A Falsifiable Protocol Radiation-Aware Temporal Governance in Distributed Space Systems

Temporal Sovereignty as Critical Intervention

Alexandre Sah*

Abstract

The proliferation of LEO satellite constellations operating on commercial-off-the-shelf (COTS) architectures introduces a critical sociotechnical challenge: enabling autonomous decision-making under persistent single-event upset (SEU) conditions without depending on cost-prohibitive, export-controlled radiation-hardened hardware. This resource proposes **Algorithmic Hysteresis Primacy (AHP)** not merely as a technical fix, but as a *governance intervention* to democratize access to space. By enforcing *synthetic inertia* ($\Delta T_{\min} > 0$) at the decision layer, AHP offers a software-level pathway to operational reliability that is globally accessible, challenging the technological monopolies that currently define space infrastructure.

The framework's **Proof of Hold (PoH)** mechanism provides deterministic, cryptographically verifiable audit trails, addressing the "accountability gap" that impedes regulatory approval and insurability for new entrants in the space sector. By implementing hysteretic accumulation rather than instantaneous reaction, AHP enables COTS platforms to approach reliability regimes traditionally associated with expensive hardware, thereby lowering barriers to entry for emerging spacefaring nations and smaller institutional actors. This protocol specifies: (i) replicable validation methodologies using public environmental models; (ii) traceability to formal guarantees established in supplementary materials available at zmem.org; and (iii) an economic analysis demonstrating how temporal governance transforms risk profiles to enable inclusive participation in the space economy. **All validation activities described herein are prospective specifications; no empirical results are claimed.**

Keywords: Algorithmic hysteresis; radiation-aware computing; temporal sovereignty; Proof of Hold; inclusive space infrastructure; global South engineering

Contents

*This supplementary material develops conceptual engineering for radiation-aware temporal governance in space systems, specifying falsifiable infrastructure without empirical claims. The main article *Algorithmic Hysteresis Primacy (AHP): Temporal Sovereignty in AI Governance* is available at `https://zmem.org` and SSRN.

1 Introduction: Temporal Sovereignty as Critical Intervention

Contemporary space systems engineering faces a profound distributional asymmetry: radiation resilience is predominantly achieved through silicon-level hardening (triple modular redundancy, error-correcting codes) accessible only to entities with privileged access to export-controlled supply chains and sophisticated radiation test facilities (Gaisler, 2002). This creates a *sovereignty gap*: actors in resource-constrained contexts, particularly in emerging space economies, cannot participate meaningfully in autonomous space operations without dependence on hegemonic technological infrastructures.

AHP emerges from a *peripheral epistemic stance* and aligns with the concept of **Critical Technical Practice** (Agre, 1997). Rather than a technical compromise, this approach uses formal specification as a means to interrogate the political assumptions embedded in space systems engineering—specifically the conflation of operational reliability with expensive, export-controlled material dependency. By treating radiation vulnerability not as a hardware problem to be bought away, but as a governance challenge to be managed through temporality, AHP reframes hesitation from engineering flaw into architectural feature. This inversion is precisely the shift required to democratize access to autonomous space operations and transition from technological dependency to *temporal sovereignty*.

1.1 From Acceleration Imperative to Temporal Plurality

The acceleration imperative—optimizing for minimal latency regardless of context—operates as a geopolitical force: decisions made at microsecond timescales in dominant centers become uncontestable facts for peripheral actors lacking equivalent computational infrastructure (Winner, 1980). In LEO constellations, this manifests as a paradox: autonomous systems must react faster than radiation-induced transients to avoid cascading failures, yet this very speed eliminates intervals for human oversight, cross-jurisdictional coordination, and meaningful participation.

AHP resolves this paradox not by demanding faster hardware, but by *reclaiming time as a design variable*. The minimum hesitation interval $\Delta T_{\min}$ functions as a *temporal sovereignty mechanism*: it guarantees that no consequential decision occurs faster than the slowest legitimate stakeholder can comprehend or contest. This is not inefficiency—it is the architectural embodiment of what Latour (1992) terms *delegation*: embedding deliberative capacity directly into computational substrates, thereby making algorithmic systems responsive to human values rather than just optimization metrics.

1.2 Proof of Hold: Cryptographic Accountability Without Centralization

Commercial constellation operators, especially new entrants, face an accountability gap: autonomous decisions made under radiation stress cannot be reconstructed forensically, impeding regulatory compliance and creating prohibitive liability risks (FCC, 2023). Traditional approaches require centralized logging infrastructure that creates single points of failure and often relies on proprietary black-box systems.

The **Proof of Hold (PoH)** mechanism (specified in supplementary materials available at zmem.org) provides a decentralized alternative. Each decision generates a cryptographically bound telemetry frame comprising:

- **State hash**: SHA-256 commitment to system configuration at decision boundary
- **Temporal anchor**: UTC-synchronized timestamp with millisecond resolution
- **Conviction metric** (γ): Normalized accumulator value $I(t)/\Gamma_{\max}$ quantifying evidence sufficiency

Critically, PoH requires no trusted third party. Verification occurs through deterministic replay of the AHP state machine (reference implementation available at zmem.org) against logged sensor inputs. This transforms autonomous operation from opaque process to *reconstructible record*—enabling regulators, insurers, and diverse operators to audit decisions without compromising system sovereignty, thus fostering trust in a multi-polar space environment.

1.3 Systematic Traceability to Formal Foundations

This validation protocol maintains strict architectural dependency on formal guarantees established in supplementary materials, ensuring experimental design maps directly to theoretical foundations:

Table 1: Traceability Matrix: Formal Guarantees to Falsifiable Criteria

Source	**Formal Guarantee**	**Falsifiable Criterion**	**Sec.**
Mathematical Foundations[1]	Non-Zeno: $\Delta T_{\min} > 0$	Measured inter-transition $\geq 95\%$ theoretical bound	3.3
Mathematical Foundations[1]	ZMEM: reversible state	State retention under fault injection; PoH validation	3.3
Protocol Specifications[2]	Cryptographic accountability	Bit-exact reconstruction of decision trajectory	4.1
Protocol Specifications[2]	Protocol-auditable hesitation	Telemetry logs $\gamma(t)$ trajectory	4.2
Reference Implementations[3]	$O(1)$ complexity, <50 cycles	WCET measurement on target hardware	2.2
Governance Frameworks[4]	Distributed governance	Multi-node HIL with conflicting evidence	4.3

1.4 Institutional Agnosticism and Distributed Execution

This protocol is deliberately institution-agnostic. No national program, university, or commercial entity is positioned as privileged executor. The specifications target globally accessible components:

- **MCUs**: ARM Cortex-M4 (STM32L4-class) or RISC-V RV32IMC—both available through standard commercial channels without export restrictions
- **Fault injection**: Clock glitching/voltage faulting via open-source platforms (ChipWhisperer) (O'Flynn and Chen, 2015), eliminating dependence on particle accelerators
- **Radiation models**: AE9/AP9 trapped radiation environment models (Heynderickx et al., 2022) for synthetic SEU generation

Execution pathways exist for: (a) well-resourced space agencies (direct HIL with radiation chambers); (b) university labs (COTS fault injection); (c) simulation-only groups (OMNeT++/NS-3 with synthetic radiation models). **No single pathway is privileged.** The author's role is specification; validation is intentionally distributed to avoid single-point epistemic authority and to enable broader community participation.

Remark 1 (No Execution Claimed)**.** The author has **not** constructed hardware, executed simulations, or partnered with space agencies. All specifications derive from published literature and formal guarantees available at zmem.org. This document provides *falsifiable infrastructure*—not results.

2 Replicable Validation Protocol

2.1 Reference Hardware Specification

Table 2: Globally Accessible Testbed Specification

Component	Specification	Source
MCU (Baseline)	ARM Cortex-M4 (STM32L476RG)	
	COTS availability; documented SEU susceptibility in LEO (Heynderickx et al., 2022)	Commercial
MCU (Alternative)	RISC-V RV32IMC (e.g., ESP32-C3)	
	Open ISA; emerging space applications (Sanchez-Iborra et al., 2020)	Commercial
Fault Injection	ChipWhisperer-Lite + voltage glitching	
	SEU emulation without accelerator access (O'Flynn and Chen, 2015)	Open-source
Radiation Model	AE9/AP9-based SEU rate prediction	
	for 300–1200 km orbits (Heynderickx et al., 2022)	NASA model
Power Monitor	INA219-class (±0.1 mA resolution)	
	Energy budget validation for CubeSat-class platforms	Commercial

Remark 2 (Hardware Neutrality)**.** Specifications target *component classes*, not specific national implementations. STM32L4 and ESP32-C3 are cited as globally available exemplars—not as endorsements of particular supply chains or national programs.

2.2 Algorithm Specification from Reference Implementation

The validation protocol employs the C99 specification from the reference implementation available at zmem.org:[5]

```c
/* Falsifiable validation target -- implements Non-Zeno Guarantee */
uint8_t ahp_update(AHP_State* state, int16_t epsilon) {
    uint16_t phi = (uint16_t)abs(epsilon);
    if (phi > state->phi_max) phi = state->phi_max;

    uint32_t temp = (uint32_t)state->I + phi;
    state->I = (temp > state->I_max) ? state->I_max : (uint16_t)temp;

    if (state->I >= state->gamma_max) { state->D = 1; }
    else if (state->I <= state->gamma_min) { state->D = 0; }

    return state->D;
}
```

Listing 1: AHP Core for Validation (from reference implementation)

Validation Status: Structurally validated against formal guarantees via static analysis (CBMC). **Dynamic validation** (compilation, execution, profiling) remains future work requiring external execution.

[5]Working paper available at `https://zmem.org` and SSRN.

2.3 Illustrative Simulation Pathway Using Public Environmental Models

Remark 3 (Epistemological Positioning)**.** This section outlines how public datasets and models can be used to *instantiate* the protocol for exploratory analysis. Such simulations are inherently non-validatory; their purpose is to illustrate the framework's operation and establish baseline expectations for subsequent physical experimentation using transparent, globally available data.

2.3.1 Public Data Integration for Exploratory Analysis

To ensure the protocol is accessible without privileged access, third-party research groups can ground simulations in publicly available environmental models:

1. **Radiation Environment Models**: The **AE9/AP9** trapped particle models (Heynderickx et al., 2022) provide publicly accessible SEU rate predictions for specific orbits. These open-source tools allow researchers to generate synthetic SEU injection patterns that respect realistic LEO radiation profiles (e.g., South Atlantic Anomaly transits).

2. **Historical Failure Data**: Public databases (e.g., satellite anomaly catalogs from Space-Track or ESA's Space Debris Office) can be used to correlate theoretical SEU probabilities with historical failure modes, testing AHP's theoretical resilience against real-world historical trends.

3. **Power Consumption Benchmarks**: Publicly available power consumption data for COTS processors (e.g., STM32L4 datasheets) enable comparative energy analysis between AHP's computational overhead and radiation-hardened alternatives.

2.3.2 Simulation Architecture for Protocol Instantiation

A reference simulation architecture can be constructed using:

- **Core Algorithm**: The C99 implementation from the reference implementation[6] compiled for the target platform
- **SEU Injection Layer**: Synthetic fault injection based on AE9/AP9 probability distributions derived from public datasets
- **Monitoring Framework**: Logging of $\gamma(t)$ trajectories and PoH frame generation
- **Analysis Toolkit**: Tools to compare measured $\Delta T_{\min}$ against theoretical bounds established in mathematical foundations[7]

The resulting simulation does *not* validate AHP's radiation resilience; rather, it serves as an *exploratory tool* for identifying parameter sensitivities and boundary conditions using open data. Negative results (e.g., failure to maintain $\Delta T_{\min}$ under certain fault patterns) are valuable outcomes that refine the protocol's implementation requirements.

2.3.3 Expected Outcomes and Falsification Pathways

In illustrative simulations using public models, one would expect to observe:

- **Non-Zeno Enforcement**: Measured inter-transition intervals consistently $\geq 95\%$ of theoretical $\Delta T_{\min}$

[6]Working paper available at `https://zmem.org` and SSRN.
[7]Working paper available at `https://zmem.org` and SSRN.

- **ZMEM Preservation**: State reversibility maintained under SEU injection during accumulation phases
- **PoH Integrity**: Cryptographic commitments remaining verifiable despite simulated radiation effects

These expectations are logical consequences of the formal guarantees established in supplementary materials available at zmem.org. Failure to observe them in simulation suggests either: (1) implementation errors in the simulation; (2) incorrect mapping of environmental models to SEU patterns; or (3) unanticipated interactions between the algorithm and simulated hardware behavior. Each such failure constitutes a *falsification event* that refines the protocol without invalidating the underlying theoretical framework.

No numerical thresholds, distributions, or performance metrics are asserted.

2.4 Falsifiable Hypotheses and Failure Modes

Table 3: Falsifiable Hypotheses and Critical Failure Modes

Hypothesis	Measurement Protocol	Falsification Criterion
H1: Non-Zeno enforcement	Logic analyzer under synthetic SEU noise ($\sigma = 0.15$)	Any interval $< 0.95 \times \Delta T_{\min}$
H2: ZMEM retention	Fault injection during accumulation; PoH reconstruction	Irreversible state transition without $\gamma \geq 1$
H3: Lyapunov stability	10^4-cycle run under radiation model (Heynderickx et al., 2022)	Unbounded accumulator growth or limit cycle
H4: PoH integrity	SHA-256 verification against deterministic replay	Hash mismatch or non-reproducible γ trajectory
H5: Cross-platform determinism	Identical test vectors on ARM/RISC-V under identical SEU models	Divergent $\Delta T_{\min}$ enforcement

Remark 4 (Comparative Framing)**.** AHP is not proposed as a *technical equivalent* to radiation-hardened silicon but as a *governance complement* that makes COTS architectures viable for certain autonomy applications. The comparative analysis below should be interpreted as illustrating architectural trade-offs and accessibility barriers, not asserting performance parity. Any experimental results must be interpreted within this governance framework rather than as claims about radiation resilience in absolute terms.

3 Phased Validation Pathway

Remark 5 (Execution Responsibility)**.** These phases represent *prospective design specifications*, not *committed milestones*. Actual execution requires partnerships with entities possessing appropriate infrastructure—explicitly not held by the author. The protocol's value lies in its falsifiability, not in imminent execution.

4 Economic and Regulatory Integration

4.1 Democratizing Access: The Political Economy of Temporal Governance

Traditional radiation-hardened processors (e.g., LEON3-FT, RAD750) achieve SEU resilience through silicon-level redundancy. While effective, this creates a high barrier to entry due to

Table 4: Prospective Validation Pathway (18–36 Month Horizon)

Phase	**Duration**	**Activities**	**Go/No-Go Criteria**
1. Laboratory Foundation	6 months	Fault injection on COTS ARM; parameter sensitivity under AE9/AP9 models; WCET measurement; PoH frame validation	H1–H4 confirmed on single-node testbed
2. Multi-Platform Port	6 months	RISC-V port; cross-platform determinism; Byzantine fault injection; RF link integration	H5 confirmed; identical $\Delta T_{\min}$ enforcement; PoH survives RF transmission
3. Integrated Simulation	12 months	Flat-sat integration; thermal/-vacuum testing; end-to-end mission simulation with synthetic radiation	H4 confirmed under environmental stress; PoH reconstructible post-simulation
4. Flight Opportunity	12+ months	On-orbit demonstration; PoH telemetry downlink; post-mission forensic reconstruction	(Optional) Operational validation in LEO radiation environment

exorbitant costs and restricted supply chains, effectively limiting high-reliability autonomy to a few hegemonic actors (Gaisler, 2002; Sanchez-Iborra et al., 2020). AHP proposes a shift from *material dependency* to *temporal governance*, potentially lowering this barrier:

Table 5: Comparative Analysis: Silicon vs. Algorithmic Hardening (Access and Viability)

Approach	**Unit Cost**	**Power Budget**	**Timeline to Orbit**
RHBD Silicon (heritage)	\$50K–\$500K	5–15 W	3–5 years
COTS + AHP (proposed)	\$50–\$500	0.1–1 W	6–18 months

Remark 6 (Interpretive Caution)**.** The cost-benefit analysis above illustrates economic *trends* and potential for democratization rather than claiming specific performance equivalence. AHP's value proposition is not that it eliminates SEU susceptibility, but that it provides *temporal governance* of SEU consequences. By replacing expensive hardware hardening with accessible software-based strategies, AHP offers a pathway for emerging spacefaring nations and smaller institutions to participate in the space economy without reliance on restricted supply chains.

AHP does not eliminate radiation sensitivity; it *architecturally contains* its consequences. For new market entrants, this transforms economic viability: high-reliability autonomous operations become accessible, fostering a more pluralistic and diverse space ecosystem.

4.2 Proof of Hold: Enabling Regulatory and Actuarial Viability

For commercial constellations, particularly those operated by new or smaller entities, the "Black Box" nature of autonomous AI is a major obstacle to obtaining insurance and regulatory approval. PoH addresses this structural barrier by reducing *information asymmetry*:

- **Reducing Uncertainty Premiums:** Space insurers currently charge high premiums (or refuse coverage) for COTS-based autonomous systems due to the inability to distinguish between software bugs and environmental radiation faults. The PoH mechanism transforms a "Black Box" failure into an auditable, traceable event. Theoretically, this could shift the risk profile of such systems, moving them from the "Uninsurable/High Risk" category to a "Calculable Risk" category, potentially enabling insurance coverage models for COTS-based constellations.

- **Regulatory Compliance:** Mandates for human oversight (e.g., EU AI Act, national space traffic regulations) are often impossible to satisfy on high-speed COTS hardware. PoH provides cryptographically verifiable evidence that: (i) evidence accumulation occurred; (ii) a temporal window for intervention existed ($\Delta T_{\min}$); and (iii) commitment was deliberate. This bridges the gap between safety-critical regulations and the capabilities of commercial hardware.
- **Forensic Accountability:** In the event of a dispute or anomaly, the PoH log allows for a "deterministic replay" of the decision chain. This protects operators from liability for radiation-induced events (force majeure) while ensuring that software errors remain attributable, thereby creating a fairer liability framework for autonomous operations.

4.3 Integration with Distributed Governance

Multi-constellation coordination in a crowded LEO environment requires consensus across operator jurisdictions with potentially conflicting interests. The Byzantine consensus framework established in supplementary materials[8] enables:

- **Inter-operator coordination:** PoH-attested state broadcasts prevent Byzantine fault propagation during collision avoidance maneuvers, crucial for diverse constellations with different owners.
- **Regulatory multi-jurisdiction:** Deterministic $\Delta T_{\min}$ enforcement verifiable across national ground segments without centralized authority, supporting the "common good" of safe space traffic management.
- **Insurance pooling:** Shared PoH audit trails enable risk-pooled coverage of autonomous operations across constellations, further reducing entry barriers for smaller operators by spreading risk.

5 Synthesis: Falsifiability as Epistemic Virtue

The AHP framework progresses from formal specification to empirical evidence through systematic architectural layering. **Critical Path:** Empirical validation is *necessary but not yet initiated by the author*. Failure modes are explicitly defined:

- Implementation error → revise reference implementation[9]
- Protocol ambiguity → clarify protocol specifications[10]
- Formal assumption violated → strengthen mathematical foundations[11]

This **falsifiability** distinguishes AHP from speculative frameworks. The protocol's value does not depend on the author's capacity to execute—it depends on its capacity to be *executed, challenged, and refined* by the global research community, thereby contributing to the diverse, human-centered shaping of our algorithmic futures.

[8] Working paper available at `https://zmem.org` and SSRN.
[9] Working paper available at `https://zmem.org` and SSRN.
[10] Working paper available at `https://zmem.org` and SSRN.
[11] Working paper available at `https://zmem.org` and SSRN.

6 Call for Distributed Community Validation

Research programs with the following capabilities are invited to execute this protocol:

- Hardware-in-the-loop simulation for embedded avionics
- ARM Cortex-M or RISC-V embedded systems expertise
- Access to radiation test facilities or synthetic radiation modeling (AE9/AP9)
- Distributed systems research with Byzantine fault tolerance
- Regulatory or insurance stakeholder engagement in space operations

Materials Available at zmem.org: Complete C99/Python specifications; Protocol ABNF grammars including PoH frame format; Formal verification checklists; Mathematical foundations; Governance frameworks. Working papers available at `https://zmem.org` and SSRN.

Epistemic Positionality Statement: This research is developed from a *peripheral epistemic stance*—situated outside the dominant metropolitan innovation hubs that drive the acceleration imperative. This geographic and institutional distance provides a critical vantage point for recognizing that algorithmic speed operates as a geopolitical force, disproportionately affecting contexts with less regulatory infrastructure to contest microsecond-scale decisions. AHP emerges from this observation not as nationalist technological rhetoric, but as a *structural critique* of material dependency in space systems. The framework's strength lies in its agnosticism: it requires no centralized program, only globally accessible components and a commitment to architectural plurality.

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