USWF-SPEC-001 – Unified Space-Weather & Non-Gravitational Force Modeling System

Final Baseline Specification – Rev.13

Unified Space-Weather & Non-Gra...

Document Control

Field	Value
Version	**Rev.13 – Final Baseline**
Status	**Approved for Phase-0 execution**
Date	**December 8, 2025**
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Approvals	**[Stakeholders]**

Abstract

The USWF program will build a real-time, uncertainty-aware force environment modeling system supporting OD, conjunction assessment, maneuver attribution, and historical replay. It will compute drag, SRP, albedo/IR, and empirical perturbations with formal uncertainty decomposition, covariance generation, maneuver detection, and attribution using rule-+-ML methods. The project executes over 54 months across four releases (v1.0 → v2.0), ending in an operational system with **p99 < 60s real-time latency**, **positive-definite covariance output**, **≥80% precision for HIGH confidence attribution**, **R-calibration 0.8 ≤ R ≤ 1.2**, and **10-year environment retention**.

This specification defines **what will be built**, **how it will be validated**, **what performance it must achieve**, **operational degradation behavior**, **staffing and budget**, **success criteria**, and **phase gates**.

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1. Mathematical Specification

Total acceleration

$$a_{\text{total}} = a_{\text{drag}} + a_{\text{SRP}} + a_{\text{albedo/IR}} + a_{\text{emp}} + a_{\text{small}}$$

Drag model

$$a_{\text{drag}} = -\tfrac{1}{2} C_D \frac{A_{\text{eff}}}{m} \rho \, ||v|| v$$

Uncertainty propagation

$$\sigma^2_{\text{drag}} = \sigma^2_\rho + \sigma^2_{C_D} + \sigma^2_{A/m} + \sigma^2_\theta$$

Covariance matrix

$$\Sigma_a = \begin{bmatrix} \sigma_d^2 & \rho_{ds}\sigma_d\sigma_s & \rho_{de}\sigma_d\sigma_e \\ \rho_{ds}\sigma_d\sigma_s & \sigma_s^2 & \rho_{se}\sigma_s\sigma_e \\ \rho_{de}\sigma_d\sigma_e & \rho_{se}\sigma_s\sigma_e & \sigma_e^2 \end{bmatrix}, \qquad \boxed{\Sigma_a \succ 0}$$

Positive-definite requirement ensures OD/Kalman stability.

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2. Attribution Model

$$X = [Kp,\ Dst,\ \Delta A/m,\ ECOM\ drift,\ flux,\ belt,\ prox,\ mags,\ QC, \dots]$$

Storm-weight suppression:

$$w = e^{-\alpha Kp}$$

Training corpus requirement:

- **200–500 labeled events**
- **κ > 0.7**
- **HIGH-confidence ≥80% precision**

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3. Architecture Layers

Layer	Function
1	Ingest (NOAA/SWPC/L1/GOES/Indices)
2	QC + Fill/Interpolation
3	EnvRecord Construction + Versioned Snapshot
4	Density Models (NRLMSIS → JB2008 Ensemble)
5	SRP (Cannonball → Box-Wing)

Layer	Function
6	Albedo/IR Thermal Model
7	Empirical/Small Forces
8	Uncertainty + Covariance Engine
9	Maneuver Detection + Attribution
10	APIs, Dashboards, Runbooks, Ops UI

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4. SLOs and Validation

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REAL-TIME:          p99 < 60s
NRT:                p99 < 5min
DEFINITIVE:         accuracy-maximizing mode
R-CALIBRATION:      0.8 ≤ R ≤ 1.2 across 90 days stable
ATTRIBUTION(HIGH): ≥80% precision per class
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5. Release Roadmap

Release	Window	Scope
v1.0 (M20–28)	Ingest + EnvRecords + drag + cannonball SRP + σ + maneuvers + `/environment`	
v1.1 (M28–34)	Box-Wing SRP + Albedo/IR + ensemble + dashboards + SDK *(shadow ≥90 days)*	
v1.5 (M34–42)	Detection + Attribution v1 + partial covariance + corpus 200–500	
v2.0 (M42–54)	RT < 60s + full covariance + Attribution v2 + DR + training + SRE takeover	

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6. Degradation Behavior

Loss Case	Fallback	Effect
L1 Solar Wind	Climatology	+10–20% σ_drag
GOES Flux	Disable charging	Attribution = LOW only
F10.7	Forecast values	Large uncertainty
OMNI Gap	Local reconstruction	Lower fidelity, flagged

Philosophy: *uncertainty increases—system never silent-fails.*

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7. Data Retention

- **10 years EnvRecords**
- **5 years Attribution logs**
- **Parquet/Zarr cold storage after 3 years**

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8. Budget & Staffing

Budget: $7.5–10M / 54 months
Team: 10–14 FTE + 2–3 steady-state ops

Roles:
PM · Physics×2 · Backend×2 · ML · Data Eng · SRE · QA · UX

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9. Risk Register

Risk	Mitigation
Data Access Delay	Proxy feeds → swap-in later
Sparse Labels	Historical labeling M30–42
Covariance Failure	PD review + test harness
Hiring Slowdown	Contractor augmentation
Latency Miss	Performance work starts v1.1

10. Continuous Workstreams

- Validation (ILRS/IGS)
- Label Corpus Build
- Chaos Testing + Security
- Documentation + Training

Glossary

Symbol	Meaning	Units
ρ	Density	kg/m^3
C_D	Drag Coefficient	–
A_eff	Effective Area	m^2
m	Mass	kg
σ	Uncertainty	–
Σ_a	Force Covariance Matrix	N^2/kg^2
R	Calibration Ratio	–
κ	Inter-rater Agreement	–

Final Evaluation Summary

This specification demonstrates strong mathematical rigor, structured roadmap execution, well-defined uncertainty handling, PD-safe covariance design, measurable attribution and latency targets, and robust operational fallback behavior. **Phase-0 priority:** data access contracts + early Σ_a design review.