Kicksat-2 Design Architecture

Radiation Evaluation

Kicksat-2 hardware was designed with a “careful COTS” methodology to ensure mission requirements while optimizing lifetime, capability, and component cost/availability. This approach leverages existing component radiation testing literature with detailed environmental modeling to drive IC component selection.

Environment Simulation:

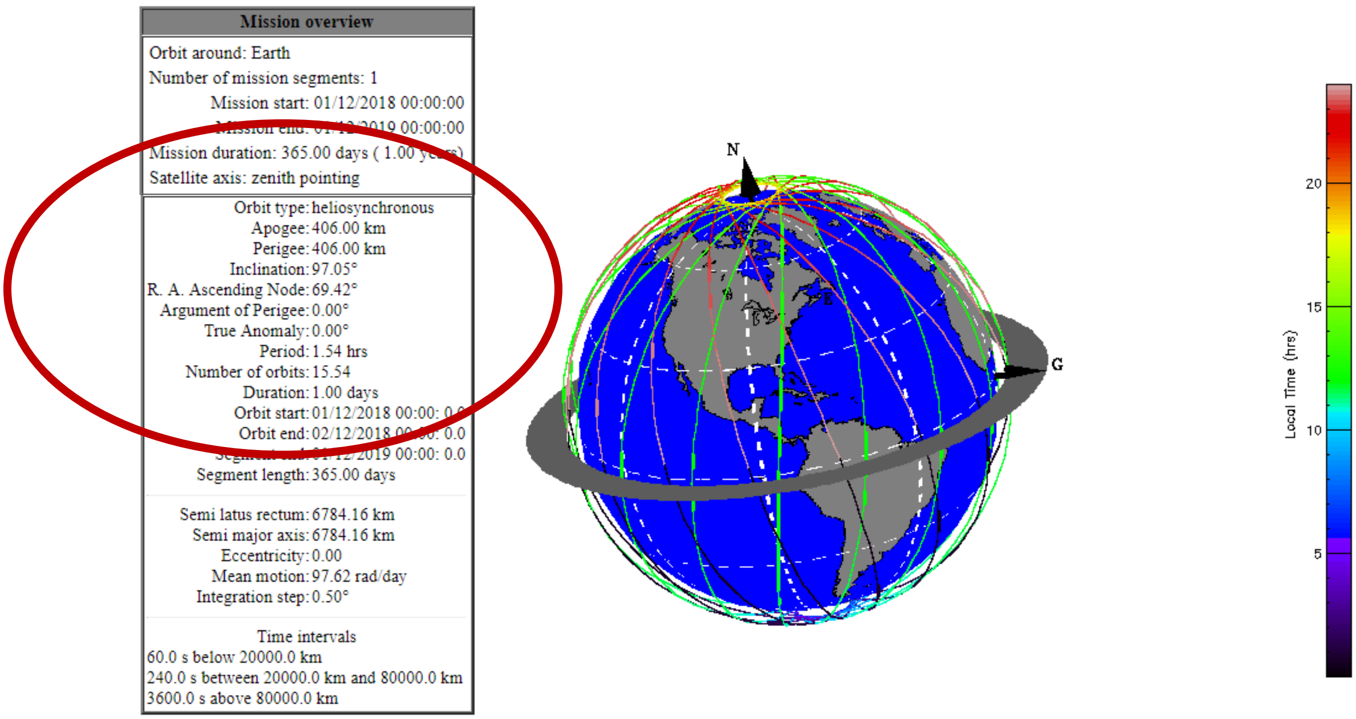

Figure 1

The ESA Space ENVironment Information System (SPENVIS) was used to generate high-level orbital parameters and subsequent radiation models. Further analysis was then performed using raw AE9/AP9 data in conjunction with Geant4, COMSOL, and VisualTCAD tools to model the anticipated radiation effects. Relevant SPEVIS input parameters used in orbital generation, and a graphical representation of a 24 hour orbital path are shown in Figure _____.

Using the parameters from Figure ____, a standalone copy of AE9/AP9 v1.50 was used to generate trapped particle data. Kicksat-2 mission altitude dictates that total ionizing dose (TID) accumulation will predominately come from trapped particles (electrons and protons). Single event effects (SEE), however, must still be considered since Kicksat-2 must not allow premature Sprite deployment.

Table I | Integrated Circuit Component Summary

P/N	Manufacturer	Function	Mission Critical?	Flight Heritage?	Radiation Test Data?
IRLML2803	Infineon	N-channel MOSFET	**Yes**	Unknown	Yes
IRLML5103	Infineon	P-channel MOSFET	**Yes**	Unknown	Yes
MAX706R	Maxim	Watchdog Timer	**Yes**	Yes	Yes
TPS54226	TI	Regulator	**Yes**	Yes	Yes
RFM23BP	HopeRF	Radio Transceiver	**Yes**	Yes	No
MR25H40	Everspin	Nonvolatile Memory	**Yes**	Yes	Yes
ATSAMD21G-A	Microchip	Microprocessor	**Yes**	Unknown	No
PE014006	TE Connectivity	Mechanical Relay	**Yes**	No	No
S1216V8	SkyTraq	GPS Module	No	Yes	No
LSM9DS1	STMicro	IMU	No	Yes	No
MAX4372TEUK+T	Maxim	Current Sensor	No	Yes	No
LTC4121-4.2	Analog Devices	Battery Charger	No	No	No
EP2W+	Mini Circuits	RF Splitter	No	Unknown	No
TY1003	Tyndall Works	Dosimeter	No	Yes	Yes

Discussion of Critical Components:

<u>IRLML2803 & IRLML5103 – Power MOSFET</u>

MOSFETs have well-documented electrical behavior in radiation environments. Incremental degradation due to ionizing radiation (TID) generally manifests as a *decrease* in gate threshold voltage for NMOS devices and an *increase* in threshold voltage for PMOS. Since discrete MOSFET devices play a critical role in the Kicksat burn-wire design, components with extensive radiation characterization were chosen and combined with multiple failsafes to ensure safe Sprite deployment.

Both the IRLML5103 and IRLML2803 were evaluated by O'Bryan et al. in 2001 for TID tolerance using the NSWC Crain facilities [XX]. Testing with the MIL-STD883 1019.8 procedure, including biased and unbiased conditions, the data shows the IRLML5103 has a TID tolerance greater than 35 krad, and the IRLML2803 greater than 30 krad. Both values far exceed the projected mission dose, and O'Bryan et al. has a strong testing track-record in the radiation effects community.

Device failure due to single event effects (SEE) such as burnout and latch-up are not relevant for the burn-wire design because the circuit sits dormant behind the mechanical relay circuit during nearly the entire mission. By protecting the burn-wire circuit with the mechanical relay, there is no bias across the MOSFET devices, thereby preventing an ionizing particle from creating parasitic effects within the channel/bulk regions and causing permeant damage.

<u>MAX706R – Watchdog Timer</u>

The MAX70X series of microprocessor supervisors have an extensive radiation test history covering TID, SEE, and SEL scenarios from a number of researchers [XX – XX]. As reported by Aaron et al, the MAX70X devices have a TID threshold of roughly 11 krad under worst-case biasing conditions [XX]. Additionally, Allen et al. reports a SEL threshold of 72 LET at 25C and about 68 LET at 85C. Both TID and SEE values are well within the required mission parameters, and failure of the MAX706R watchdog cannot result in the premature deployment of Sprites.

TPS54226 - Regulator

The TPS542XX family of DC-DC converters from Texas Instruments has been evaluated for TID and SEE tolerance by multiple researchers [XX – XX]. Specifically, Cochran et al. reported a TID tolerance of 15 – 20 krad, and Allen et al. reported no destructive SEL events occurring on devices biased at 10V or less and under a variety of temperature conditions. The efficiency of the TPS54226 device coupled the device behavior in radiation environments made it the most reliable choice for the Kicksat mission.

RFM23BP – Radio Module

The HopeRF RFM23BP module is a COTS radio integrated onto a PCB. Based on Silicon Labs' Si4431 transceiver, which has known flight heritage, the module also contains BJT devices, a N-channel UHF amplifier, a SPDT switch, and an LDO [XX]. Although the flight heritage demonstrates adequate reliability for the Kicksat mission, PCB rework was performed to replace the LDO and SPDT switch with components with better documented radiation tolerance.

MR25H40 – Nonvolatile Memory

The MR25H40 is a 4MB non-voltage memory device constructed from magnetoresistive memory devices. The fundamental operation of magnetoresistive memory makes it inherently more tolerant to TID effects. Cochran et al. reports a TID tolerance of 90 – 100 krad during their 2007 work at Goddard Space Flight Center Radiation Effects Facility [XX]. Additionally, O'Bryan et al. was unable to observe upsets in the device using 89 MeV and 189 MeV protons during their 2007 work at the Indiana University Cyclotron Facility [XX].

The high radiation tolerance of the magnetic memory is used to store mission-critical parameters that are periodically verified and referenced during key mission objectives such as Sprite deployment and configurational backups for the microprocessor.

ATSAMD21G-A - Microprocessor

The Kicksat spacecraft operates from a Microchip SAMD2X family of microprocessor. Although there is no published literature on the radiation tolerance of this device, inferences can be made from Cochran et al., 2008 TID work on a "complex 65nm CMOS microprocessor" [XX]. Using the MIL-STD883 1019.8 test method, Cochran et al. reports no degradation detected up to the maximum tested level of 1000 krad. Furthermore, the ATSAMD21G device now has flight heritage after launching onboard OA-9 within the Brown Space Engineering EQUiSat 1U CubeSat.

The ATSAMD21G was chosen for the Kicksat mission because of its 32-bit ARM Cortex-M0+ architecture, low power consumption, and wide accessibility. The confidence level of the device to perform mission-critical duties was enhanced as described in the ______ section.

PE014006 – Mechanical Relay

The PE014006 relay was added to the design to provide an additional layer of protection from premature Sprite deployment. The power relay is inherently a mechanical device that can only be engaged when enough current is driven across the input terminals to actuate a mechanical switch. It therefore is not susceptible to TID degradation. The construction of the device employs a large isolation distance which also protects the relay from SEE-actuated events.

Sprite Deployment Scheme

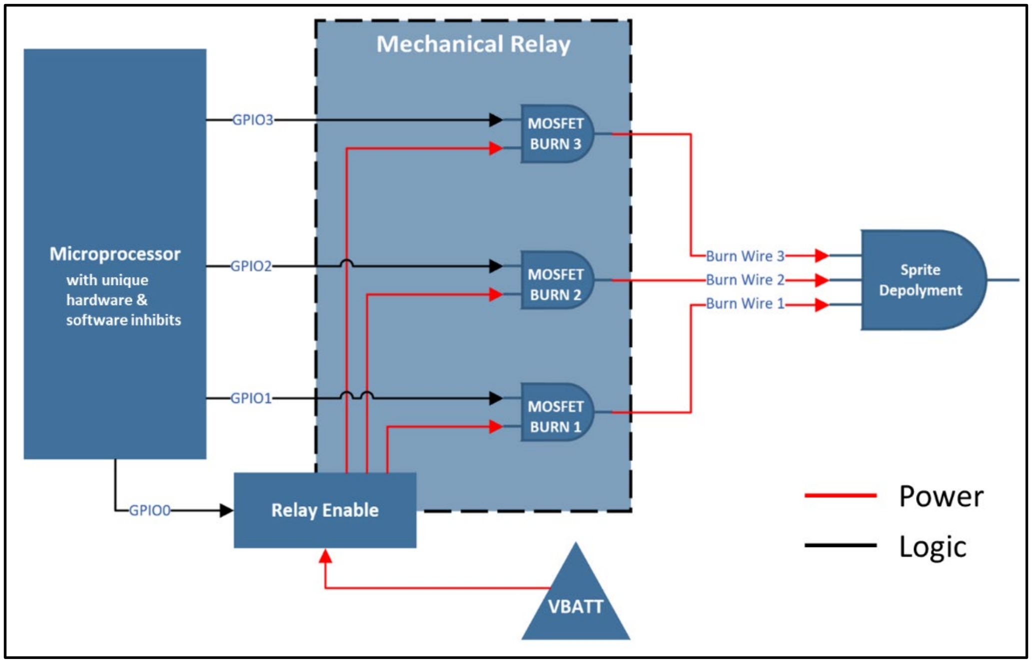

Figure 2

The Kicksat-2 deployment scheme employs hardware and software safeguards to prioritize timely Sprite deployment above mission operational parameters, while also addressing detrimental environmental effects such as radiation-induced SEE and transient voltage spikes.

- See “Kicksat2_Inhibits_v2b_2018-07-16.PPTX” for further detail

Hardware

Figure ___ and Fig. ____ illustrate the four hardware mechanisms in place to prevent premature deployment. A section of the schematic is also included in Fig. _____ as an alternative method of visualizing the safeguards. It’s important to note that each possible failure mode of the hardware defaults to a no-deployment condition. This hardware includes:

1. Three burnwires must be severed to release the Sprites.
2. Each burnwire circuit is operated by a separate I/O pin on the microprocessor.
3. A mechanical relay is placed in-line within the high-current path from the battery to the burnwires to further safeguard from early deployment by decoupling the electrical and mechanical aspects of the design.
4. An external, radiation tolerant, watchdog timer is used to monitor activity of the microprocessor and can disable all relay and MOSFET actuation if continuous checkpoints are not met.

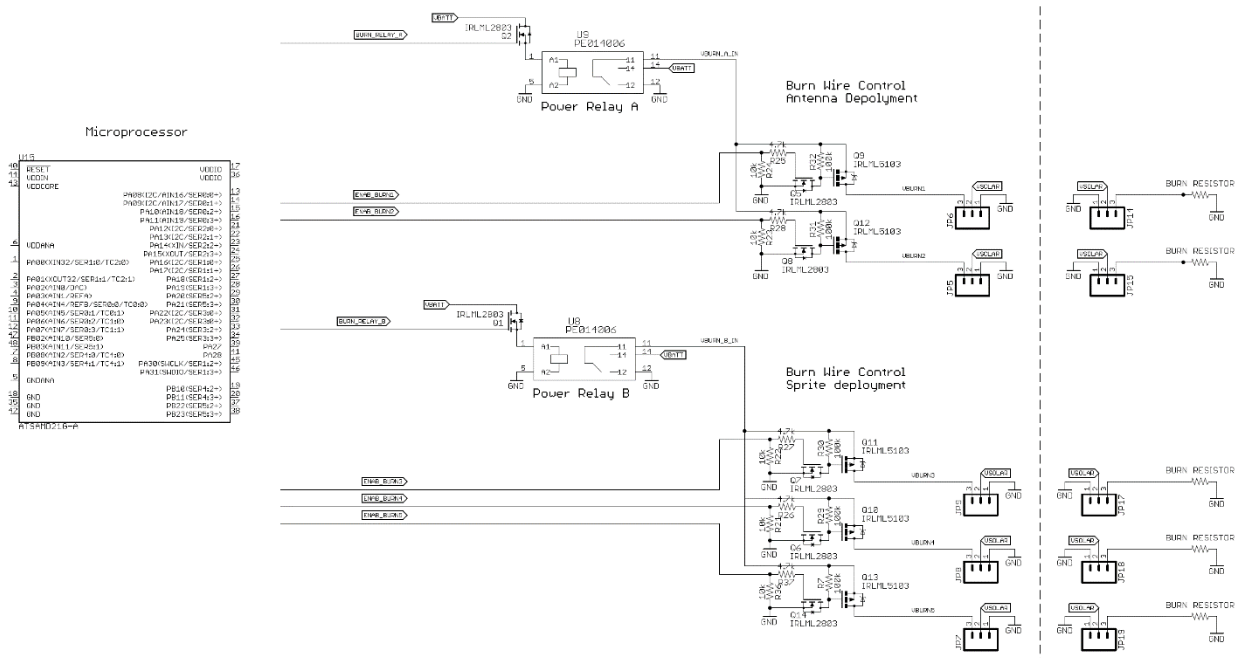

Figure 3

Software

1. Each software checkpoint is reached via compartmentalized multi-byte strings that contain several Boolean conditions per string. This technique makes the software increasingly more tolerant of radiation-induced bit flips.
2. Kicksat-2 firmware defaults to a no-deployment condition that uses a silicon-enabled feature requiring two checkpoints to be reached before entering a valid deployment scenario on each of the four mechanical inhibits:
    - During each start-up of the microprocessor, the pins controlling the relay and burn-wires are put in a multiplexing receive mode (UART) that is inherently pulled LOW. This mode removes the MCU's hardware ability to pull the pin HIGH. Three, non-adjacent register bits must be flipped in order to configure each pin to general purpose input/output (GPIO) mode, and then to a fourth register to set it HIGH.

<u>Radiation analysis of software/hardware upset rate for deployment mechanism:</u>
SAMD21 single-event upset (SEU) cross-section hasn't been published in literature. However, we can use radiation data from the ST-16 supervisor processor to make a reasonably-educated comparison (ST-16 cross section for 105 MeV protons = 3.27e-14 cm2) [XX].

The prior SPENVIS simulation can then be used to calculate a particle fluence of about 100 protons/cm2 per second hitting SAMD21 die. Assuming an energy invariant cross-section: that's about one upset every 3e11 seconds.

- $\frac{86400\frac{seconds}{day}}{3x10^{11}\frac{seconds}{upset}} = 2.88e-7$ (1 in 3.4e6) probability of bit flip in a day

number required bit flips for deployment = 4+3(4) = 16

$(2.88x10^{-7})^{16} = 2.24x10^{-105}$ (1 in $4.46x10^{106}$) chance of SEU-induced burn-wire actuation via GPIO bit-flip over three-month mission

It's actually an even smaller chance because…

1. there's also a chance of flipping the bit BACK to its original state
2. the relay circuit must be engaged before the burn-wire transistors are energized
3. flight code will be monitoring the burn-wire register states for bit flips.

References:

K. Aaron et al., "Compendium of Recent Total Ionizing Dose Test Results Conducted by the Jet Propulsion Laboratory from 2003 through 2009," *IEEE Radiation Effects Data Workshop*, 2009.

G. Allen, "Compendium of Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory," *IEEE Radiation Effects Data Workshop*, 2008.

D. Cochran et al., "Total Ionizing Dose and Displacement Damage Compendium of Candidate Spacecraft Electronics for NASA," *IEEE Radiation Effects Data Workshop*, 2009.

G. Allen et al., "Heavy Ion Induced Single-Event Latchup Screening of Integrated Circuits Using Commercial Off-the-Shelf Evaluation Boards," *IEEE Radiation Effects Data Workshop*, 2016.

D. Cochran et al., "Compendium of Recent Total Ionizing Dose Results for Candidate Spacecraft Electronics for NASA," *IEEE Radiation Effects Data Workshop*, 2008.

O'Bryan et al., "Compendium of Recent Single Event Effects Results for Candidate Spacecraft Electronics for NASA," *IEEE Radiation Effects Data Workshop*, 2008.