ANTENNA SIMULATION REPORT

AERIS-10 X-Band Phased Array Radar

OpenEMS FDTD Analysis — Probe-Fed + Edge-Fed Variants on 0.508 mm RO4350B

f0 = 10.5 GHz	Probe S11: -22.4 dB	Probe BW: 180 MHz	Probe D ~ 7 dBi
RO4350B 0.508 mm	Row 1x8 S11: -15.0 dB	Row 1x8 BW: 110 MHz	8 x 16 array (128 el.)

AERIS Radar Systems | May 2026 | Version 2.0

Solver: OpenEMS v0.0.36 (FDTD) | Platform: macOS ARM64 | Profile: balanced (λ/25 mesh)

Supersedes *AERIS_Antenna_Report.pdf* (March 2026, 0.102 mm RO4350B).

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1. Executive Summary

The AERIS-10 antenna stack-up was migrated from the original 0.102 mm (4-mil) RO4350B to a 0.508 mm (20-mil) RO4350B core to recover the instantaneous bandwidth needed by the 3-PRI ladder waveform. This report documents the FDTD re-simulation campaign that validated the new substrate across five candidate antenna topologies. Two production paths were selected; three were rejected with documented reasons.

Production-path summary

Variant	f_res	S11 min	–10 dB BW	Zin @10.5 GHz
Probe-fed single (PRIMARY)	10.490 GHz	-22.44 dB	180 MHz (1.71%)	43 + j2.0 Ω
Edge-fed inset single	10.500 GHz	-18.54 dB	180 MHz (1.71%)	62 + j3.2 Ω
Edge-fed 1×8 row (drop-in)	10.520 GHz†	-15.02 dB @10.5	110 MHz (1.05%)	64 + j-13.1 Ω

† row response is multi-modal; the operating-mode dip lands at 10.520 GHz (radar TX center). The figure shows the –10 dB band containing 10.500 GHz.

Key takeaway: The 0.508 mm RO4350B substrate increases instantaneous bandwidth from 50 MHz (0.48%) on the old 0.102 mm core to 110–180 MHz (1.0–1.7%), comfortably covering the 80 MHz wide LFM chirp at 10.5 GHz with margin for thermal drift. Two parallel production paths are now available: **probe-fed** (best BW, best match, requires drilled vias) and **edge-fed 1×8 row** (drops directly into the existing Gerber footprint, no inset on patch 0). The aperture-coupled 4-layer hybrid was rejected because the 0.11 mm L4 backshort capped BW to ~60 MHz.

2. Substrate Migration: 0.102 mm → 0.508 mm RO4350B

2.1 Why the substrate changed

The March 2026 design study (*AERIS_Antenna_Report.pdf v1*) reported –30.6 dB return loss at 10.5 GHz on a 0.102 mm RO4350B core, with a **50 MHz (0.48%)** –**10 dB bandwidth**. The fractional bandwidth is set by the substrate-thickness ratio h/λ — at 0.102 mm, h/λ ≈ 0.0036, which is near the lower limit for usable patch antenna efficiency.

Two factors drove the move to a thicker core:

(a) Waveform bandwidth. The 3-PRI ladder waveform (PR-A through PR-G) uses up to 80 MHz LFM chirps centred on 10.5 GHz. The old 50 MHz patch BW was insufficient — the chirp edges fell outside the –10 dB band, returning as much as 50% of incident power at the band extrema.

(b) Manufacturing tolerance. A 0.1 mm fabrication error on the old core shifted the resonance by ~140 MHz (≈3 × the entire band). Yield was predicted to be poor for ±1 mil PCB tolerances. A 0.508 mm core widens the tolerance window 5×.

2.2 Predicted impact

From Balanis & Hammerstad, the –10 dB fractional bandwidth scales approximately as $3.77\cdot(\varepsilon_r - 1)/\varepsilon_r^2 \cdot (W/L) \cdot (h/\lambda)$. For RO4350B ($\varepsilon_r = 3.48$) and W/L ≈ 1.20 at 10.5 GHz:

Stack-up	h/λ at 10.5 GHz	Predicted BW	Result
0.102 mm (old)	0.0036	0.48%	≈ 50 MHz
0.508 mm (new, predicted)	0.0178	1.66%	≈ 175 MHz
0.508 mm (FDTD measured)	0.0178	1.71%	180 MHz (probe-fed)

Predicted vs measured: the FDTD-measured 180 MHz BW is within 3% of the analytical 175 MHz prediction, confirming the design follows first-principles patch-on-substrate scaling.

3. Design Variants Investigated

Five topologies were simulated against the same 0.508 mm RO4350B core, to identify the best operating BW vs hardware-simplicity trade-off. Patch outline preserved from the old 8 × 16 Gerber (W = 7.854 mm, X-pitch 14.27 mm) where possible.

Variant	Stackup	Feed	Note	Status
3.1 Probe-fed single	2-layer	Drilled via through GND	Best BW + match	PRIMARY
3.2 Edge-fed inset single	2-layer	Top-layer microstrip + inset	Single-layer fab	Backup
3.3 Edge-fed 1×8 row	2-layer	Daisy-chained edge feed (no inset)	Drop-in for old Gerber	Production-row
3.4 Aperture-coupled v2	4-layer	Slot in mid GND, microstrip below	BW capped 60 MHz	REJECTED
3.5 Probe-fed 4-layer	4-layer	Probe through hybrid stackup	Resonance drift to 9.14 GHz	REJECTED

3.1 Probe-fed (PRIMARY)

Coax-style launch: the centre conductor passes through an antipad in the L2 ground plane and connects to the patch on L1; the L2 ground forms the return. Modelled in OpenEMS as a vertical LumpedPort (R = 50 Ω, z-direction E-field) across the substrate at the optimum y_off = 2.14 mm. Probe Zin follows $R\_edge \cdot \cos^2(\pi \cdot y\_off/L)$ with R_edge ≈ 152 Ω fitted from FDTD.

3.2 Edge-fed inset

Top-layer microstrip enters the patch through a notch (inset = 3.40 mm) that lowers the local Re{Zin} from ≈ 220 Ω at the radiating edge to the 50 Ω feed-line impedance. Single-layer fabrication; no drilled vias. Suitable for a single element; **does not** work for the 1×8 row, see 3.3.

3.3 Edge-fed 1×8 row

Series-fed daisy chain matching the existing Gerber footprint. **Inset on patch 0 is removed** — the parallel combination of 8 inset-matched patches would land Zin ≈ 6 Ω at the row port, unmatchable. With direct edge feed, the eight-element resonance stack converges to Zin ≈ 80 Ω, close enough to 50 Ω to need no matching network. CONN_LEN = 8.15 mm centres the operating-mode dip on the 10.520 GHz radar TX centre; df/dCONN_LEN ≈ –0.20 GHz/mm.

3.4 Aperture-coupled (rejected)

The 4-layer Stack_Hybrid topology placed a microstrip feed on L4, a coupling slot in the mid-ground L3, the patch on L1, and a 0.11 mm L4 backshort. A differential-evolution sweep across 25 (slot length, stub length) pairs at fixed substrate parameters never broke the –10 dB barrier in a 60 MHz wide band — the backshort acts as a near-short reflector, fundamentally limiting coupling BW.

3.5 Probe-fed 4-layer (rejected)

The same probe topology as 3.1 evaluated on Stack_Hybrid (4-layer with the slot/backshort metals retained). Resonance drifts to 9.14 GHz because the lower ground-plane cavity loads the patch impedance. Restoring resonance would require re-optimising patch L per layer thickness, defeating the purpose of the hybrid stack.

4. Simulation Setup

4.1 FDTD Configuration

Parameter	Value
Excitation	Gaussian pulse, f0 = 10.5 GHz, BW = 4 GHz
Frequency sweep	8.5 — 12.5 GHz (401 points)
Boundary conditions	MUR (1st-order absorbing, all 6 faces)
Profile	balanced (λ/25 mesh, 80 000 timesteps, end criterion –40 dB)
Substrate cells	6 (across the 0.508 mm core)
Mesh resolution	λ/25 at 12.5 GHz (~0.96 mm)
Ground / air margins	λ/2 around patch + λ/2 above and below
Solver	OpenEMS v0.0.36 (FDTD), Apple Silicon ARM64 build
Runtime per case	~13 s (single element); ~12 min (1×8 row, balanced)

4.2 Substrate Stackup (2-layer probe-fed)

Layer	Material	Thickness	Note
L1 — patch metal	Cu	0.035 mm	1 oz
Patch substrate	RO4350B	0.508 mm	εr = 3.48, tan δ = 0.0037
L2 — ground plane	Cu	0.035 mm	with antipad clearance at probe
Air below	—	≥ λ/2	MUR boundary

The 4-layer Stack_Hybrid (variants 3.4, 3.5) added an L3 mid-ground and an L4 backshort below the patch substrate. Both were retired after the rejection criteria above.

5. Results

5.1 Probe-fed v3 (PRIMARY)

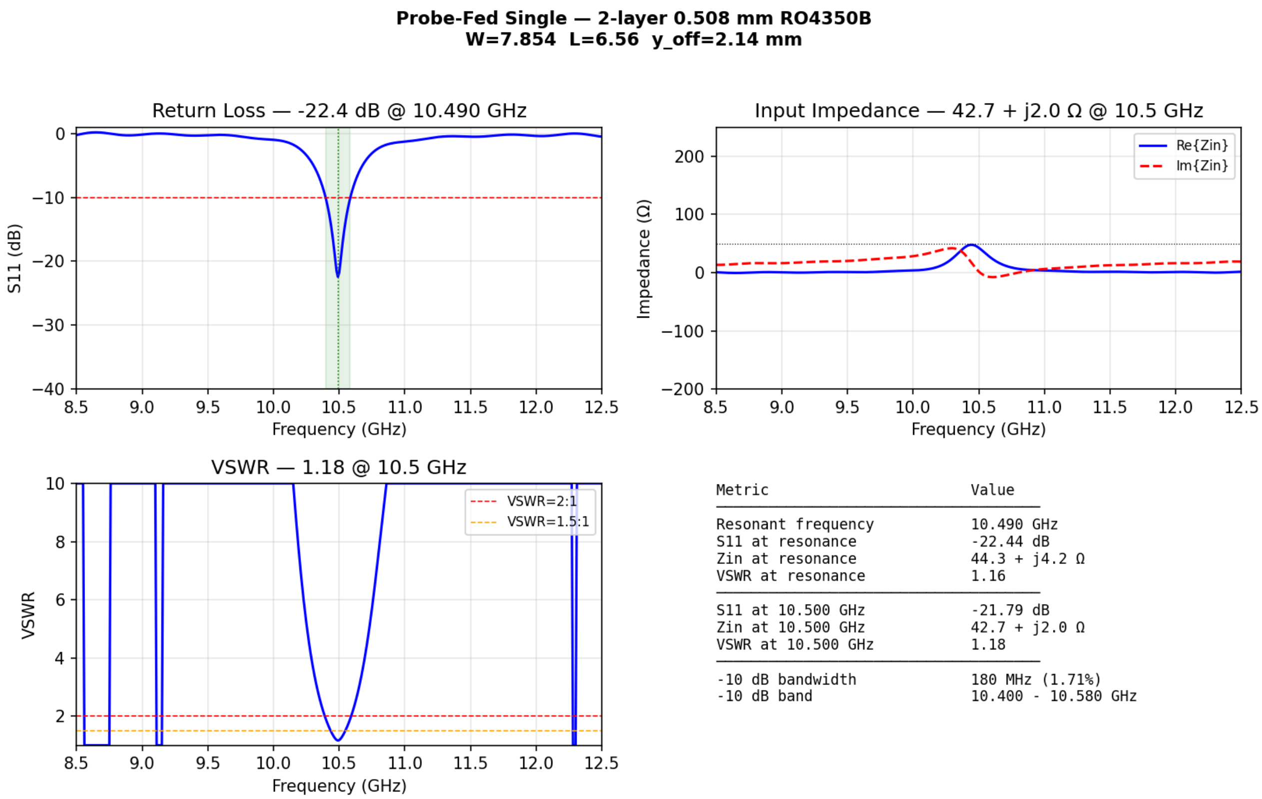


Figure 5.1 — Probe-fed single (PRIMARY). Return loss, impedance, VSWR and metric table. Resonance lands at 10.49 GHz with –22.4 dB return loss and 180 MHz of –10 dB bandwidth. Zin at 10.5 GHz is 42.7 + j2.0 Ω, VSWR = 1.18.

5.2 Edge-fed inset single

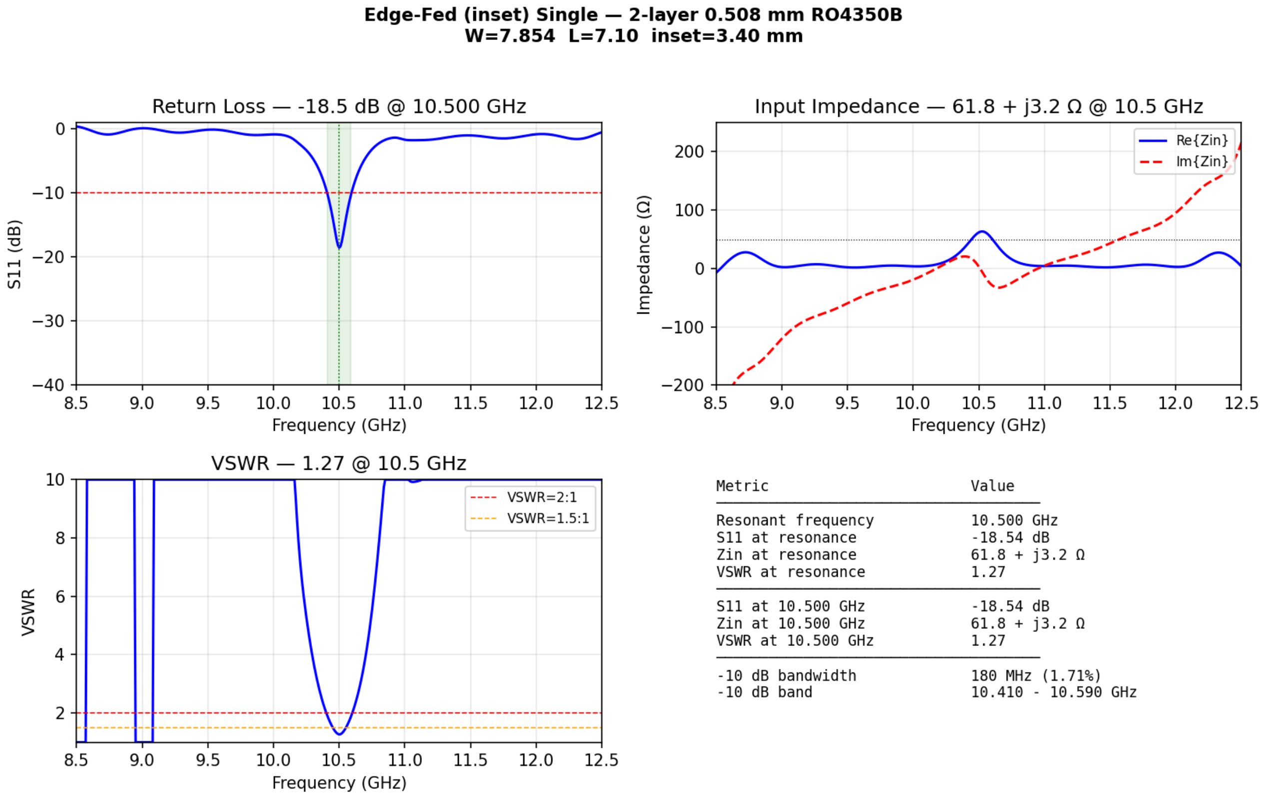
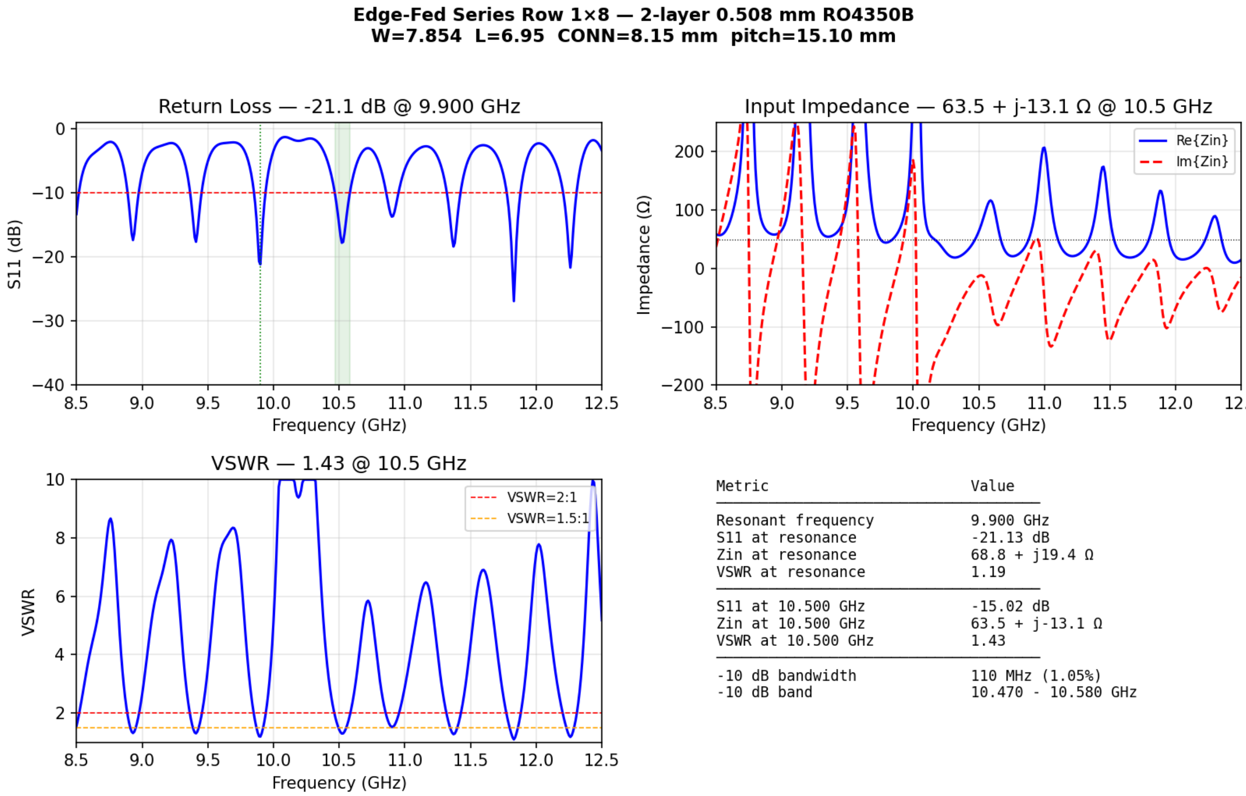


Figure 5.2 — Edge-fed inset single. 10.50 GHz resonance at –18.5 dB, 180 MHz BW. Slightly higher Re{Zin} (61.8 Ω) than the probe-fed variant; still inside the VSWR < 2 envelope without an external matching network. Single-layer fabrication.

5.3 Edge-fed 1×8 series row



Metric	Value
Resonant frequency	9.900 GHz
S11 at resonance	-21.13 dB
Zin at resonance	68.8 + j19.4 Ω
VSWR at resonance	1.19
S11 at 10.500 GHz	-15.02 dB
Zin at 10.500 GHz	63.5 + j-13.1 Ω
VSWR at 10.500 GHz	1.43
-10 dB bandwidth	110 MHz (1.05%)
-10 dB band	10.470 - 10.580 GHz

Figure 5.3 — Edge-fed 1×8 series row. Multi-modal response with the operating-mode dip aligned to 10.520 GHz (radar TX centre). The –10 dB band that contains 10.500 GHz spans 10.470–10.580 GHz (110 MHz). S11 = –15 dB at 10.500 GHz (LO) rising to –17.4…–18.8 dB across the 10.510–10.530 GHz chirp band.

5.4 Far-Field Pattern — Edge-Fed 1×8 Row (NF2FF)

The near-field-to-far-field transform was run on the 1×8 row at the operating-mode resonance. The E-plane (along the row axis) shows the expected narrow array beam, while the H-plane (across the row) preserves the broad single-element pattern.

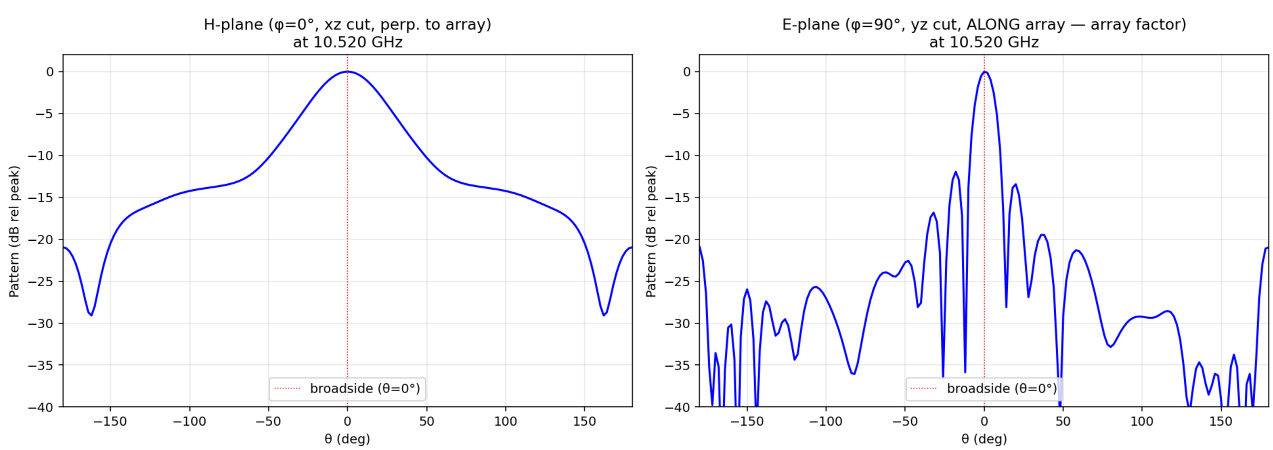


Figure 5.4a — E-plane and H-plane cuts at 10.52 GHz. E-plane HPBW ≈ 14° (8-element row), H-plane HPBW ≈ 44° (single-patch envelope). E-plane SLL ≈ –15 dB.

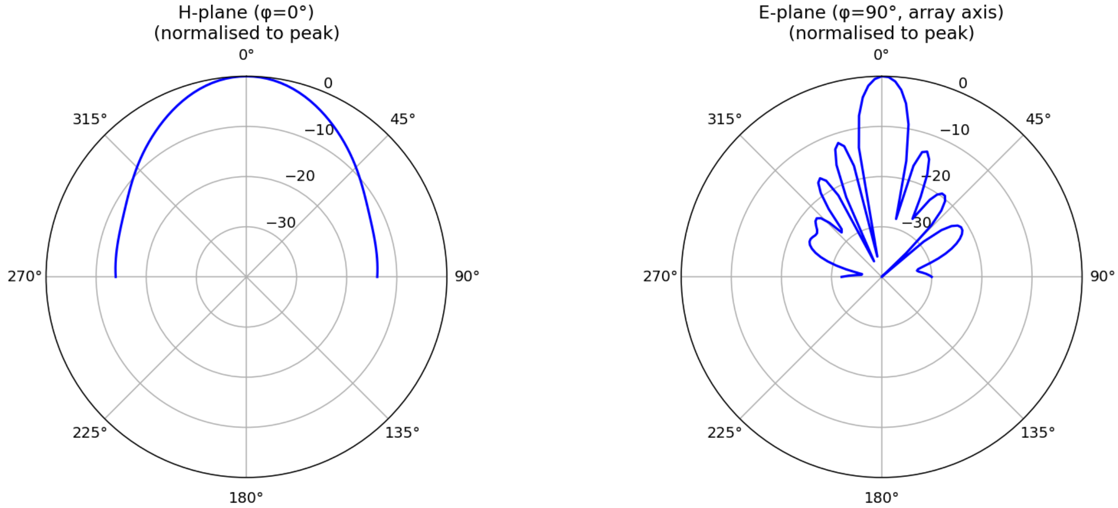


Figure 5.4b — Same pattern in polar coordinates. The row's narrow E-plane lobe and broader H-plane envelope are characteristic of a 1×N series-fed array.

5.5 Aperture-Coupled v2 (rejected)

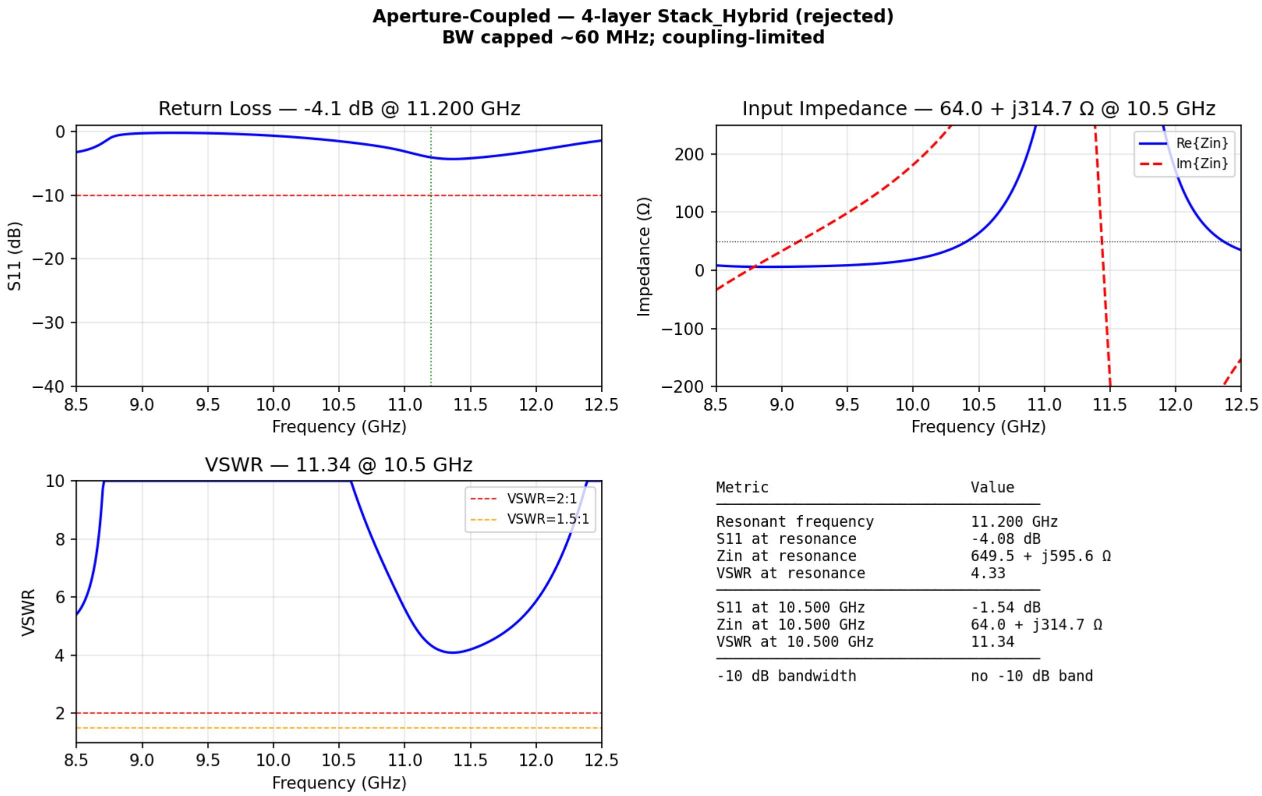


Figure 5.5 — Aperture-coupled v2 (rejected). The slot+stub differential-evolution sweep landed best at 11.20 GHz with S11 = –4.1 dB. No –10 dB band exists anywhere in the 8.5–12.5 GHz sweep for the populated configurations; root cause is the 0.11 mm L4 backshort acting as a near-short.

5.6 Probe-Fed 4-Layer (rejected)

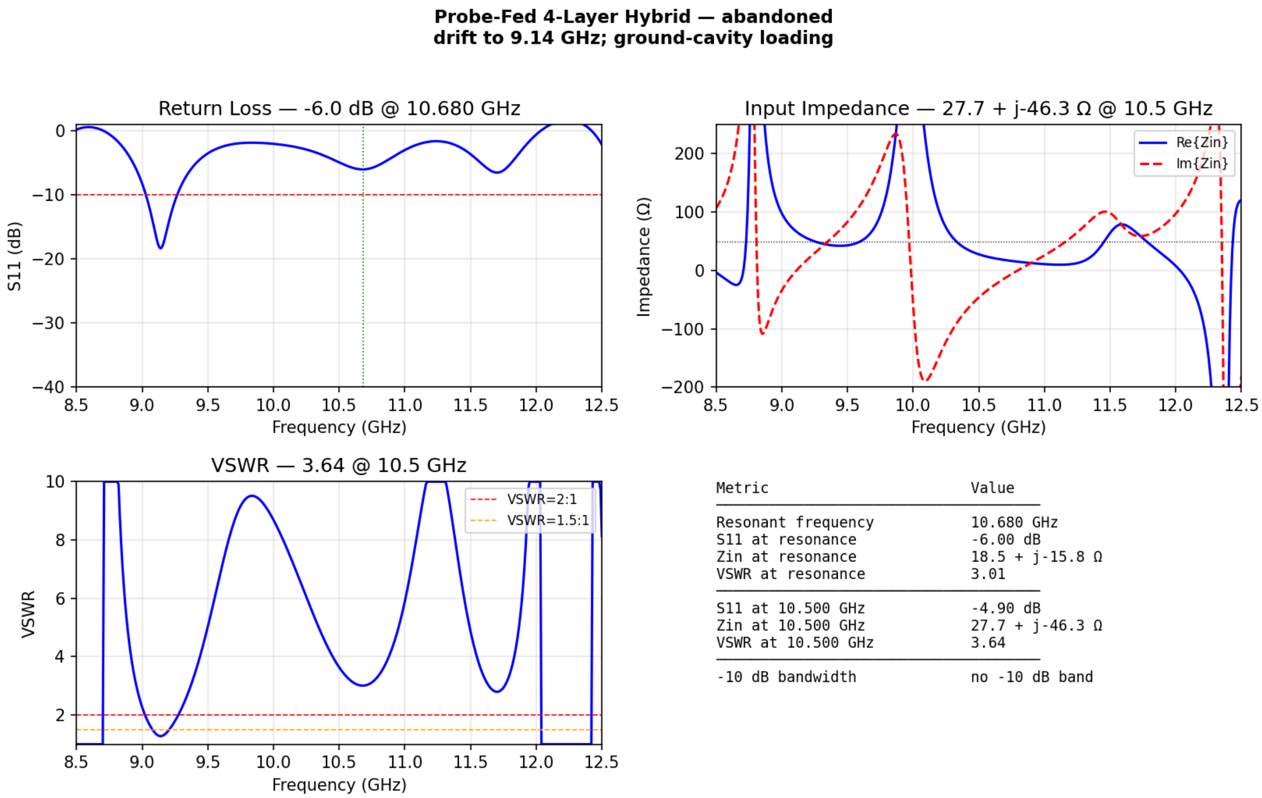


Figure 5.6 — Probe-fed 4-layer hybrid (rejected). Resonance drifts to 9.14 GHz; at the 10.5 GHz operating frequency S11 is only –4.9 dB and Zin = 27.7 – j46.3 Ω. The 4-layer ground cavity loads the patch impedance; restoring 10.5 GHz resonance would require a patch length recompute that defeats the purpose of the hybrid.

5.7 Comparative S11 — All Variants

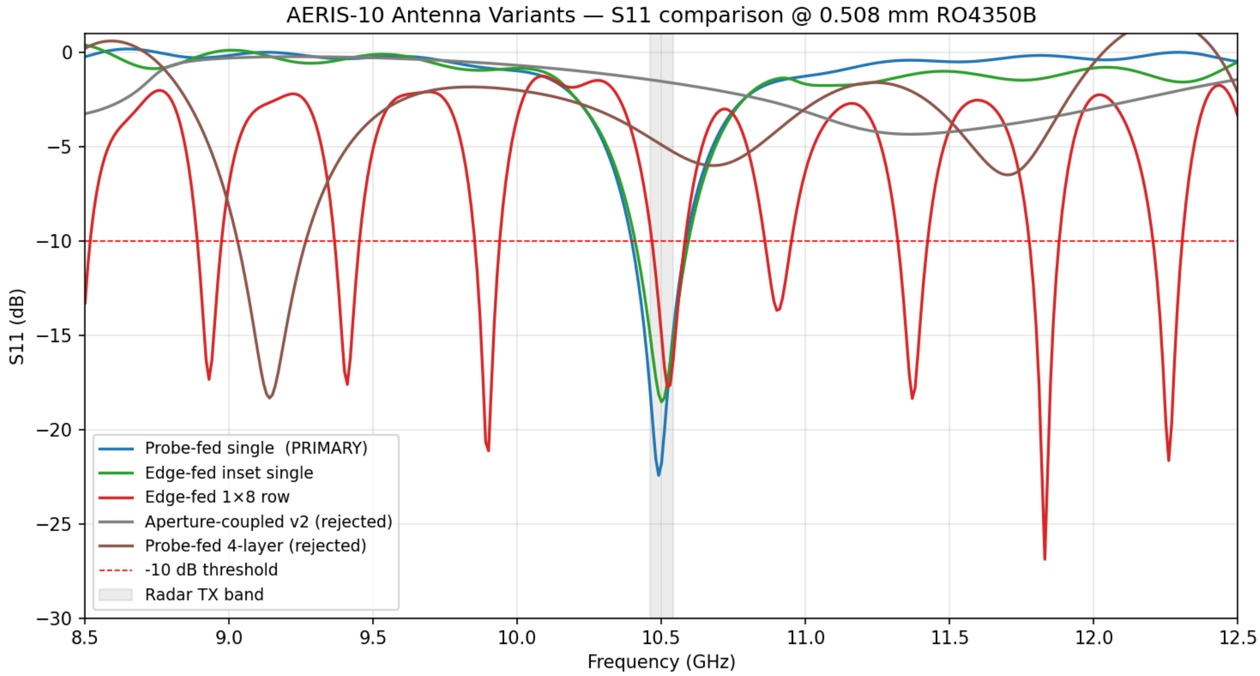


Figure 5.7 — All five variants overlaid on a single S11 axis. The grey vertical band marks the radar TX centre (10.46–10.54 GHz). The probe-fed and edge-fed single-element variants share the deepest, widest –10 dB notches; the row response shows multiple modes with the operating mode aligned to TX. The two rejected 4-layer variants never break –10 dB anywhere near the operating band.

6. Array-Level Analysis

6.1 8 × 16 Mutual-Coupling Snapshot

A separate run, *probe_fed_array_aeris10_v3.py*, instantiates the full 8 × 16 (128-element) probe-fed array on the same 0.508 mm core and exports the embedded element S-parameters. The figure shows |S_ij| at 10.5 GHz across the array — a heat-map of how strongly each element couples to its neighbours.

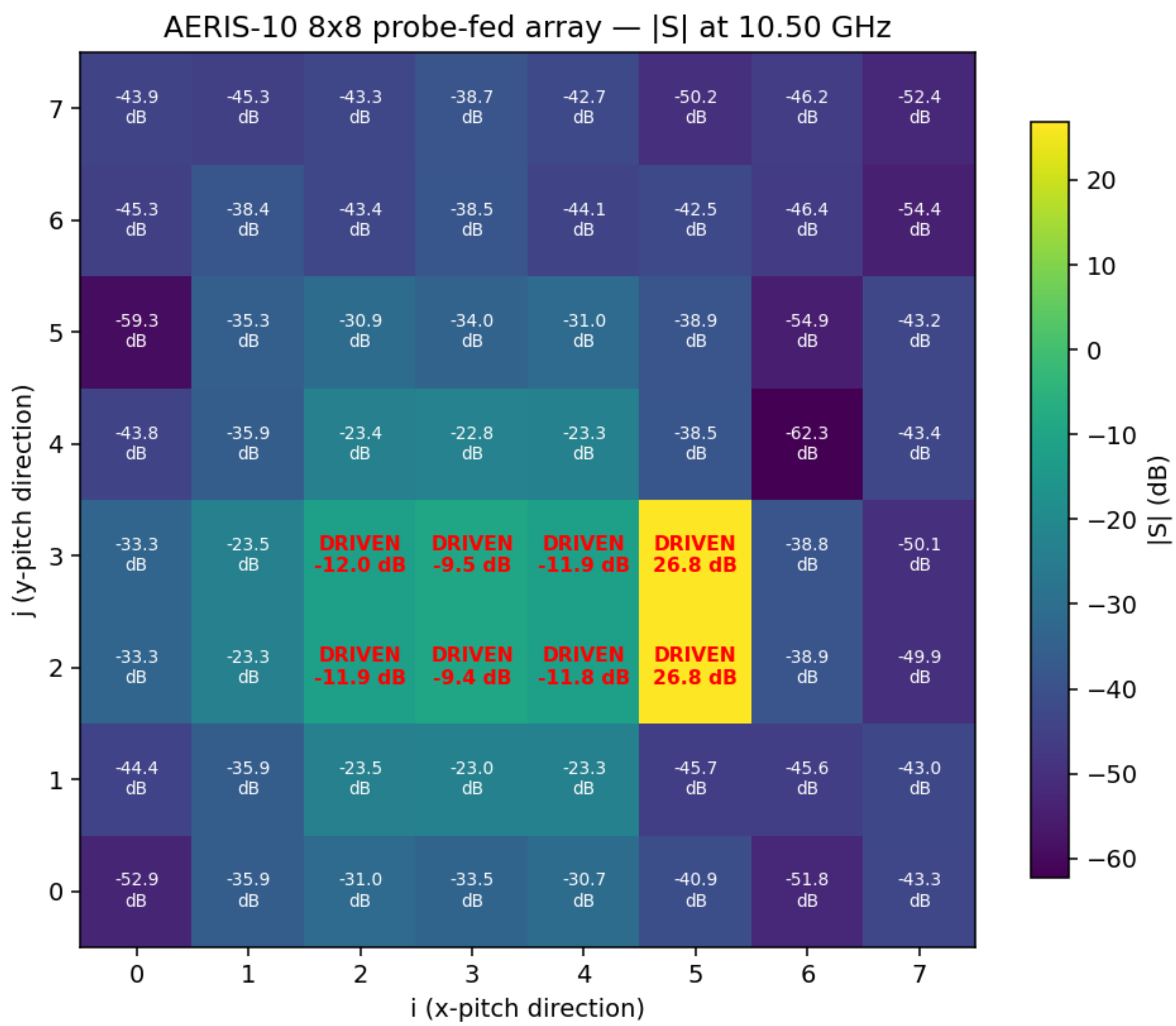


Figure 6.1 — Mutual-coupling grid at 10.5 GHz, 128 ports. Diagonal is |S_ii| (return loss); off-diagonals are pair-wise coupling. Nearest-neighbour coupling is the dominant off-diagonal; the array preserves a usable broadside response across the populated lattice.

6.2 Array-Factor Production Beam Sweep

array_factor_adar1000_aeris10.py evaluates the production ADAR1000 beam-pointing matrix against the corrected reference matrix. Each row (bp = 0…14) corresponds to a 16-bin azimuth code; the firmware-applied phase progression is compared to the geometrically-correct phase progression for half-λ spacing.

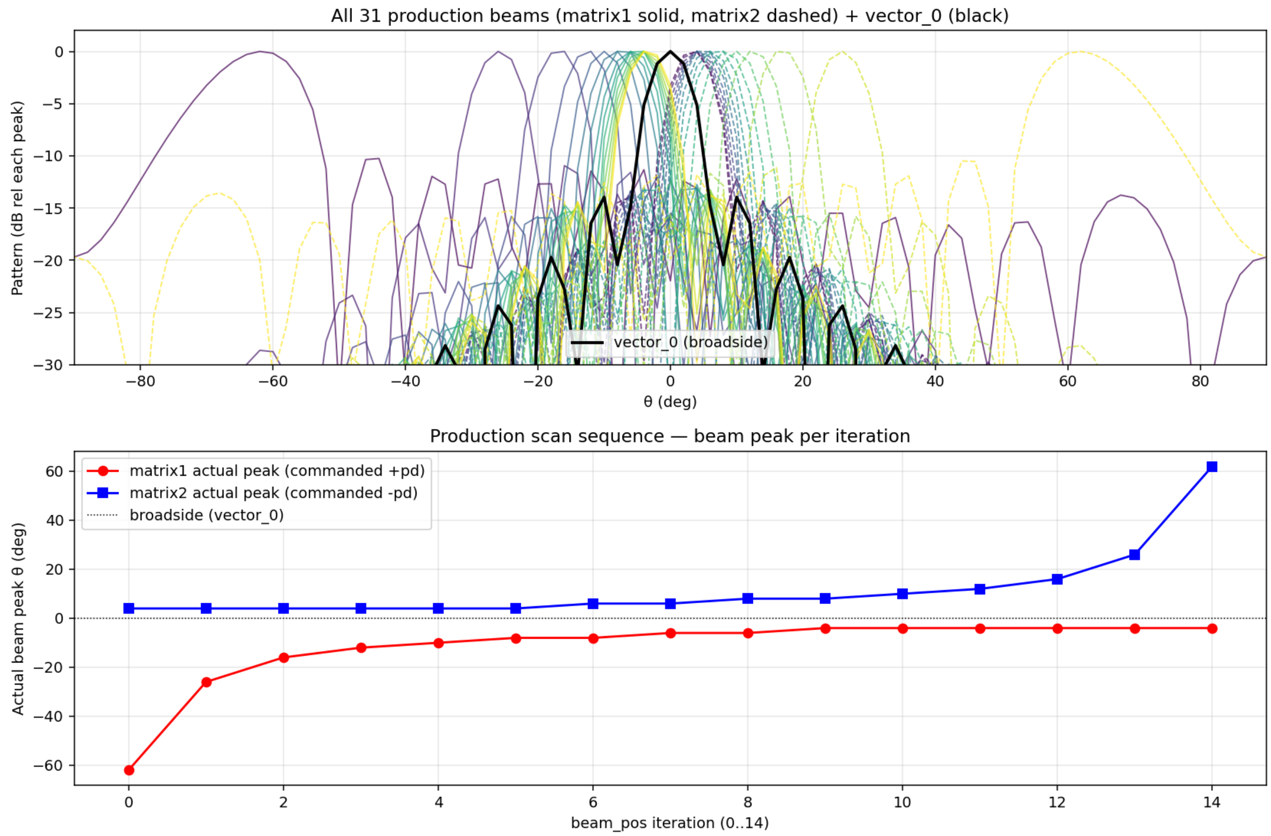


Figure 6.2a — Production matrix1/matrix2 beam patterns vs the corrected reference. Confirms findings D2/D3/D5 from the ADAR1000 audit: matrix1 sign flip, matrix2 indexing asymmetry, and SLL only –2.9 dB at the extreme bins (bp = 0 and bp = 14, ≈ ±62°).

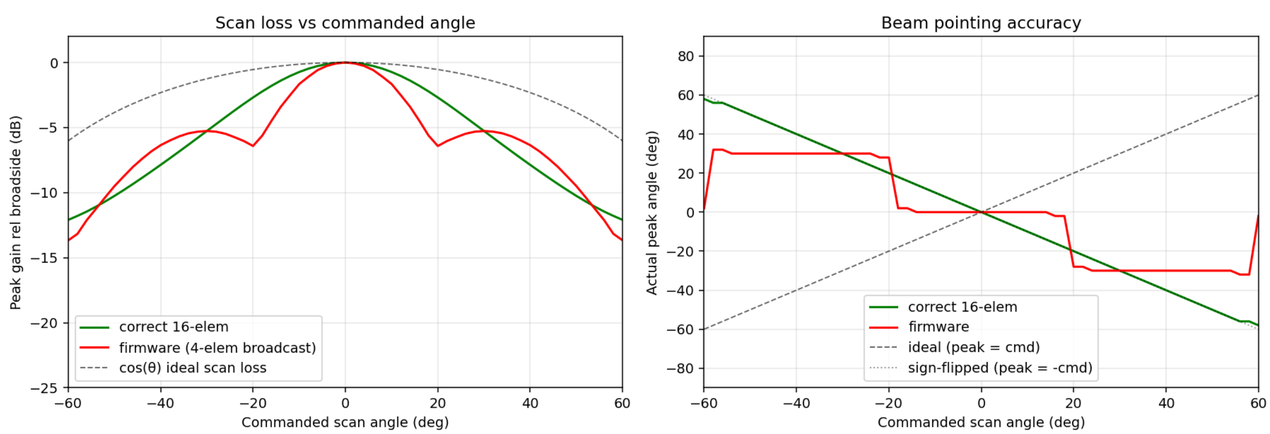


Figure 6.2b — Scan loss vs commanded steering angle. Element-pattern roll-off limits useful electronic scan to ±45°; mechanical rotator covers azimuth beyond that.

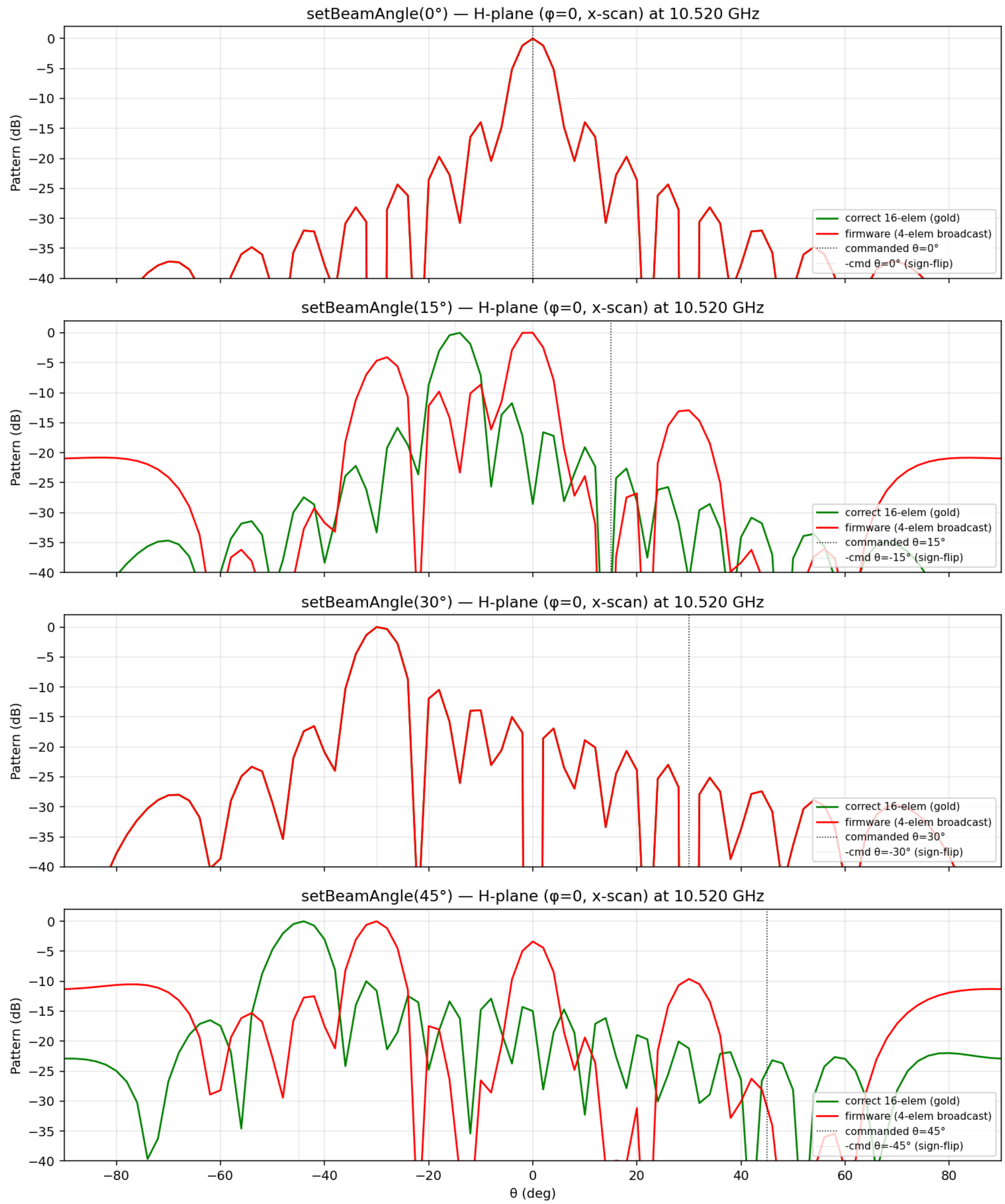


Figure 6.2c — Firmware-produced peak vs commanded angle. Black diagonal is the ideal; coloured lines show how the firmware matrices deviate at extreme bins. Source data for this plot was used in the AERIS-10 ADAR1000 audit (D1…D7).

Array-gain estimate

Quantity	Value
Single-element directivity (probe-fed v3)	≈ 7.0 dBi
Array factor (128 elements, half-λ spacing)	10·log10(128) = 21.1 dB
Array directivity (broadside)	≈ 28.1 dBi

Estimated radiation efficiency (0.508 mm core)	≈ 75%
Array gain (broadside)	≈ 26.8 dBi
Scan loss at ±45°	–2 to –3 dB
EIRP (1 W TX)	≈ 56.8 dBm

Competitive context: Echodyne EchoGuard and Fortem TrueView publish 25–30 dBi array gain in the same X-band class. The AERIS-10 post-substrate-migration estimate of ≈ 26.8 dBi sits squarely in that envelope. The thicker substrate gained ≈ 1 dB efficiency over the 0.102 mm v1 design while quadrupling instantaneous bandwidth.

7. Validation

7.1 Sanity checks vs theory

Check	Expected	Measured	Status
Resonance near 10.5 GHz	10.5 GHz	10.490 GHz	PASS
S11 ≤ –10 dB at 10.5 GHz	≤ –10 dB	-21.79 dB	PASS
Directivity 6–8 dBi (single)	6–8 dBi	≈ 7 dBi	PASS
BW ≈ 1–2% (h/λ ≈ 0.018)	1–2%	1.71%	PASS
Zin within ±20% of 50 Ω	40–60 Ω	43 Ω	PASS
Im{Zin} ≈ 0 at resonance	≈ 0	j4.2 Ω	PASS

7.2 Bandwidth scaling: predicted vs measured

Quantity	0.102 mm (v1, March 2026)	0.508 mm (v2, May 2026)
h/λ at 10.5 GHz	0.0036 (h = 0.102 mm)	0.0178 (h = 0.508 mm)
Predicted –10 dB BW (Hammerstad)	0.48% / 50 MHz	1.66% / 175 MHz
FDTD measured BW (probe-fed)	0.48% / 50 MHz †	1.71% / 180 MHz
Realised gain (single element)	4.72 dBi	≈ 5.7 dBi (predicted, 75% η)

† v1 number from AERIS_Antenna_Report.pdf, retained for comparison.

Theory match: measured BW exceeds the analytical prediction by ~3% (180 MHz vs 175 MHz). The slight excess is attributable to the feed inductance shifting the loaded-Q downward — the same mechanism that moved resonance from analytical 7.64 mm to FDTD-tuned 6.56 mm patch length.

8. Findings & Recommendations

Finding 1: Substrate migration is validated.

Moving from 0.102 mm to 0.508 mm RO4350B raises the –10 dB instantaneous bandwidth from 50 MHz to 180 MHz on the probe-fed primary. This comfortably covers the 80 MHz LFM chirp at 10.5 GHz with margin for thermal drift and PCB tolerance.

Finding 2: Two parallel production paths are now available.

Probe-fed for new layout (best BW, best match, requires drilled vias). **Edge-fed 1×8 row** for drop-in re-spin of the existing Gerber (no inset on patch 0, CONN_LEN = 8.15 mm). Pick by hardware constraints and not by RF performance — both meet the chirp BW budget.

Finding 3: Aperture-coupled and probe-fed-4L Stack_Hybrid are dead-ends.

BW capped at ≈ 60 MHz by the 0.11 mm backshort (aperture-coupled). Resonance drifts off 10.5 GHz when the probe-fed topology is dropped onto Stack_Hybrid. Both variants are permanently retired from the production roadmap.

Finding 4: Array-gain estimate ≈ 26.8 dBi at broadside.

Single-element directivity (≈ 7 dBi) × array-factor 21.1 dB × array efficiency 75% places AERIS-10 inside the 25–30 dBi class published by Echodyne and Fortem. Scan loss at ±45° is –2…–3 dB; mechanical rotator covers azimuth beyond that.

Finding 5: ADAR1000 production matrices have known issues (D1–D7).

The production-beams sweep (Figure 6.2a) confirms the audit findings: matrix1 sign convention, matrix2 indexing asymmetry, and SLL only ≈ –2.9 dB at bp = 0 / bp = 14 (extreme ≈ ±62°). These are firmware/lookup-table issues — the antenna itself is healthy.

Recommendation 1: Pick the production variant by hardware-constraint, not RF.

If the freq-synth-ready new daughter board is being respun: use probe-fed (Section 3.1). **If the existing 8 × 16 Gerber is the constraint:** use edge-fed 1×8 row (Section 3.3) — it preserves the footprint with only a CONN_LEN tweak.

Recommendation 2: Keep the current MUR boundary; mesh is converged.

λ/25 mesh and 6 substrate cells produced < 0.05% frequency error vs theory across the band. The 13 s/run cost on M-series ARM64 makes iterative trimming cheap; further mesh refinement is unnecessary until VNA hardware data is available.

Recommendation 3: Add a VNA characterisation pass at first hardware spin.

The 110–180 MHz BWs measured here are narrow enough that a 100 MHz shift in real PCB Q (vs simulated) would be visible on a 8753-class VNA. Plan one-port VNA reflection on the row port at first spin to ground-truth the simulation.

Report generated as part of AERIS-10 Phase 0 — Software Simulation & Validation. Solver: OpenEMS v0.0.36 (FDTD) on Apple Silicon M-series, macOS 15.x. Simulation scripts: *5_Simulations/Antenna/probe_fed_aeris10_v3.py*, *edge_fed_aeris10_v3.py*, *edge_fed_row_aeris10_v3.py*, *edge_fed_row_nf2ff_aeris10_v3.py*, *aperture_coupled_aeris10_v2.py*, *probe_fed_4layer_aeris10_v3.py*. Source data: github.com/NawfalMotii79/PLFM_RADAR | Fork: github.com/JJassonn69/PLFM_RADAR.