

Supplementary Material S1: SENTINEL-HS synthetic verification

Detailed methods, robustness results and reproducibility index for the Acta Astronautica submission

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S1. Scope and interpretation

This supplement accompanies the Acta Astronautica submission of the manuscript. It provides the full operating-point, robustness and generator details behind the synthetic verification study; it does not turn those results into evidence of operational effectiveness, spacecraft reliability or regulatory acceptance.

S2. Full recall-burden operating points

Supplementary Table S1a. Recall and precision across the declared burden grid.

Target burden (%)	Imagery recall	Arithmetic same recall	Arithmetic opt. recall	Multiplicative recall	Imagery precision	Arithmetic same precision	Arithmetic opt. precision	Multiplicative precision
2.5	12.68	27.35	26.87	20.89	14.80	32.24	30.59	24.29
5.0	22.94	42.07	42.19	38.51	12.98	23.93	24.31	21.83
7.5	31.03	51.28	51.97	50.72	11.83	19.62	20.35	19.13
10.0	37.77	59.03	61.40	59.12	10.78	16.91	17.56	16.77
12.5	44.49	64.07	67.47	65.77	10.22	14.72	15.61	15.15
15.0	50.03	68.81	72.51	71.54	9.55	13.17	14.05	13.74
20.0	60.39	76.37	80.84	79.02	8.66	11.04	11.67	11.50
25.0	67.98	81.25	86.01	84.50	7.87	9.44	9.97	9.84
30.0	74.65	85.16	90.25	88.64	7.22	8.24	8.75	8.55

Supplementary Table S1b. Frozen calibration thresholds and pairwise recall differences.

Target (%)	Imagery threshold	Arithmetic same threshold	Arithmetic opt. threshold	Multiplicative threshold	vs imagery (pp)	vs arithmetic same (pp)	vs arithmetic opt. (pp)
2.5	0.4885	0.4454	0.4095	0.5568	8.21	-6.46	-5.98
5.0	0.4503	0.4204	0.3869	0.5094	15.57	-3.57	-3.68
7.5	0.4279	0.4045	0.3728	0.4823	19.69	-0.55	-1.24
10.0	0.4105	0.3920	0.3609	0.4626	21.35	0.09	-2.28
12.5	0.3959	0.3821	0.3522	0.4474	21.28	1.70	-1.70
15.0	0.3829	0.3733	0.3444	0.4343	21.51	2.74	-0.97
20.0	0.3618	0.3584	0.3308	0.4134	18.63	2.65	-1.82
25.0	0.3443	0.3461	0.3197	0.3955	16.52	3.24	-1.52

Target (%)	Imagery threshold	Arithmetic same threshold	Arithmetic opt. threshold	Multiplicative threshold	vs imagery (pp)	vs arithmetic same (pp)	vs arithmetic opt. (pp)
30.0	0.3284	0.3349	0.3097	0.3801	13.99	3.47	-1.61

S3. Mission-specific calibration and action use

Supplementary Table S2. Mission-specific thresholds frozen on mission-stratified calibration data and evaluated on held-out states.

Mission	States	Critical	Imagery threshold	Imagery burden	Imagery recall	Multiplicative threshold	Multiplicative burden	Multiplicative recall	Difference (pp)
Wildfire response	51,138	1,117	0.4005	10.19	36.97	0.4478	9.86	59.80	22.83
Border and maritime surveillance	49,596	1,788	0.4365	9.97	35.29	0.4782	10.25	53.13	17.84
Critical-infrastructure protection	49,266	1,442	0.3866	9.94	39.11	0.4597	10.48	64.22	25.10

Supplementary Table S3. Default multiplicative action-state utilisation in the held-out test.

Action state	Share (%)
A0 Accept	27.226
A1 Verify	62.555
A2 Re-task/fuse	9.070
A3 Escalate	0.894
A4 Withhold/alternate	0.255

S4. Thirty-seed stability

Supplementary Table S4a. Distributional summary across 30 independent held-out seeds.

Metric	Statistic	Imagery baseline	Arithmetic same	Arithmetic optimised	Default multiplicative
Recall (%)	Mean	37.50	57.79	60.24	58.17
Recall (%)	SD	1.26	1.38	1.18	1.33
Recall (%)	Minimum	34.88	55.69	57.79	55.49
Recall (%)	Maximum	39.57	61.00	62.33	61.07
AURB	Mean	0.460	0.615	0.647	0.624
AURB	SD	0.008	0.009	0.009	0.009
AURB	Minimum	0.444	0.594	0.631	0.597

Metric	Statistic	Imagery baseline	Arithmetic same	Arithmetic optimised	Default multiplicative
AURB	Maximum	0.478	0.631	0.665	0.637
AUROC	Mean	0.805	0.872	0.895	0.883
AUROC	SD	0.004	0.004	0.004	0.004
AUROC	Minimum	0.794	0.862	0.888	0.871
AUROC	Maximum	0.813	0.880	0.903	0.890
AUPRC	Mean	0.103	0.245	0.249	0.172
AUPRC	SD	0.004	0.012	0.012	0.007
AUPRC	Minimum	0.095	0.217	0.224	0.156
AUPRC	Maximum	0.114	0.273	0.274	0.187

Supplementary Table S4b. Seed-level recall and discrimination metrics. Full 22-column output is in outputs/multi_seed.csv.

Seed	Critical (%)	Imagery recall	Arithmetic same	Arithmetic opt.	Multiplicative	Difference vs imagery	Multiplicative AUROC	Multiplicative AUPRC
20261814	2.936	36.24	56.74	59.20	56.95	20.71	0.883	0.173
20262823	2.816	38.71	57.60	62.22	57.88	19.18	0.888	0.166
20263832	2.878	37.53	59.90	61.57	61.01	23.49	0.885	0.174
20264841	2.850	37.05	59.09	59.16	58.81	21.75	0.885	0.171
20265850	2.892	37.97	61.00	61.41	61.07	23.10	0.888	0.173
20266859	2.842	38.56	57.99	60.31	58.27	19.70	0.885	0.170
20267868	2.846	38.02	56.78	59.73	56.64	18.62	0.880	0.171
20268877	2.910	35.95	56.98	59.18	58.14	22.20	0.881	0.172
20269886	3.022	36.93	57.84	60.16	58.37	21.44	0.881	0.180
20270895	2.974	39.54	58.10	58.71	58.31	18.76	0.887	0.181
20271904	3.020	36.62	56.16	59.01	57.48	20.86	0.880	0.174
20272913	3.046	36.24	57.52	60.80	58.83	22.59	0.887	0.180
20273922	2.950	36.88	57.76	59.53	57.90	21.02	0.880	0.171
20274931	2.922	37.03	57.97	60.10	58.45	21.42	0.887	0.178
20275940	2.890	34.88	55.78	57.79	56.82	21.94	0.881	0.161
20276949	3.058	38.65	60.56	62.07	59.12	20.47	0.890	0.187
20277958	2.852	39.34	59.89	61.43	60.59	21.25	0.883	0.171
20278967	2.986	37.11	58.07	61.02	57.00	19.89	0.878	0.177
20279976	2.834	38.60	59.77	60.27	59.92	21.31	0.885	0.166
20280985	2.708	38.55	57.83	62.33	57.83	19.28	0.882	0.160
20281994	2.982	39.57	57.01	59.89	57.14	17.57	0.880	0.171

Seed	Critical (%)	Imagery recall	Arithmetic same	Arithmetic opt.	Multiplicative	Difference vs imagery	Multiplicative AUROC	Multiplicative AUPRC
20283003	3.012	36.59	57.57	60.69	58.10	21.51	0.886	0.180
20284012	2.888	36.77	56.72	61.08	57.83	21.05	0.882	0.169
20285021	2.914	35.35	57.52	59.85	58.54	23.20	0.883	0.169
20286030	2.962	36.80	57.66	61.44	58.54	21.74	0.884	0.174
20287039	2.826	38.36	56.33	59.59	56.12	17.76	0.881	0.163
20288048	3.024	36.38	55.69	58.93	56.61	20.24	0.880	0.176
20289057	2.850	39.37	58.95	61.33	59.02	19.65	0.885	0.173
20290066	2.862	37.04	56.11	58.56	55.49	18.45	0.871	0.156
20291075	2.944	38.25	56.93	59.99	58.29	20.04	0.881	0.176

S5. Parameter and critical-label sensitivity

Supplementary Table S5a. Score-parameter and critical-cutoff robustness summaries.

Analysis	Median	5th percentile	95th percentile	Positive advantage (%)	Interpretation
Score parameters (300)	21.01	17.17	24.46	100.0	Weights and interactions varied
Critical cutoffs (500)	18.58	6.97	30.14	100.0	Each cutoff independently $\times$ U(0.8, 1.2)
Critical prevalence (500)	3.37	1.58	6.09	-	Percentage of held-out states

Supplementary Table S5b. Fusion-rule ordering across the 500 critical-cutoff configurations.

Comparison	Configurations with positive default advantage (%)	Median difference (pp)	5th percentile	95th percentile
Default multiplicative vs imagery baseline	100.0	18.58	6.97	30.14
Default multiplicative vs same-weight arithmetic	43.4	-0.42	-3.14	4.23
Default multiplicative vs optimised arithmetic	37.4	-2.72	-12.48	8.99

S6. Secondary consequence-translation sensitivity

Supplementary Table S6. Common scaling of stipulated action effects. The zero-effect case produces no policy difference by construction.

Action-effect scale	Imagery expected outcome (%)	Multiplicative expected outcome (%)	Absolute difference (pp)	Relative difference (%)
0.00	35.480	35.480	0.000	0.000
0.25	35.461	33.660	1.801	5.079
0.50	35.442	31.840	3.602	10.163
0.75	35.423	30.020	5.403	15.253
1.00	35.403	28.199	7.204	20.349
1.15	35.392	27.107	8.285	23.409
1.30	35.380	26.027	9.354	26.437

S7. Integrity-fault results

Supplementary Table S7. Fault-response sensitivity across assumed integrity-monitor detection rates.

Fault	Monitor detection (%)	Attacked critical	Weak action, no response (%)	Weak action, protected (%)	Fail-safe escalation (%)
Timestamp rollback	70	1,514	91.48	25.96	70.26
Timestamp rollback	85	1,514	91.48	14.00	84.76
Timestamp rollback	95	1,514	91.48	3.63	94.90
Confidence inflation	70	1,490	72.62	21.68	69.79
Confidence inflation	85	1,490	72.62	10.81	84.99
Confidence inflation	95	1,490	72.62	3.69	94.96
Stale-cache replay	70	1,486	95.90	30.55	70.09
Stale-cache replay	85	1,486	95.90	13.39	85.23
Stale-cache replay	95	1,486	95.90	4.10	95.18

S8. Generator and temporal-process specification

The complete machine-readable specification is in outputs/parameter_manifest.json. Key declared values are reproduced below so that the manuscript and supplement can be understood without executing the code.

Supplementary Table S8. Machine-readable generator and stress-process entries (complete JSON supplied separately).

Parameter path	Declared value
generator.scenario_probabilities.Wildfire response	0.34

Parameter path	Declared value
generator.scenario_probabilities.Border and maritime surveillance	0.33
generator.scenario_probabilities.Critical-infrastructure protection	0.33
generator.mode_probabilities.Optical	0.32
generator.mode_probabilities.SAR	0.27
generator.mode_probabilities.Thermal	0.16
generator.mode_probabilities.Fused	0.25
generator.age_hours.family	lognormal
generator.age_hours.scenario_medians_h	[1.6, 4.5, 7.0]
generator.age_hours.log_sigma	0.75
generator.age_hours.clip_h	[0.05, 72]
generator.timeliness_transform_tau_h	[3.5, 9.0, 16.0]
generator.cloud.family	beta
generator.cloud.shape	[2.1, 3.5]
generator.cloud.wildfire_offset	0.08
generator.image_quality.Optical	$0.62 * \text{cloud} + 0.18 * \text{Beta}(2,5)$
generator.image_quality.SAR	$0.15 * \text{cloud} + 0.28 * \text{Beta}(2,4)$
generator.image_quality.Thermal	$0.25 * \text{cloud} + 0.30 * \text{Beta}(2,4)$
generator.image_quality.Fused	$0.20 * \text{cloud} + 0.14 * \text{Beta}(2,5)$
generator.provenance.base	$\text{Beta}(1.5,7)$
generator.provenance.anomaly	$0.18 * \text{Bernoulli}(0.08)$
generator.task_relevance.base	$\text{Beta}(2.0,5.5)$
generator.task_relevance.scenario_offsets	[0.03, 0.08, 0.12]
generator.model_uncertainty.base	$\text{Beta}(2.2,5.2)$
generator.model_uncertainty.scenario_offsets	[0.04, 0.07, 0.09]
generator.model_uncertainty.fused_offset	0.03
generator.delivery_continuity.base	$\text{Beta}(1.7,7)$
generator.delivery_continuity.outage	$0.25 * \text{Bernoulli}(0.10)$
generator.delivery_continuity.border_maritime_offset	0.1
generator.observation_noise_sd.Timeliness	0.035
generator.observation_noise_sd.Image quality	0.05
generator.observation_noise_sd.Provenance	0.04
generator.observation_noise_sd.Task relevance	0.045
generator.observation_noise_sd.Model uncertainty	0.055
generator.observation_noise_sd.Delivery continuity	0.045

Parameter path	Declared value
temporal_stress_process.mission_episode_probability	0.52
temporal_stress_process.start_step	DiscreteUniform(18, steps-24)
temporal_stress_process.duration_steps	DiscreteUniform(5,13)
temporal_stress_process.type	DiscreteUniform(0,2)
temporal_stress_process.amplitude	Uniform(0.28,0.50)
temporal_stress_process.paired_dimension_multipliers	[0.8, 0.85, 0.9]

S9. Reproducibility file index

Supplementary Table S9. Structure of the reproducibility archive. SHA-256 checksums for every distributed file are listed in SHA256SUMS.txt.

Category	Representative contents and purpose
Governance and metadata	README.md; CITATION.cff; zenodo.json; code and data licences; validation, revision and citation-audit reports; SHA256SUMS.txt.
Manuscript	Acta Astronautica main manuscript and Supplementary Material S1 in editable DOCX and rendered PDF formats.
Code	Synthetic-state generation, comparator calibration, robustness analysis, figure generation, manuscript construction and journal-specific preparation scripts.
Machine-readable outputs	Parameter manifest; calibration and held-out summaries; seed, cutoff, ablation, temporal, integrity-fault and consequence-sensitivity outputs; released state sample.
Figure sources	Figures 1-10 in high-resolution raster and vector formats, together with the figure manifest and source tables.
Editable equations	Office Math XML fragments and equation-source notes used to preserve editable mathematical content.

S10. Reproduction commands

```

pip install -r requirements.txt
python code/simulate_v6.py
python code/make_figures_v6.py
python code/build_manuscript_v6.py
python code/polish_manuscript_v7.py
python code/build_supplement_v7.py

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Calibration seed: 20260701. Primary held-out test seed: 20260805. The 30-seed and parameter-sensitivity analyses are generated by simulate_v6.py. Journal-specific Acta Astronautica files are supplied in manuscript/. The journal-preparation scripts are retained as provenance for formatting and framing changes, not as a portable numerical reproduction step.