom boards with no flight heritage.
Motor controller (Custom board with with MSP430)	Yes	2.5mm aluminum shell used; Custom boards with no flight heritage.
DCDC Converter	No	Rad hardened
Batteries	No (selective)	Rad tolerant with only electronics shielded
NSS DPM	No	Payload as provided

Table 2 - Component list with shielding information

Note 1: *Shells are 2.5mm thick aluminum on five faces. The sixth face lies between the avionics component and radiator. This piece supplements the radiation shielding provided by the honeycomb radiator and also provides thermal grounding between hot board components and the radiator.*

Note 2: *Most COTS components are radiation tolerant to 5 krad, with many of them tolerant upwards of 20 krad. Some fail under 1 krad.* [1]

Rover is significantly shielded on the top by the lander during transit. On the lunar surface, radiation influx will be precluded bottom-up and MoonRanger will experience only 50% of the radiation environment.

Simulation of TID using SPENVIS simulator for 1 full orbit through the Van Allen belts results in doses of approximately 1 krad with 2.5 mm thick Aluminium shielding.

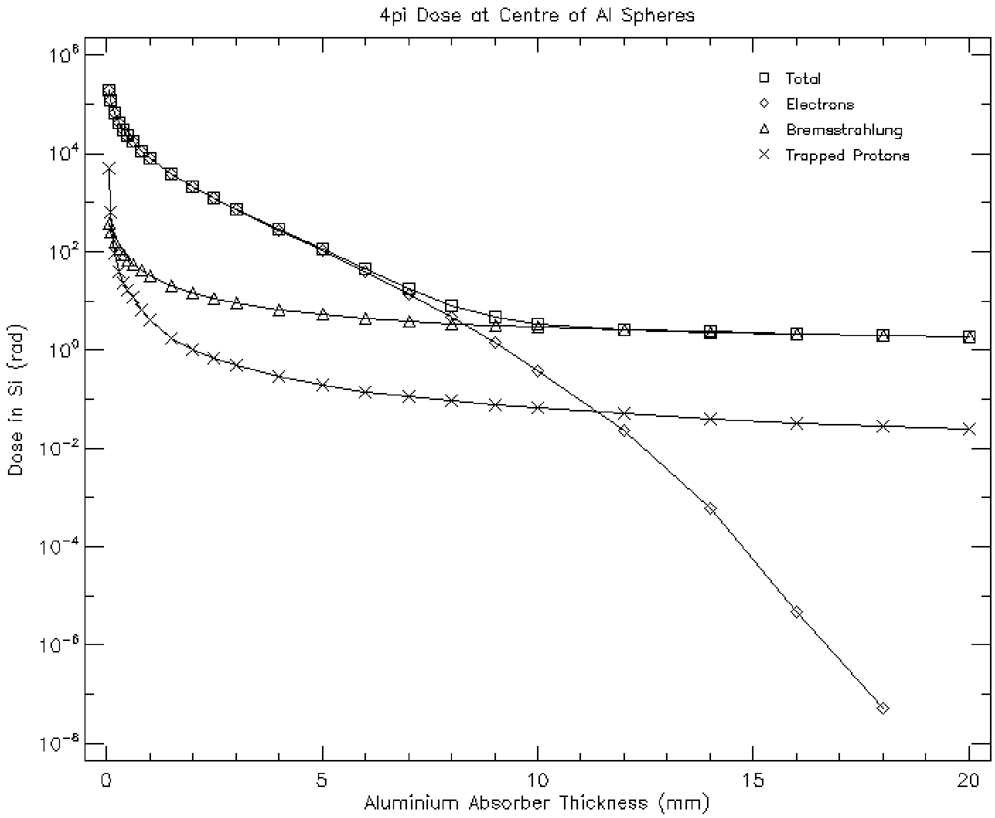

Figure 2 - Plot of TID in Si v/s Aluminium shielding thickness by SPENVIS (ESA SPace ENVironment Information System https://www.spenvis.oma.be/)

Radiation Environment Described by DSNE Specification

The above results will be compared with DSNE specification in the following sections.
Equivalency assumed: 1cGy(Si) = 1 rad(Si).

In the DSNE program, TID specifies the total cumulative dose from TID and DDD in specified environments and various thicknesses of aluminum shielding. A shield thickness of 2.5 mm is assumed unless otherwise noted. DSNE TID is calculated with simulation (SPENVIS) for a spherical aluminum shield. TID can be obtained for different environments listed in the TID Applicability Matrix in Table 3.3.1-1.
For the initial transit stage, the DSNE specification for Staging and Transit orbits (LEO 185 x 1806 km) applies. The daily trapped belts TID inside shielding from combined trapped belt electrons and protons are plotted in figure 3 below. The TID rate inside a shield of aluminum of a thickness of 2.5 mm the TID is 200 cGy(SI)/day. Since the transit phase is less than one day, the resulting TID is approximated to be 200 cGy(Si) or 200 rad(Si).

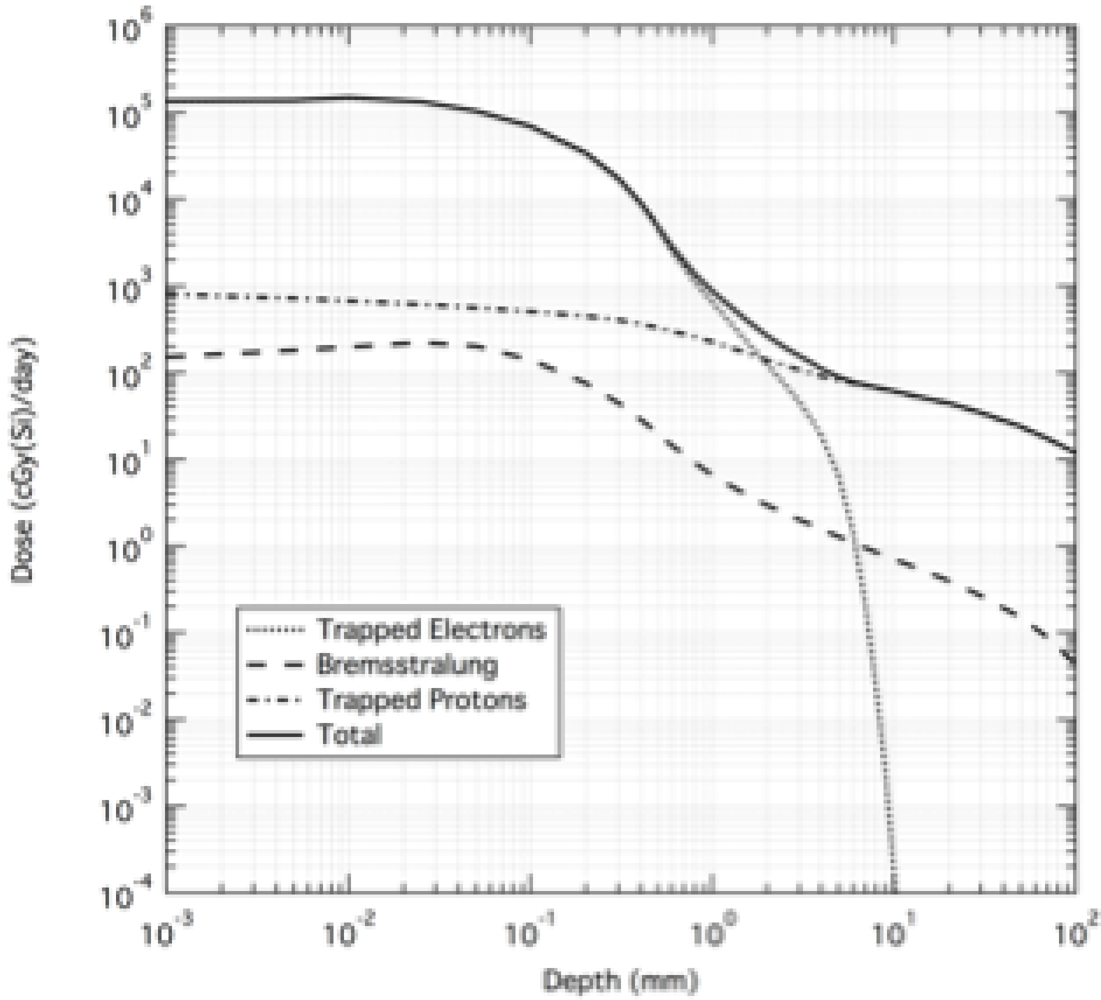

Figure 3 - Plot of Daily Trapped Belts TID inside aluminum shielding for initial phase of transit (From Figure 3.3.1.10.1-3, DSNE, reference 5)

For the final transit stages, high earth orbit (HEO) spanning 407 to 233,860 km is used. (See section 3.3.1.2.4 Reference 5, DSNE) From the plot shown in figure 4, for a thickness of 2.5 mm Aluminum shield, the TID rate for trapped belts within HEO is 50 Gy(Si)/day. Since the transit phase is less than one day this phase contributes 50 cGy(Si) or 50 rad(Si).

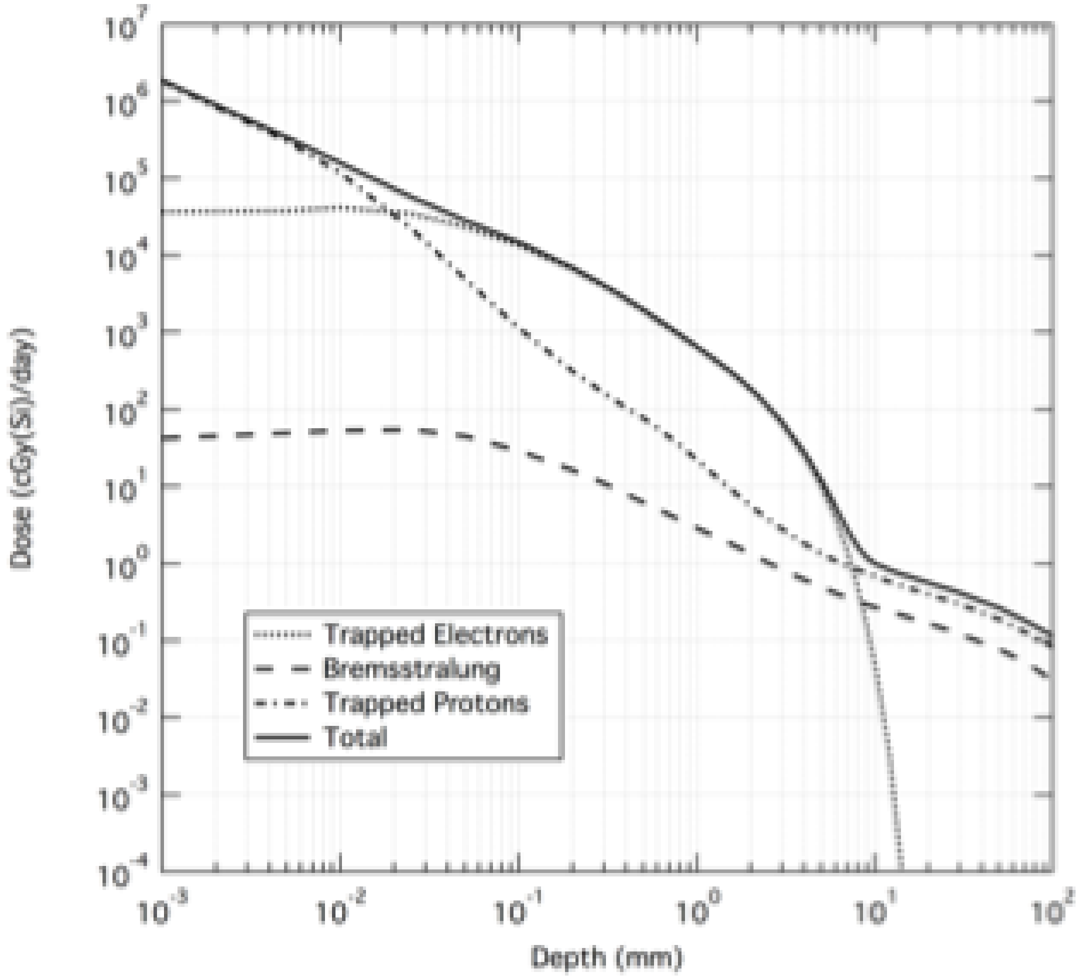

Figure 4 - Daily Trapped Belts TID inside Aluminum Shielding (From figure 3.3.1.2.4-3, reference 5, DSNE)

Using the TID for trapped belt for transit of the radiation belts the plot in figure 5 below, the total dose is obtained for a thickness of 2.5 mm of aluminum. (See section 3.3.1.2.2 DSNE, reference 5). ThisTID is found to be approximately 500 cGy(Si) or 500 rad(Si). Note this value is not plotted as a TID rate but integrated TID and the model transit duration is not provided. The approximation was scaled in the DSNE from the model by a factor of two to account for the uncertainty of the model.

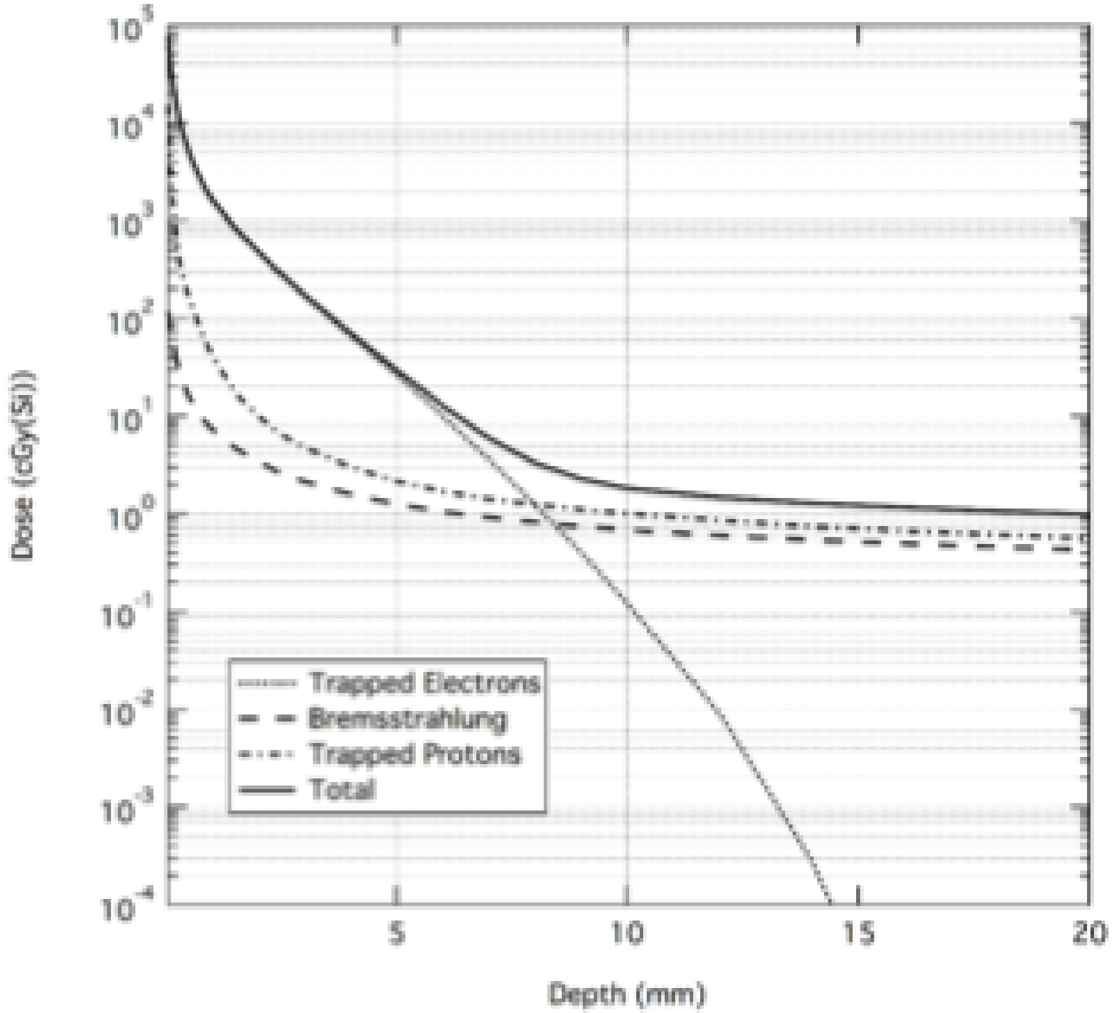

Figure 5 - Trapped belts TID inside Shielding for Radiation Belt Transit (from DSNE, figure 3.3.1.2.2-3, reference 5)

The radiation environment of the lunar surface TID with the unshielded SPE environment from daily GCR fluence is shown in figure 6. The dose rate for 2.5 mm aluminum shielding is 2 x 10E3 cGy (Si)/year, or 6.8 cGy(Si)/day. For a 14 day mission, the total TID on the lunar surface is 96 cGy(SI) or 96 rad(Si).

The lunar orbit TID is approximately double the daily lunar surface TID rate.

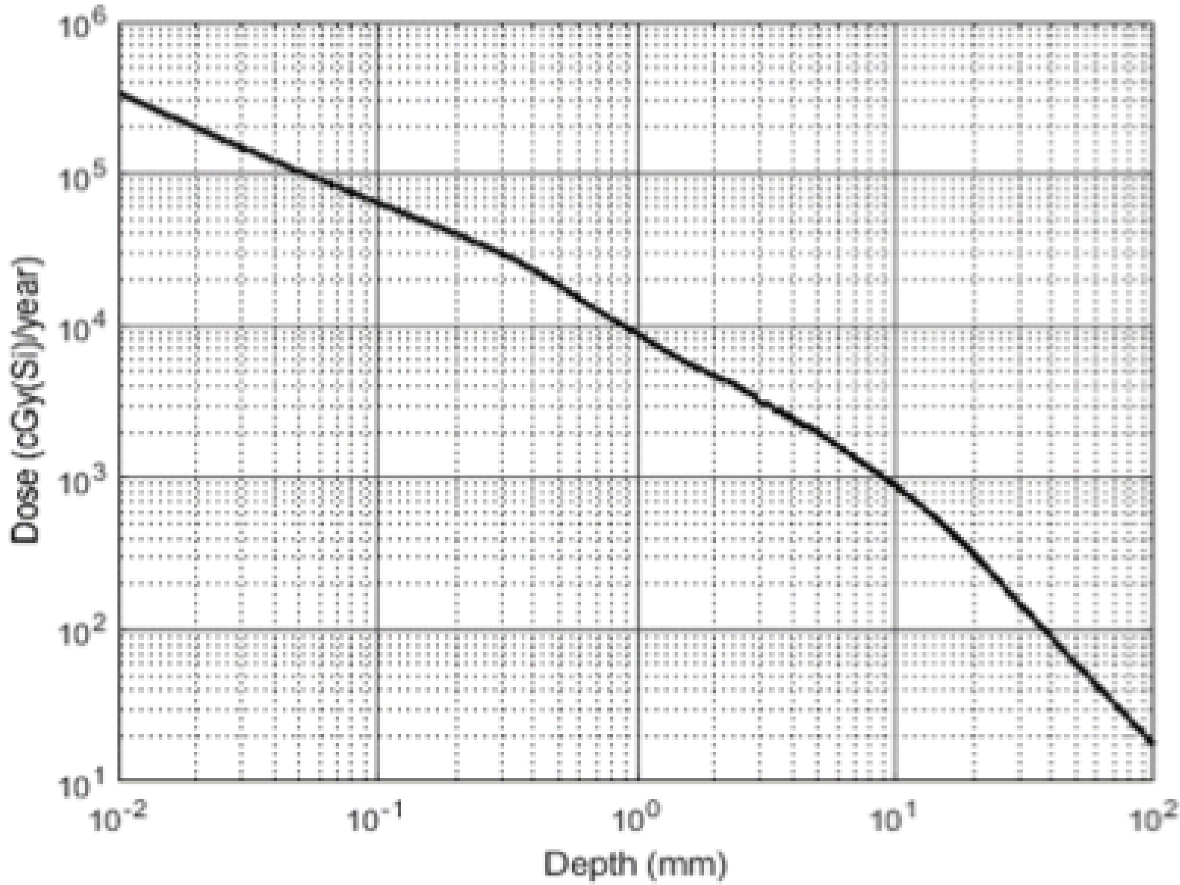

Figure 6 - Plot of total unshielded SPE TID in Si v/s Aluminium shielding thickness (From Figure 3.3.1.10.2-3, DSNE, reference 5)

Phase	Duration (days)	DSNE section	DSNE Table	SPE (cGy(Si) or rad(Si))	GCR (cGy(Si) or rad(Si))	TID (cGy(Si) or rad(Si))
Belt Transit	0.17	3.3.1.2.2	3.3.1.2.2-3			96
Cislunar injection	5	3.3.1.10.2	3.3.1.10.2-3 3.3.1.10.2-4	54	0.17	27
Lunar orbit + landing	1.125	3.3.1.10.2	3.3.1.10.2-3 3.3.1.10.2-4	12	0.04	6
Surface operation	14	3.3.1.6	3.3.1.10.2-3 3.3.1.10.2-4	150	0.48	75
Total						**204**

Table 3 - TID for mission phases

The combined TID for the mission including transit and surface operation phases is estimated to be approximately 610 rad(Si) or slightly more than the TID of 500 rad(Si) estimated in the Shielding section above.

Single event effects (SEE) are considered in the DNSE program for environments exposed to Solar Particle Events (SPE) and Galactic Cosmic Rays (GCR) and are discussed in DNSE section 3.3.2. The applicable DSNE section for mission phases are obtained from the SEE Applicability Matrix in DSNE table 3.3.2-1. These are summarized in table 4 shown below. The calculation of the SEE event number estimation is currently being completed.

Phase	**Duration**	**DSNE section**	**SEE events**
Belt Transit		3.3.2.2	TBD
Interplanetary	1 day	3.3.2.4	TBD
Lunar orbit	1 day	3.3.2.5 3.3.2.6 3.3.2.2	TBD
Surface operation	14 days	3.3.2.6	TBD
Total			**TBD**

Table 4 - SEE estimation

Equivalence of mission and Earth orbit ionizing radiation exposure

Using the DSNE specifications of ionizing radiation environments, a comparison can be made between LEO or GEO and MoonRanger mission survivability. We will make this comparison to establish if a claimed space heritage for Cubesat hardware is applicable to MoonRanger's mission..

Latch-up detection

Load current is monitored through multiple e-Fuses and Smart High Side Switches (later referred to as load switches). These components rely on GPIO inputs from the peripheral computer for complete functionality and implement protection in three modes:

1. Latch-off (load voltage is retained at 0V until reset by toggling a GPIO input)
2. Auto-retry (cycle power repeatedly, with a pre-configured time between retries)
3. Limit-only (reduce load voltage to limit the current to a predefined level)

To implement the power cycling behavior, a pair of comparators and several passive components monitor the current through load switches. The comparator pair implements a two-stage, delayed comparison with hysteresis. If the current through the load switches exceeds a limit (determined by passive components), for a set amount of time (also determined by passive components), the comparator system disables the load switches and consequently turns off the load.

Intrinsic Reliability

MoonRanger's central computer's (Nvidia TX2i) Memory Controller includes error-detection and error-correction features that provide substantial resistance to bit-flips caused by single-event upsets in the computer memory. In case of a bit-flip, the central computer automatically recovers from it. If the error is in L1 caches, it detects the error, flushes the corrupted data, and reloads correct data from the L2 cache facilitating automatic software recovery and preventing corruption of data and/or software crashes.
In the event of permanent radiation (or other) hardware damage of a memory cell, the TX2i software will automatically retire the page containing the bad cell.[3]

The software enabled Error Correction Code (ECC) includes [2]

- Full DRAM scrubbing in MB1 to generate parity bits required for ECC
- Single-bit Error (SBE) Correction in the SCE firmware
- Double-bit Error (DBE) detection and reboot in the SCE firmware
- Memory available to the kernel is extended from two regions to the actual available regions
- Position independent U-Boot support

The central computer is power cycled by the peripheral computer in the event of loss of heartbeat between the central and peripheral computer over the RS422 channel. An external watchdog timer cycles the power to the peripheral computer in the event of a hardware or software fault.

In-house Radiation Testing

MoonRanger's central computer (with carrier board), cameras (with carrier board) and primary WiFi module have been incrementally exposed to a TID of 4000 rad over the course of four tests. The post-exposure evaluation of the DUT showed no observable degradation in performance.

The radiation test is performed using ^{137}Cs source on unshielded (air) components. The observed absorption rate is 203.5 rad/min.

Post exposure tests include hot and cold reboot and memory benchmark tests for the central computer and its carrier board. The WiFi module is tested for transmission speed and reliability using a 40 MB file. Cameras are tested in both dark and normal lighting conditions to locate dead pixels.

Independent Radiation Testing

MoonRanger's central computer (with carrier board), has been extensively tested by John Hopkins University Applied Physics Laboratory (JHU APL). [4] It was found that the unbiased state is significantly more rad hard - survival upto 45 krad. It was also found that the central computer has a ≥ 90% chance of surviving 6 months in a lunar space environment.

The dosing was performed in a ^{60}Co irradiator at 3.5 rad/s in 5 krad intervals in the following power configurations:

- On: continuously powered (biased)
- Soft Reboot: command line reboot loop
- Hard Reboot: power on reset loop
- Off: dosed unbiased, booted every 5 krad to check functionality

Proton testing was also performed with boards being exposed to 60, 120, and 200 MeV protons.

Environment	**Worst case* (reboots/device/day)**	**Best Case* (reboots/device/day)**	**Worst case survival* (% chance at 6 months)**	**Best case survival* (% chance at 6 months)**
Lunar	2.27E-03	8.12E-04	90%	96%

* Based on solar activity

Table 5 - Test data from: C. Heistand, S. Katz and A. Voegtlin, "NVIDIA Jetson TX2i Radiation Report," SEE/MAPLD Workshop, October 6-8, 2020.

Solar activity during mission

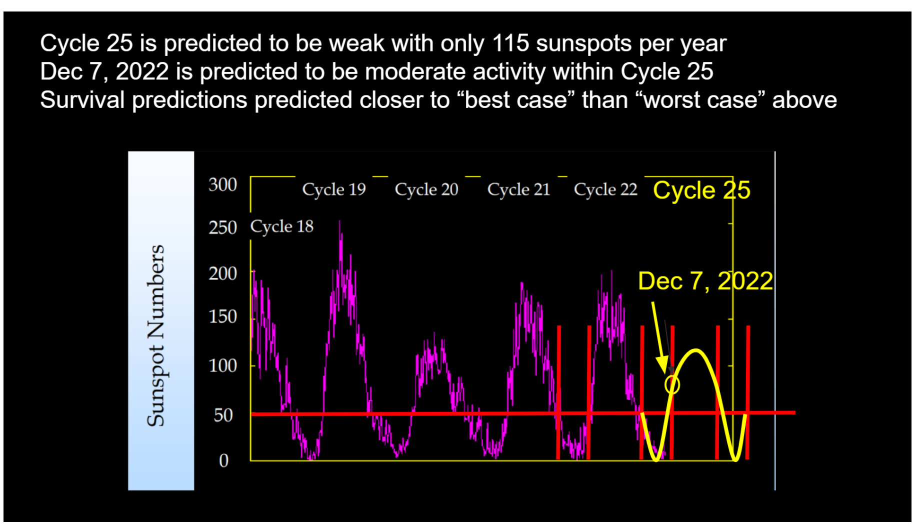

Figure 7: Predicted solar activity

Since the mission's solar activity is expected to be low, since MoonRanger's mission duration is only 3 weeks versus the 24 weeks of the cited test/evaluation report, and since MoonRanger is powered down during transit, MoonRanger's radiation survival is expected to be greater than the 96%."best case" reported in that study.

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