From CFD to a thermal RC model

Reduced-order modeling of four satellite electronics boards

Geometry. Heat paths. Stored energy.
A traceable numerical comparison.

16 STATES PER BOARD

COMMS withheld transient: 720 s
Temperature RMSE: 0.123 K

RMSE uses all 16 states and equally weighted saved samples.
Numerical model study; no hardware or flight correlation.

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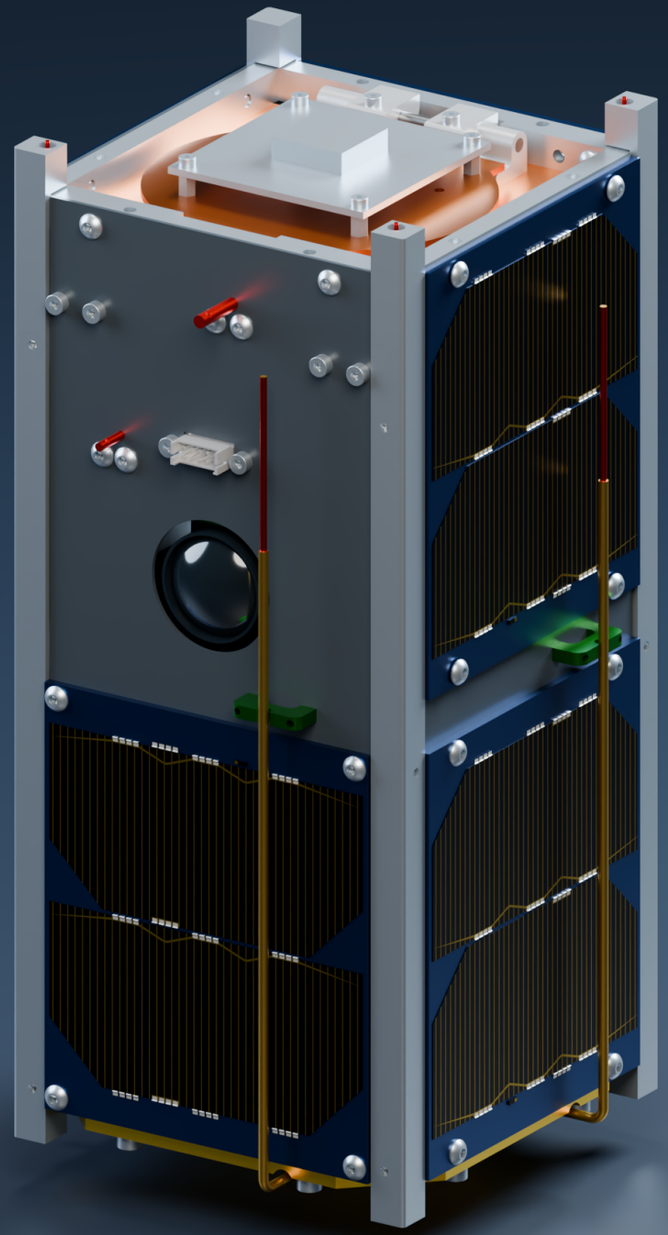
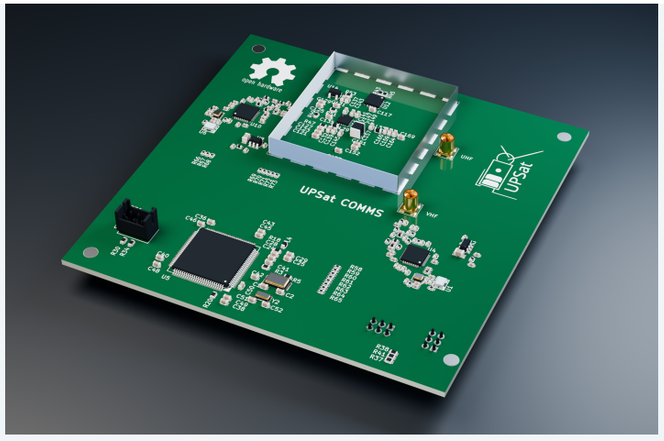


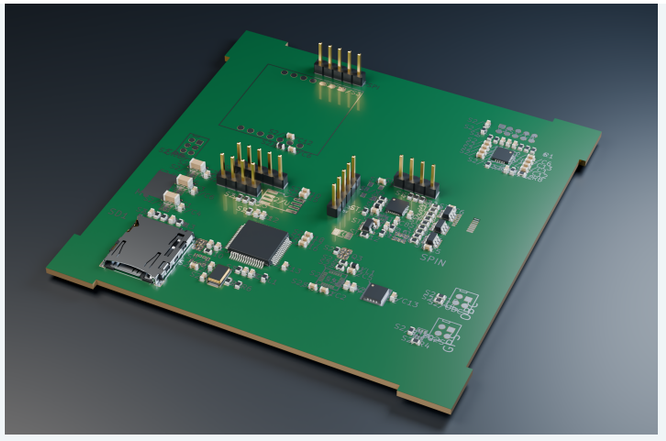
Historical spacecraft CAD visualization. [S1]

Four boards, one modeling framework

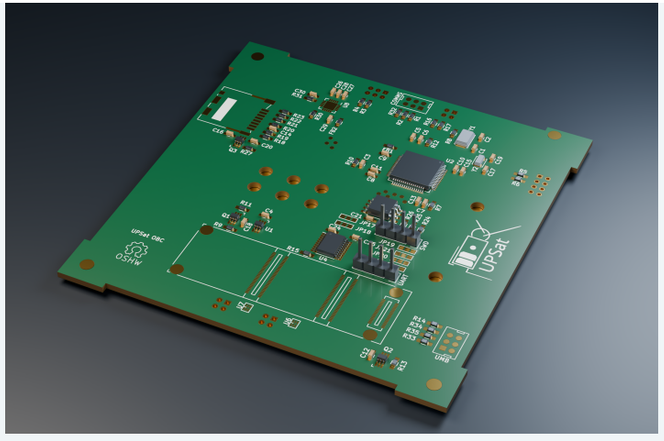
The work reduces each board independently to a compact model that retains source placement and heat paths to four mounts.



COMMS Communications | 4 source groups



ADCS Attitude determination and control | 4 source groups



OBC On-board computer | 4 groups; partial CAD population

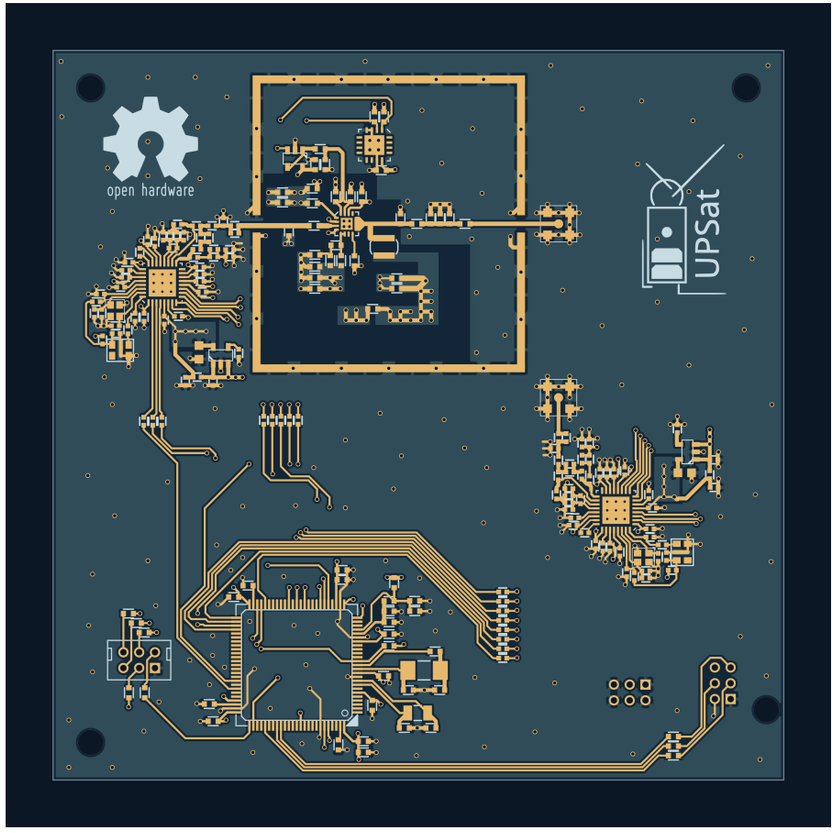


EPS Electrical power system | 6 groups; battery excluded

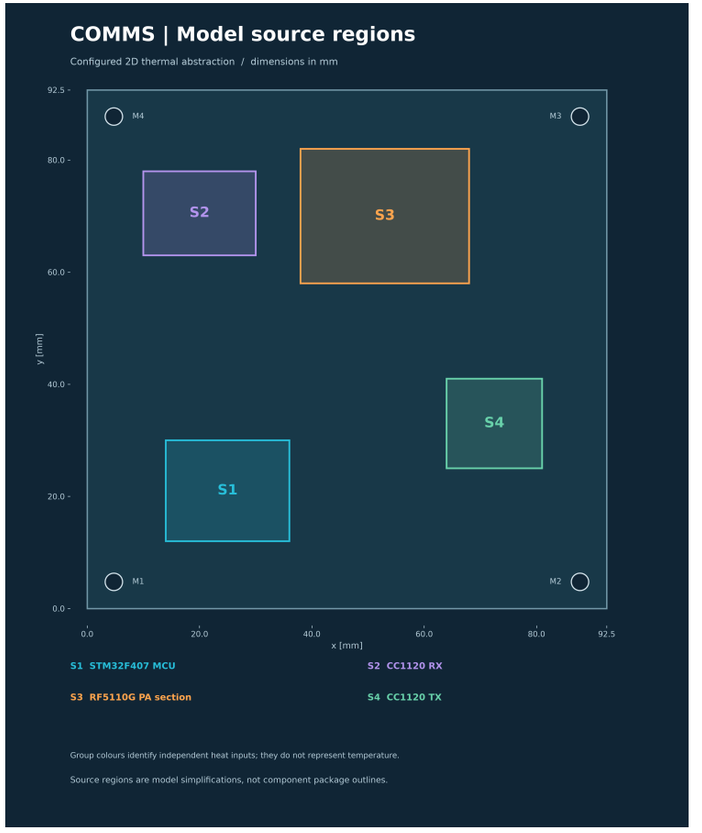
CAD renders provide hardware context. The thermal models use homogeneous PCB sheets; component packages, batteries and dynamic interboard coupling are outside the present abstraction. Hardware attribution and revision: [S1].

Translate component placement into heat inputs

COMMS is the worked example: four source footprints feed a 4 x 4 grid through normalized area-overlap weights.



Native COMMS top layout. Geometry context, not a measured temperature field.



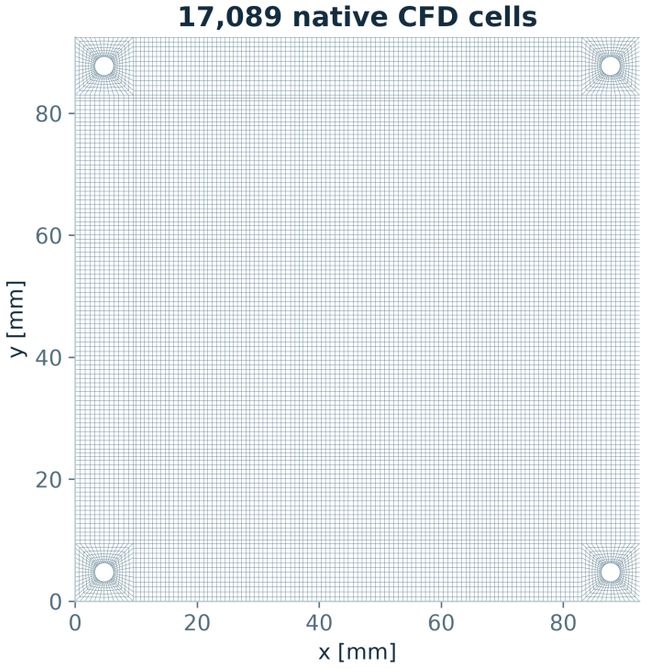
Configured thermal-source map. N01 starts at the lower left; numbering proceeds along x, then upward.

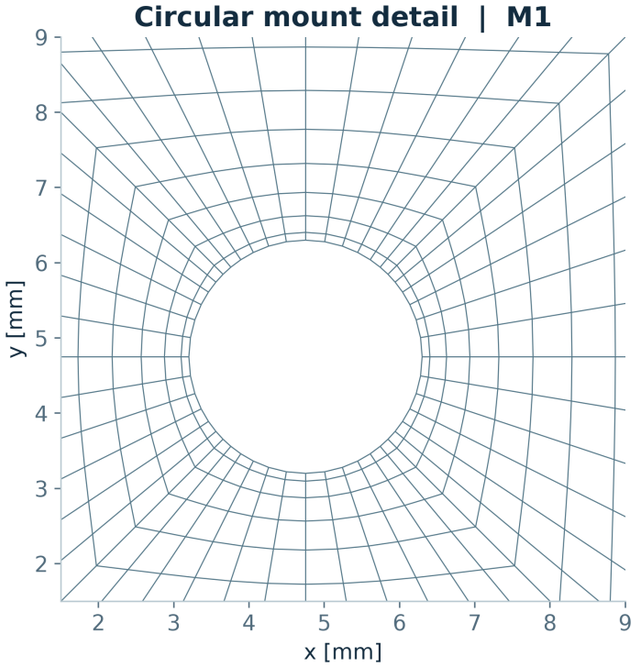
92.5 x 92.5 mm sheet | 1.6 mm thickness | 3.10 mm mount holes

Assumed material: k = 10 W/(m K), density = 1850 kg/m3, cp = 900 J/(kg K). OBC/EPS source footprints still require physical registration to the native PCB layouts.

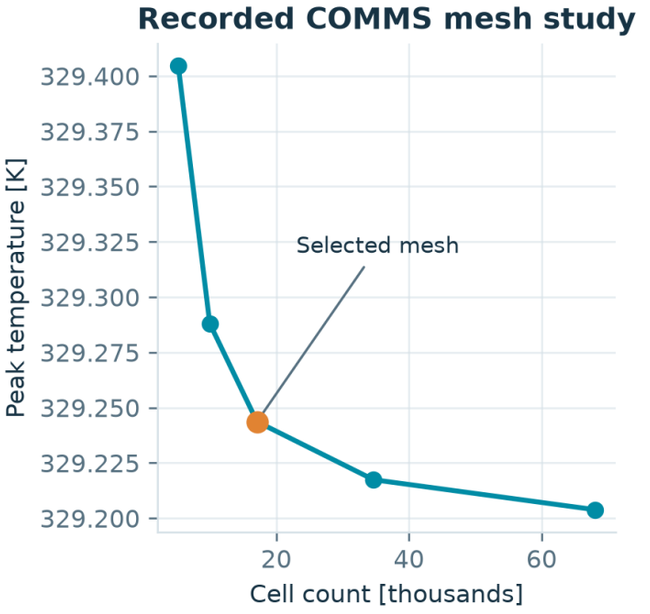
Resolve the sheet and the mount boundaries

The selected common topology contains 17,089 cells. Heat enters through configured source regions and leaves through prescribed mount temperatures.





Native production topology and circular mount refinement. Heat-source zone assignment differs between boards.



COMMS mesh study; a separate operating case from the withheld mixed-load comparison.

0.0398 K

Change in peak temperature between the selected COMMS mesh and the finest listed mesh. Five meshes span 5,226 to 68,032 cells.

34 calibration cases

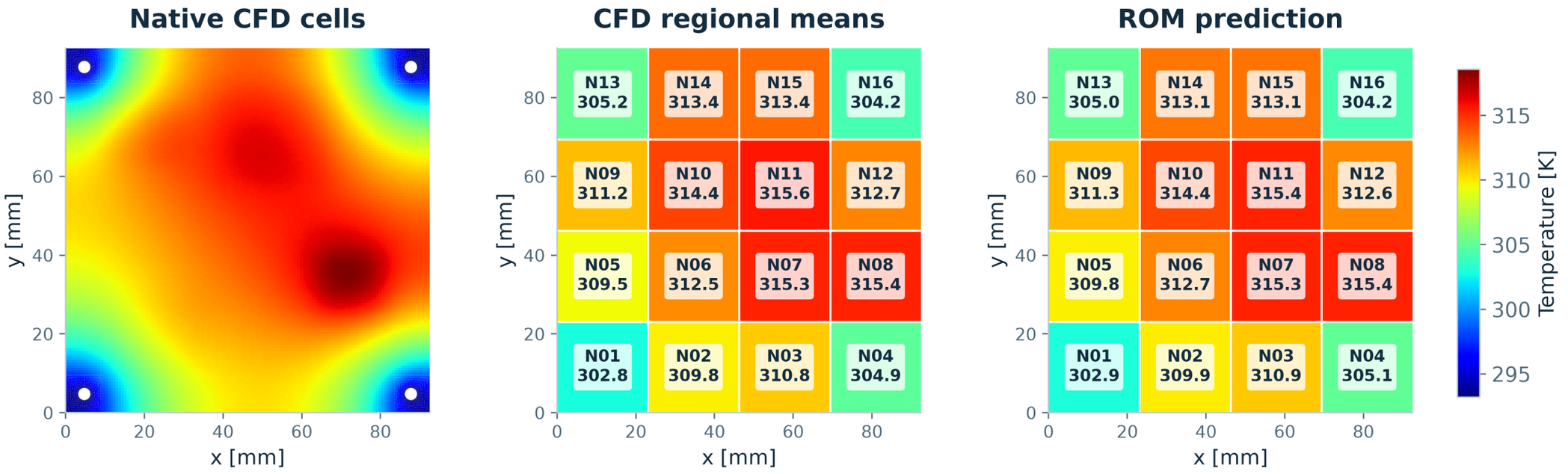
Eight cases each for COMMS, ADCS and OBC; ten for EPS. Convergence and global steady energy balance were checked separately.

Scope of the evidence

The steady mesh study supports this reference model. It does not establish COMMS transient time-step or mesh independence.

A temperature field becomes 16 regional states

Area-weighted CFD means are the comparison target. The compact model predicts regional temperature rather than component junction temperature.



COMMS | 17,089 CFD cells → 16 temperature states | RMSE 0.164 K · max error 0.299 K

COMMS withheld steady mixed case. The three panels share one temperature scale. Native local cell values, CFD regional means and ROM predictions are distinct quantities.

0.164 K

Steady node-temperature RMSE

0.299 K

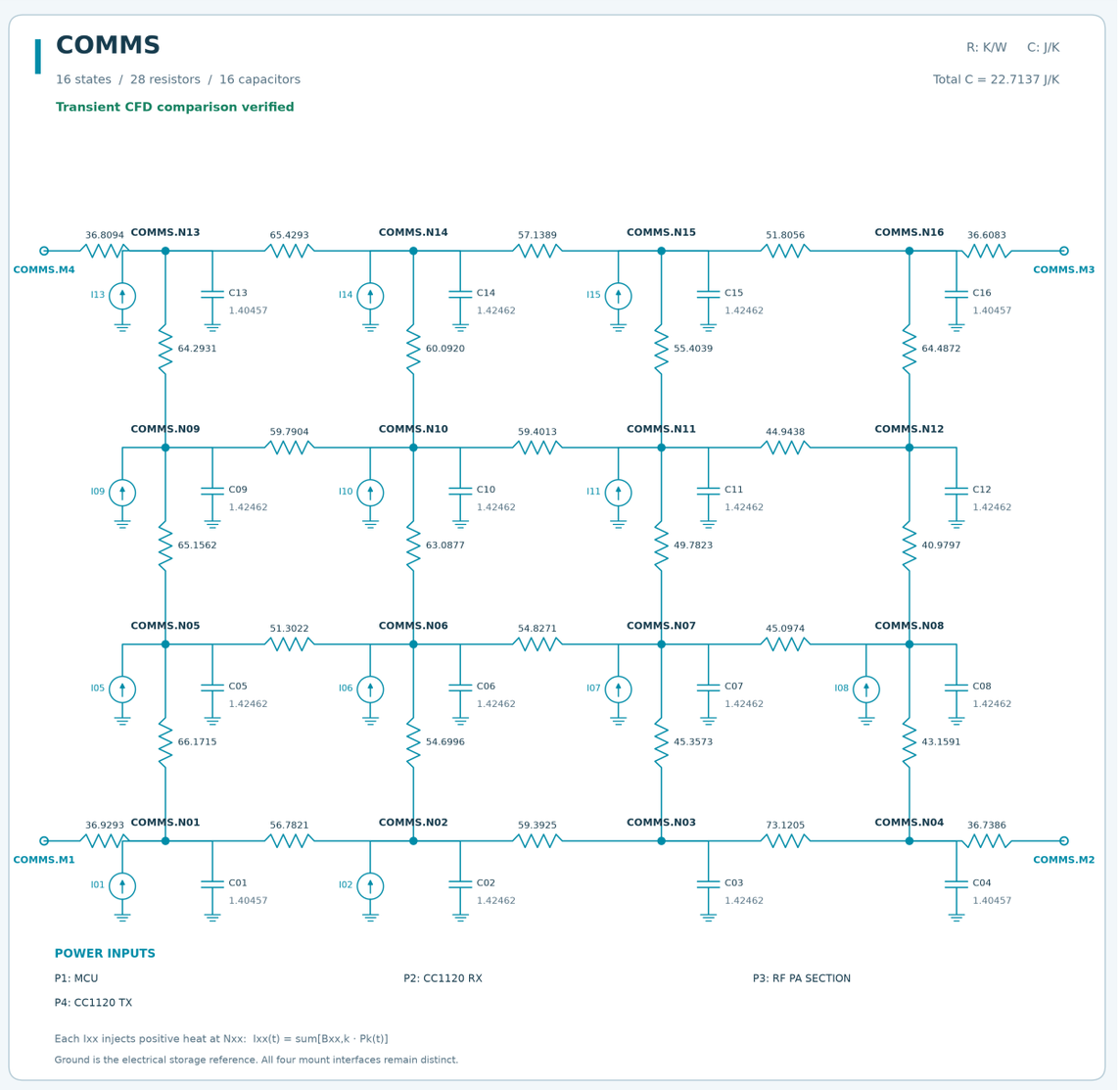
Maximum steady node error

Synthetic load: 1.20 W

Four mount temperatures:
293.15, 293.35, 293.15, 293.45 K.
This is a numerical test case.

Represent spreading, storage and source injection

Each board has 24 in-plane links, four sheet-to-mount links and 16 physically derived sheet capacitances.



Heat balance

C dT/dt + G T = B P + H Tmount

G describes conductance, B distributes source power and H connects the prescribed mount temperatures.

Thermal quantity	Electrical analogue
Temperature [K]	Voltage [V]
Heat-flow rate [W]	Current [A]
Resistance [K/W]	Resistance [ohm]
Heat capacity [J/K]	Capacitance [F]

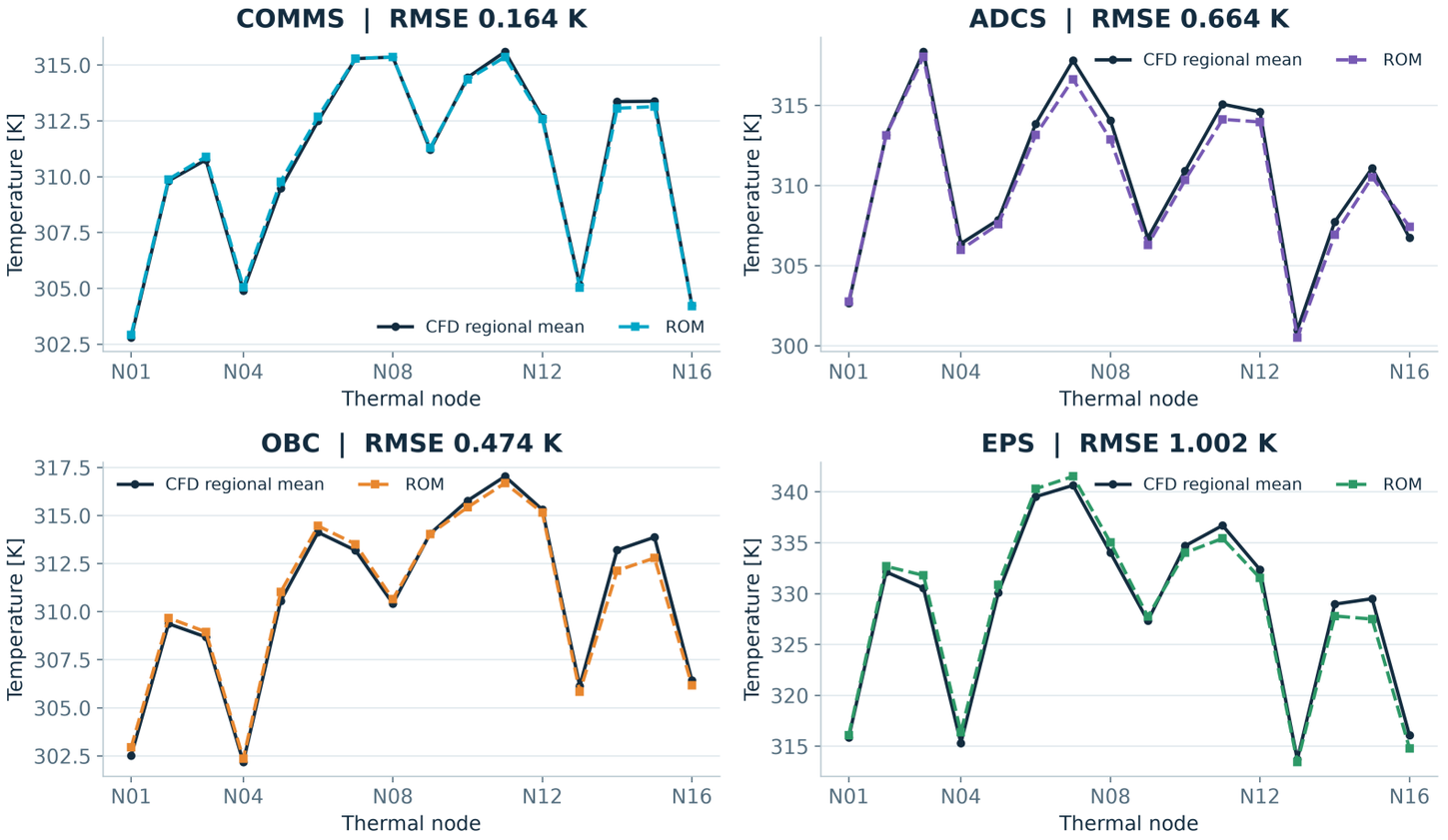
22.7137 J/K per sheet

C = density x cp x area x thickness. Small corner reductions account for mount holes. Capacitor ground is a storage reference, not an extra physical heat sink.

Corrected LTspice circuits reproduced all four matrix responses (maximum difference 0.000011 K). Legacy v4.4 exports need a one-node resistor-index correction.

Audit the same comparison across all four boards

Saved native CFD regional means were matched to the audited steady ROM results for one withheld mixed-load case per board.



Board	RMSE / max [K]
COMMS	0.1637 / 0.2987
ADCS	0.6642 / 1.1794
OBC	0.4744 / 1.0828
EPS	1.0016 / 2.0066

Keep the test conditions visible

COMMS, ADCS and OBC each use 1.20 W. EPS uses 2.40 W. These are independent synthetic tests, so the curves do not rank physical board performance.

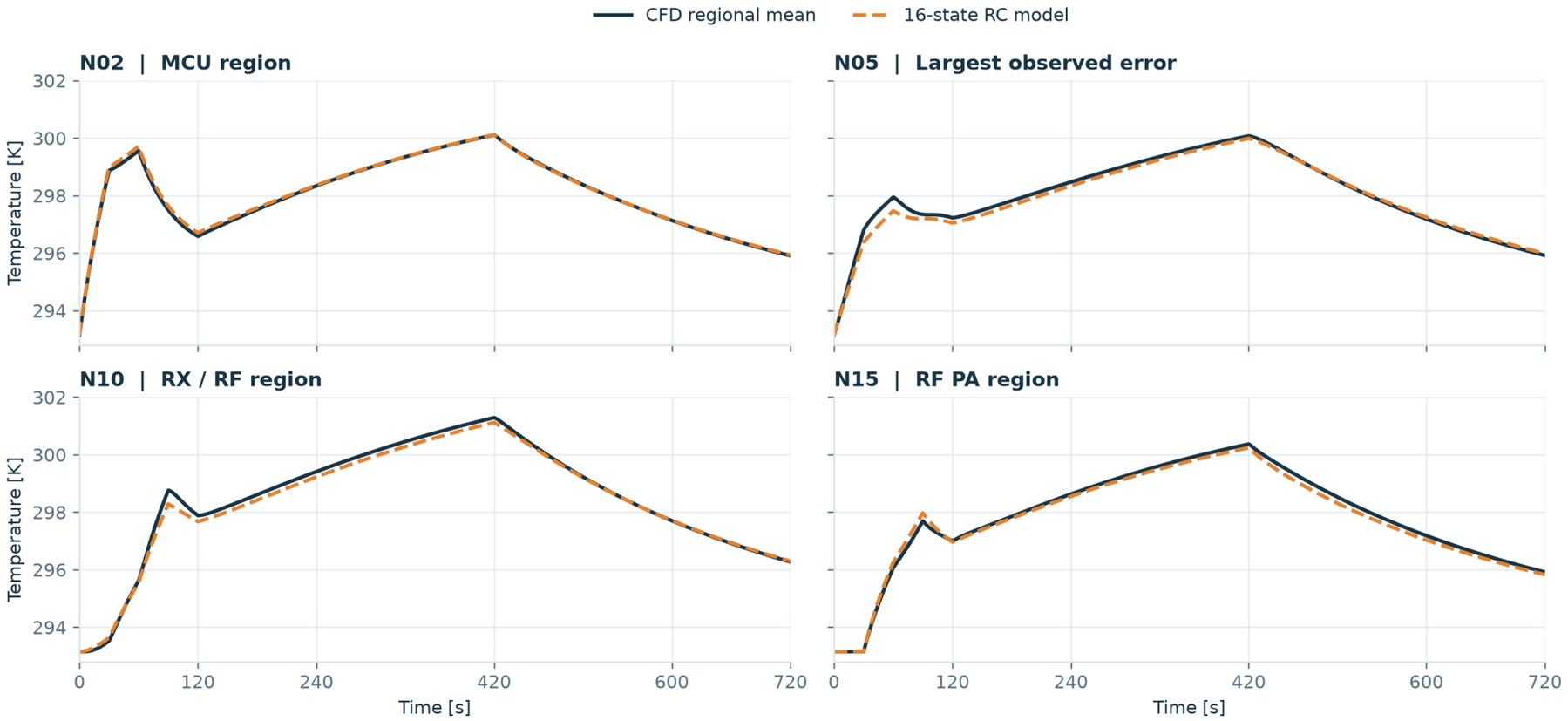
Use the audited revision

The values shown here come from the steady audit. Earlier fit summaries and legacy figures can report different errors.

RMSE and maximum absolute error use all 16 regional temperatures. The numerical reference is a 2D conduction model.

Challenge COMMS with a withheld 720-second history

Six stages combine source pulses, overlap, cooling and a mount-temperature change. The R and C values remain unchanged.



1,081

Saved samples including t = 0

16

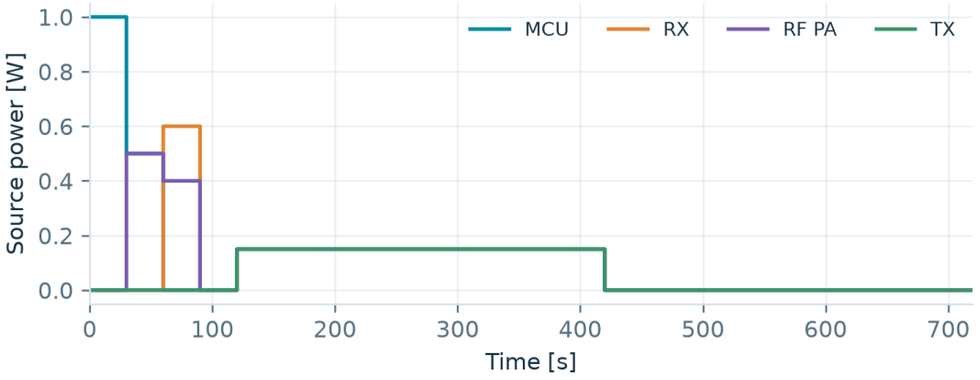
Temperature states compared

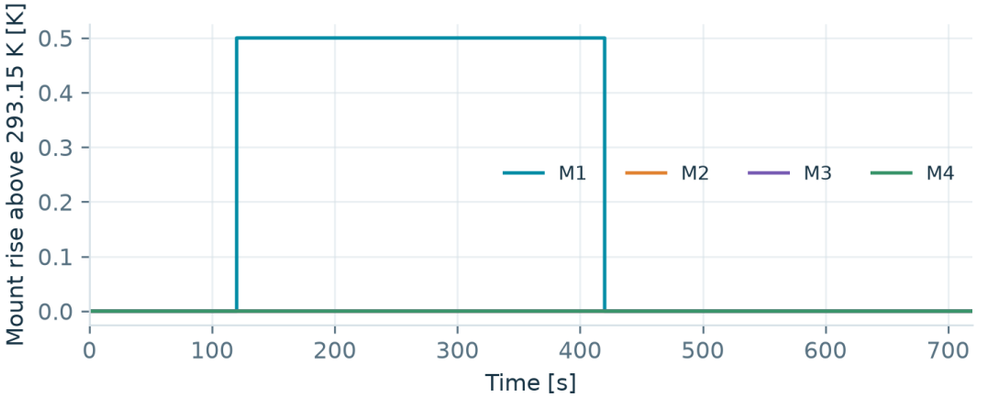
0.25 s steps, then 1 s

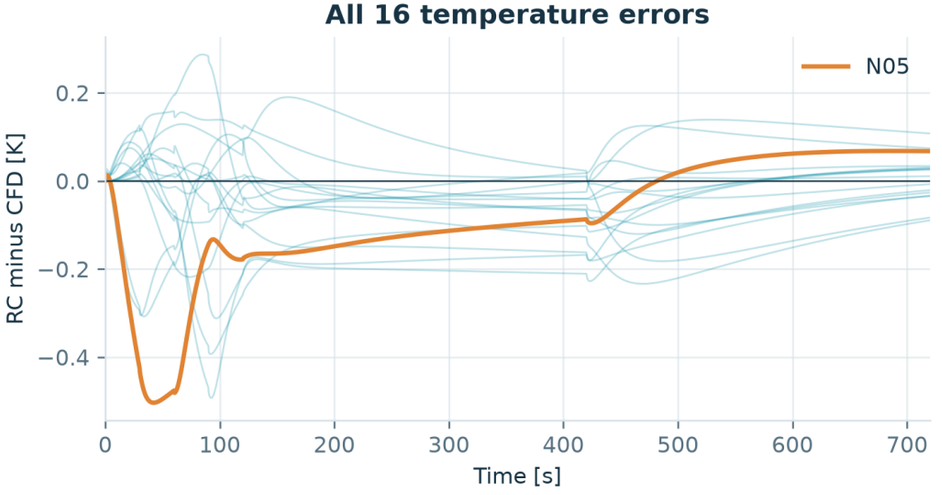
Four 30 s stages, followed by two 300 s stages. No transient fitting.

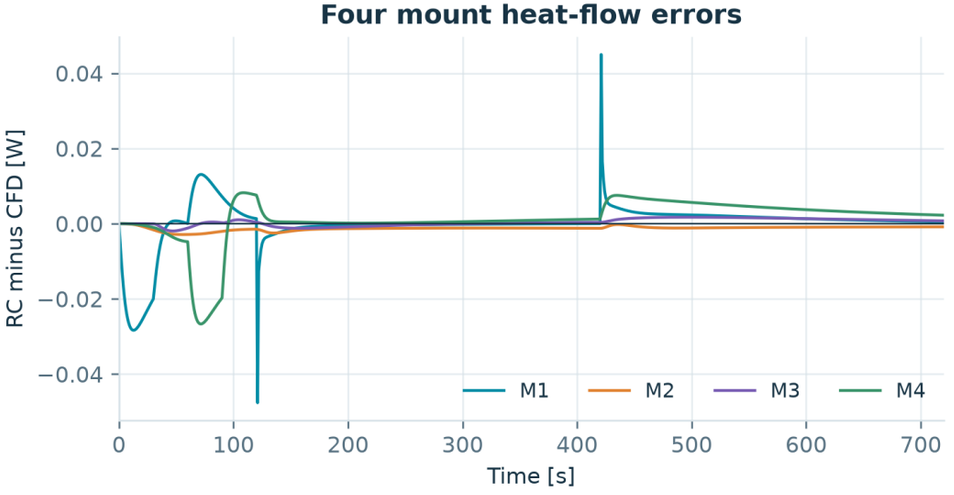
Read the error together with the test definition

The recorded-sample RMSE is 0.123 K. A time-weighted calculation gives 0.106 K because the saved sampling interval changes during the run.





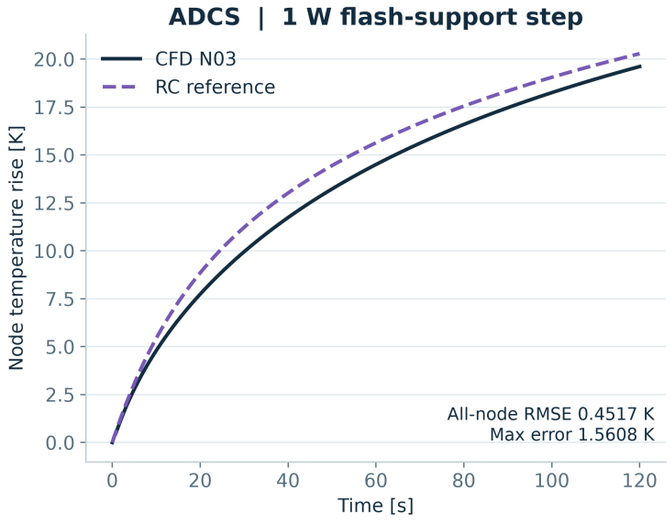


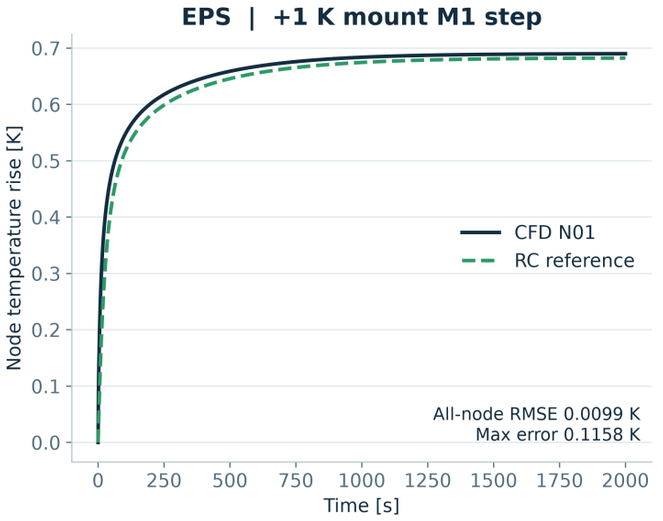


Maximum temperature error: 0.5037 K at N05, 42.25 s. Mount heat-flow RMSE: 0.006363 W, excluding the initial instant; maximum absolute error: 0.047625 W. Heat flow is positive into the board.

One complete profile; two focused pilots

The evidence supports a scoped COMMS result. The other boards remain at different stages of transient verification.





Board	Transient CFD evidence
COMMS	720 s withheld profile complete
ADCS	Focused pilot; broader profile pending
OBC	Transient comparison pending
EPS	Focused pilot; broader profile pending

Earlier pilots: ADCS 1 W flash-support step for 120 s; EPS +1 K M1 step for 2000 s. These exercise different inputs and time scales.

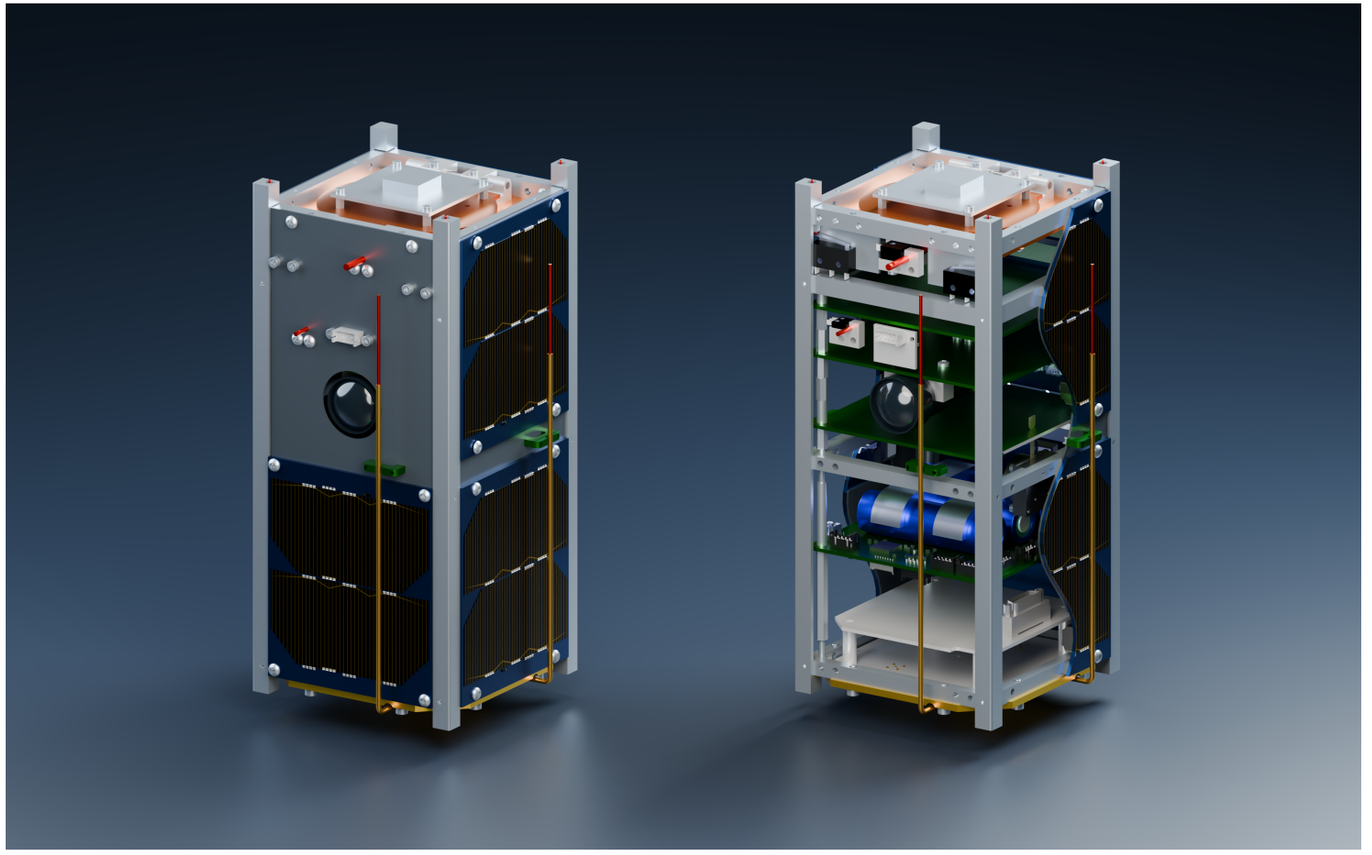
Energy closure requires a precise claim

The saved 0.066546% is the final cumulative mismatch at 720 s using trapezoidal integration. Exact integration of the prescribed source steps gives 0.147636% final mismatch with sampled mount fluxes.

The early cumulative relative mismatch reaches 11.11% at 1 s; the maximum absolute cumulative mismatch is 0.1667 J. Its mechanism remains unresolved. A focused startup/time-step check is needed before a stronger conservation claim.

The next step is the physical interface model

Four board blocks provide 64 states and 16 external mount terminals. A coupled spacecraft model also needs the conductance and storage between those terminals.



Historical assembly and cutaway visualization. Batteries appear as hardware context; battery thermal behavior is excluded from the four board models. [S1]

Interfaces still to establish

Contact, rod and structural resistances are not yet specified. A common prescribed mount temperature acts as an ideal reservoir; it does not create dynamic mutual heating.

Additional physics

Component thermal masses, junction-to-board paths, radiation and environment conditions require their own models or measurements.

Next verification work

Complete withheld profiles for ADCS, OBC and EPS; resolve COMMS startup energy behavior; add interface physics and verify the coupled model response.

The deliverable is a traceable board-level numerical model and verification workflow.

Sources, revisions and reproducibility

This case study was rebuilt from native images, numerical tables and verified work records. Earlier reports were used as context; their PDF pages were not used as figures.

S1 | Hardware and visual assets

Native assets: UPSat_Final_Report / Selected_Images; UPSat_Satellite_Hero; UPSat_Wavy_Cutaway. Spacecraft CAD: Andreas Ampatzoglou / AML-UP, via Libre Space Foundation, CERN OHL v1.2; historical STEP export 28 March 2016. Final as-flown configuration is not established. COMMS hardware credits Manos Theodoridis / APEL / University of Patras and Libre Space Foundation contributors; ADCS/OBC credit Libre Space Foundation contributors. EPS hardware is from the UPSat EPS repository. Board README and CERN OHL v1.2 license notices are retained in the project references.

S2 | Model definition and steady audit

UPSat_4Boards_2D_Transient_RC_ROM_v4_4_PHYSICS_BASED_RC_VALIDATION: config/boards.json; per-board rc_model_v4_4.json; audited steady validation and resistor tables. Source maps are configured model regions. OBC/EPS source registration to native PCB placement remains open.

S3 | Native scientific figures

UPSat_Final_Visual_Report / Evidence / science_summary.md and the associated native PNG/SVG figures. The four-board steady figures use the audited comparison: RMSE 0.1637 / 0.6642 / 0.4744 / 1.0016 K for COMMS / ADCS / OBC / EPS.

S4 | Completed COMMS transient evidence

Run 20260926_133301_164847, MIXED_PULSE_WITHHELD: RC_vs_CFD_timeseries.csv, history.csv and RC_VALIDATION_METRICS.json. Independent audit: UPSat_COMMS_Transient_Validation / Evidence / independent_audit.md. Report curves and error metrics are regenerated from the saved CSVs.

S5 | Four-board model and circuit audit

UPSat_Four_Board_RC / Evidence / four_board_model_audit.md and Circuit_Verification.json. Confirms positive passive sheet models, node mapping, source weights, derived C and steady reproduction. Corrected native LTspice runs reproduce the four matrix models (maximum error 1.10e-5 K); this circuit check does not complete four-board CFD transient validation. Original package status strings may predate the completed COMMS run.

Editable source, native assets, SHA-256 manifest, copied evidence, regenerated SVG/PNG plots and QA images accompany this revision. All figures remain numerical evidence or CAD context as labeled. No hardware or flight validation is claimed.