Radiation-Mitigated Edge AI for Autonomous Space Operations

Course: SPCE 5400 – Small Satellite Engineering & Operations

Assignment: Project Outline (50 points)

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Table of Contents

Executive Summary

RAD-AI is a 6U CubeSat designed to test how commercial AI chips perform in LEO's radiation environment. We're building on ESA's Phi-Sat-1 (2020) and TRISAT-R (2022) while NASA's HPSC matures for deep-space use [1, 2].

The Problem: Autonomy is critical for *Artemis* and *Mars Sample Return* where communication delays hit 6-40+ minutes [3, 4]. Radiation-hardened processors are too slow; commercial AI chips deliver performance but fail in radiation [5, 6]. We urgently need empirical orbit data during this 2025-2027 window before HPSC becomes available [7].

Our Solution: RAD-AI tests a RISC-V processor with AI accelerator using Triple Modular Redundancy and selective shielding. Unlike Phi-Sat-1's static cloud detection, we demonstrate **real-time radiation event detection and autonomous mode switching** — the system detects high-radiation zones (South Atlantic Anomaly) and automatically adjusts processing to prevent corruption [8].

Market Validation: Cosmic Shielding's 2024 CubeSat demo of shielded Nvidia GPUs attracted commercial and military customers. AFRL partnerships show the market needs COTS+mitigation solutions NOW [9].

Impact: Provides flight data on COTS AI degradation and mitigation effectiveness, informing LEO constellation designs and HPSC integration strategies.

Bottom Line: $100,000–$120,000 development + free CSLI launch (valued at ~$250,000) [10]. Three years: design, build/test, flight ops.

Section 1 – Introduction

1.1 Mission Concept

RAD-AI validates COTS AI hardware with radiation mitigation in LEO, targeting a critical 2025-2027 gap. We explicitly build on:

- **Phi-Sat-1 (ESA, 2020):** First AI CubeSat with Intel Movidius for cloud detection [11, 12]
- **TRISAT-R (2022):** First fault-tolerant RISC-V in orbit [13, 14]
- **NASA HPSC (2021-2025):** Authoritative rad-hard solution providing 100x performance boost, first processors expected early 2025 [7, 15]

Our Differentiation:

1. **Radiation-aware autonomous computing** — AI detects and responds to radiation events in real-time, unlike Phi-Sat-1's static application [16]
2. **Timely validation** — COTS+mitigation data during 2025-2027, exactly when early HPSC adopters need integration guidance [17]
3. **Cost-effective bridge** — validates low-cost strategies for LEO missions that can't wait for HPSC [18]

We're coupling a RISC-V processor (SiFive U74) with FPGA-based AI acceleration, implementing TMR software mitigation and selective shielding [19, 20]. The system performs real-time vision while autonomously detecting radiation changes and logging degradation metrics.

1.2 Objectives

Primary: Demonstrate AI-driven autonomous computing with radiation-aware operation in LEO for 12 months.

Secondary:

1. Measure SEUs and TID accumulation on mitigated COTS hardware [21]
2. Validate real-time radiation detection and adaptive processing
3. Generate flight dataset for future designs and HPSC integration
4. Track AI accuracy degradation over time

Success Criteria:

- Minimum: 30 days operation with valid telemetry
- Baseline: Six months continuous data
- Full: Twelve months with demonstrated SAA adaptive behavior

1.3 Problem Validation

NASA's 2024 *Artemis* program identifies autonomous precision landing as cornerstone technology [3]. *Mars Sample Return* requires onboard hazard avoidance — impossible with 6-44 minute delays [4]. NASA's TA4 explicitly calls out "radiation-tolerant autonomy" as a critical gap [22].

The Capability Gap: RAD750 processors (~200 MHz, no AI) can't meet 10-30 Hz vision requirements [23]. NVIDIA Jetson delivers ~500 GFLOPS but fails beyond 20 krad (Si), with recent tests showing Orin "marginally sufficient for a three-year LEO mission" [24, 25]. That word "marginally" tells you everything.

HPSC and RAD-AI's Role: NASA's HPSC provides 100x performance improvement for deep-space missions [7, 15]. But a transition gap exists: near-term LEO constellations, commercial satellites, and university missions need solutions during 2025-2027. RAD-AI provides empirical data exactly when HPSC adopters design integration strategies — we're complementary bridge technology, not a competitor [26, 27].

Market Proof: Cosmic Shielding successfully demonstrated Jetson Orin NX with radiation shielding on Aethero CubeSat, proving long-duration operation [9]. AFRL actively partners for COTS mitigation [9]. OPTOS (2019) operated 3 years in LEO using COTS with collaborative hardening, showing "no System Error" and proving system reliability exceeds component reliability [28]. If OPTOS succeeded, we can build on their lessons.

1.4 Design Drivers

Orbit: 400–600 km LEO (CSLI-compatible), providing 6–10 SAA passes daily, yielding 5–10 krad TID/year [29]. Satisfies NASA's 25-year deorbit guideline [30].

Form Factor: 6U (20×10×34 cm, <14 kg) [31]: 1.5U AI payload, 1.5U power, 3U bus.

Power: ~36 W average (15–30 W AI peaks, ~2 W cameras, 20% margin). Solar arrays generate ~45 W BOL, 60 Wh Li-ion battery [32].

Duration: 12 months operational for statistical significance. 8–15 year orbital lifetime [33].

Section 2 – Process

2.1 Development Approach

Hybrid strategy: COTS 6U bus (Blue Canyon XACT-6U ~$80,000 [34]) with custom AI payload. Three units per CubeSat 101 [35]: Engineering Test Unit (find mistakes early), FlatSat (software dev), two Flight Units (redundancy).

2.2 Subsystems

AI Payload (Custom):

Processing:

- SiFive U74 RISC-V quad-core (1.5 GHz) [36]
- FPGA AI accelerator (Lattice CrossLink-NX)
- TMR software, 2mm tantalum shielding, watchdog timers, EDAC [37, 38]

Sensors:

- Two 1W cameras (640×480) [39]

- RADFETs (TID tracking), Cosmic Ray Telescope (SEU correlation) [40]
- Temperature/voltage monitors

Innovation – Autonomous Adaptation:

1. Real-time radiation detection (<1 min latency analyzing RADFET + orbital position)
2. Autonomous modes: Normal (10 Hz AI), Protected (3 Hz + increased TMR during SAA), Safe (minimal processing if upsets spike)
3. Continuous performance logging for post-mission analysis

Technical implementation: <10 MB ML model for star-field tracking, radiation classifier trained on SPENVIS data [29], state machine with hysteresis to prevent mode thrashing.

Spacecraft Bus (COTS):

- **ADCS:** Magnetorquers, nano star tracker (~1W), gyros, sun sensors [39, 41]
- **C&DH:** ARM Cortex-M4 (isolated from AI payload), 2×64GB redundant storage [42]
- **Comms:** UHF transceiver (8W, 9600 bps), deployable antenna, amateur radio compatible
- **Power:** GaAs solar (~30% efficiency), 60 Wh Li-ion, autonomous load shedding [32]

Ground Segment:

- Primary: University UHF station (we control it)
- Secondary: SatNOGS global network (free backup) [43]
- Cloud: AWS storage/processing (~$5k/year) [44]
- Ops: Automated monitoring, weekly uplinks, daily downloads (target 100 MB/day)

Testing:

- Environmental: 14.1 Grms vibration, -40°C to +60°C thermal-vac, EMI/EMC per NASA GEVS [45]
- Radiation: Proton beam at LBNL (~$2,500/day) [46], up to 30 krad TID, SEU cross-section [47]
- Software: HIL sim with radiation injection, Monte Carlo TMR analysis, end-to-end FlatSat scenarios
- Timeline: All testing complete 1 month before review [35]

2.3 Mission Operations

Phase 1 (Weeks 1-4): Commissioning — activate subsystems, calibrate sensors, establish AI baseline, validate ground links.

Phase 2 (Months 2-4): Characterization — normal ops with full AI, document SAA passages, validate mitigation, refine baselines.

Phase 3 (Months 5-12): Science ops — continuous autonomous operation, periodic algorithm updates, long-term degradation tracking, comparative radiation zone analysis.

Data Products: Real-time telemetry (radiation, AI metrics, mode transitions), science data (images, inference results, error logs), post-mission degradation curves.

2.4 Key Risks

Following CubeSat 101: "Budget includes 10%+ reserve" [35, Ch. 2, p. 17]. We're using 20%.

CSLI Compliance: No pyrotechnics, RF license within 30 days of manifesting, Benefits NASA autonomy tech, Accessible testing facilities [35].

Section 3: Launch & Budget

3.1 Launch Models

Primary: NASA CSLI — Free LEO access via NASA-procured vehicles [35]. Tech demos comprise 66% of selections [35, Ch. 1]. Annual solicitation (March-April), notification ~6 months later, manifesting 1-3 years out. Value: ~$250,000 [10].

Backup Options: ORS/NRO rideshares (low cost with CSLI), commercial brokers ($50k-$100k if self-funded), ISS deployment (~$90k/U, lower altitude limits radiation exposure).

3.2 Budget

3.3 Funding Strategy

Primary: NASA CSLI — RAD-AI scores well on selection criteria: Benefits NASA (Artemis/MSR autonomy, HPSC data), Feasible (proven subsystems, realistic schedule), High merit (addresses TA4 gap [22]), Flexible (any LEO orbit). **Estimated selection probability: 55-65%** based on strong NASA alignment, honest heritage acknowledgment, and technical feasibility.

Supplemental Sources:

- **NASA STMD Grants:** STRG ($50k-$150k/award) [49], Flight Opportunities
- **DoD/AFRL:** University Nanosat ($50k-$100k) [50], SBIR if commercialization identified
- **University:** Research seed grants ($10k-$30k), alumni sponsorship, in-kind support (lab/faculty/ground station)
- **Industry:** SiFive educational licensing (~$10k value) [36], Blue Canyon/AAC educational pricing (10-20% off), NVIDIA/Google dev kit donations, Cosmic Shielding partnership potential

Section 4: Strategic Positioning

Why Now? HPSC targets deep-space missions, but near-term LEO needs exist during 2025-2027: HPSC first processors (2025) → early adopter integration planning (2025-2026) → first HPSC missions in dev (2026-2027) → RAD-AI ops (2025-2027, perfectly timed). Cosmic Shielding's 2024 success attracted "new customers" [9]. AFRL partnerships confirm market demand [9].

Cost Context: RAD-AI (~~$120k) provides empirical data at 1-2% the cost of HPSC development (~~$50M NASA contract [51]) — ideal for university and commercial LEO missions.

Unique Contribution: First demonstration of *adaptive radiation-aware AI computing* that autonomously adjusts based on real-time environment — critical for deep-space missions where ground intervention is impossible.

Conclusion & Next Steps

RAD-AI addresses validated NASA autonomy needs while providing pragmatic COTS+mitigation data during the critical 2025-2027 HPSC transition. It's technically feasible (proven heritage), well-timed (confirmed market demand), appropriately scoped (realistic for masters project), mission-aligned (supports Artemis/MSR), and complementary (not competing with HPSC).

Immediate (Weeks 1-6):

1. Finalize CSLI application
2. Initiate university funding requests
3. Contact industry partners (SiFive, Cosmic Shielding)
4. Begin AI algorithm/mitigation trade studies

Development (Months 7-30): PDR (7-10) → CDR (11-16) → Integration/Test (17-24) → FRR (25-30)

Operations (Months 31-42): Commissioning → Science ops → Analysis/publication

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