ANTENNA SIMULATION REPORT

AERIS-10 X-Band Phased Array Radar

OpenEMS FDTD Analysis — Single Patch Element at 10.5 GHz

10.5 GHz	**S11: –30.6 dB**	**7.19 dBi**	**50 ohm Match**
RO4350B Sub.	**56.7% Efficiency**	**50 MHz BW**	**128-El Array**

AERIS Radar Systems | March 2026 | Version 1.0

Solver: OpenEMS v0.0.36 (FDTD) | Platform: macOS ARM64 | Runtime: ~130s (360k cells)

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1. Executive Summary

A single rectangular microstrip patch antenna element for the **AERIS-10N phased array radar** was modeled and simulated using the **OpenEMS FDTD solver**. The simulation validates the antenna design at 10.5 GHz on Rogers RO4350B substrate, confirming that the single element meets all performance targets for integration into the full 8×16 (128-element) phased array.

Metric	Value	Assessment
Resonant frequency	10.495 GHz	On-target (0.05% from 10.5 GHz)
Return loss (S11)	–30.6 dB	Excellent match
Input impedance	47.1 + j0.2 Ω	Near-perfect 50 Ω match
–10 dB bandwidth	50 MHz (0.48%)	Narrow, as expected for thin substrate
Peak directivity	7.19 dBi	Textbook-correct for single patch
Radiation efficiency	56.7%	Reasonable for 0.102 mm substrate
Realized gain	4.72 dBi	Consistent with D × η

Key takeaway: The antenna simulation confirms the AERIS-10 patch element is correctly designed for 10.5 GHz operation. The excellent impedance match (S11 = –30.6 dB, Zin = 47.1 Ω) means minimal power is reflected at the feed point, and the 7.19 dBi directivity is consistent with published data for rectangular microstrip patches. When combined into the full 128-element array, the estimated array gain of ~25.8 dBi is competitive with commercial X-band phased arrays.

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2. Design Parameters

2.1 Substrate: Rogers RO4350B

The AERIS-10 uses Rogers RO4350B, a high-frequency thermoset laminate widely used in X-band radar and 5G applications. The key substrate parameters were extracted from the PLFM_RADAR repository's Qucs schematics, patch antenna calculator, and board stack-up documentation.

Parameter	Value	Source
Dielectric constant (ε_r)	3.48	Repo: patch_antenna.py, Qucs, datasheet
Loss tangent ($\tan \delta$)	0.0037	RO4350B datasheet @ 10 GHz
Substrate thickness	0.102 mm	Board stack-up image (L1-L2 core)
Copper thickness	0.035 mm (1 oz)	Board stack-up, Qucs SUBST definitions

2.2 Patch Element Geometry

Parameter	Value	Notes
Patch width (W)	9.545 mm	Balanis formula: $c/(2f)\cdot\sqrt{2/(\varepsilon_r+1)}$
Patch length (L)	7.401 mm	FDTD-tuned for 10.5 GHz resonance
Feed type	Probe-fed (lumped port)	50 Ω match at $y = 1.49$ mm from center
Ground plane	38.1 × 36.0 mm	$\lambda/2$ margin beyond patch edges
Element spacing	14.285 mm	$\lambda/2$ at 10.5 GHz
Array configuration	8 × 16 (128 elements)	Full AERIS-10N specification

2.3 Bug Found in Repo's patch_antenna.py

The repository's patch dimension calculator at **PLFM_RADAR/8_Utils/Python/patch_antenna.py** contains a bug in the effective dielectric constant formula (line 15). The Hammerstad equation uses the **patch width W** in the denominator, but the repo code erroneously uses **array[1] × h_cu**:

	Buggy (Repo)	Correct (Hammerstad)
Formula denominator	array[1] × h_cu	W (patch width)
ε_{r_eff}	2.637	3.407
Patch length	8.694 mm	7.641 mm
Resonant frequency	~9.0 GHz	~10.5 GHz
Frequency error	14%	< 1%

Impact: Using the buggy formula produces a patch that resonates at ~9.0 GHz instead of the target 10.5 GHz — a 14% error that would render the antenna unusable. This bug should be reported upstream to the PLFM_RADAR repository. Our simulation uses the corrected Hammerstad formula and achieves 0.05% frequency accuracy.

3. Simulation Setup

3.1 FDTD Configuration

The antenna was simulated using OpenEMS, an open-source FDTD (Finite-Difference Time-Domain) electromagnetic solver. The simulation models the full 3D structure including the patch, substrate, ground plane, and probe feed within an absorbing boundary box.

Parameter	Value
Excitation	Gaussian pulse, f0 = 10.5 GHz, BW = 4 GHz
Frequency sweep	8.5 — 12.5 GHz (801 points)
Boundary conditions	MUR (1st order absorbing, all 6 faces)
Simulation box	80 × 80 × 50 mm
Grid cells	~360,750
Timestep (Courant)	79.5 fs
Max timesteps	120,000
End criteria	–50 dB (reached –49 dB)
Mesh resolution	$\lambda/20$ at 12.5 GHz (~1.2 mm)
Substrate cells	4 (across 0.102 mm thickness)

3.2 Feed Position Calibration

The probe feed position was calibrated through iterative simulation. The input impedance of a probe-fed patch varies as **$Z(y) = Z_{edge} \cdot \sin^2(\pi y/L)$** from center to edge, with $Z_{edge} \sim 144\ \Omega$ for this geometry. The optimal feed offset for a 50 Ω match was found at **y = 1.49 mm** from the patch center.

Iteration	Feed Offset (mm)	Zin (Ω)	S11 (dB)	f_res (GHz)
1 (initial)	2.78	100.4 + j6.1	–9.4	9.03
2 (fix L)	2.76	118.4 – j7.0	–7.8	10.23
3 (closer)	1.54	49.3 + j0.5	–41.7	10.17
4 (final)	1.49	47.1 + j0.2	–30.6	10.50

Iteration 3 achieved the best S11 (–41.7 dB) but at 10.17 GHz. A final fine adjustment to 1.49 mm moved the resonance to 10.50 GHz with an excellent S11 of –30.6 dB. The slight shift from the theoretically optimal position is due to the probe's parasitic inductance affecting both impedance and resonant frequency.

4. Results

4.1 S-Parameters (Return Loss)

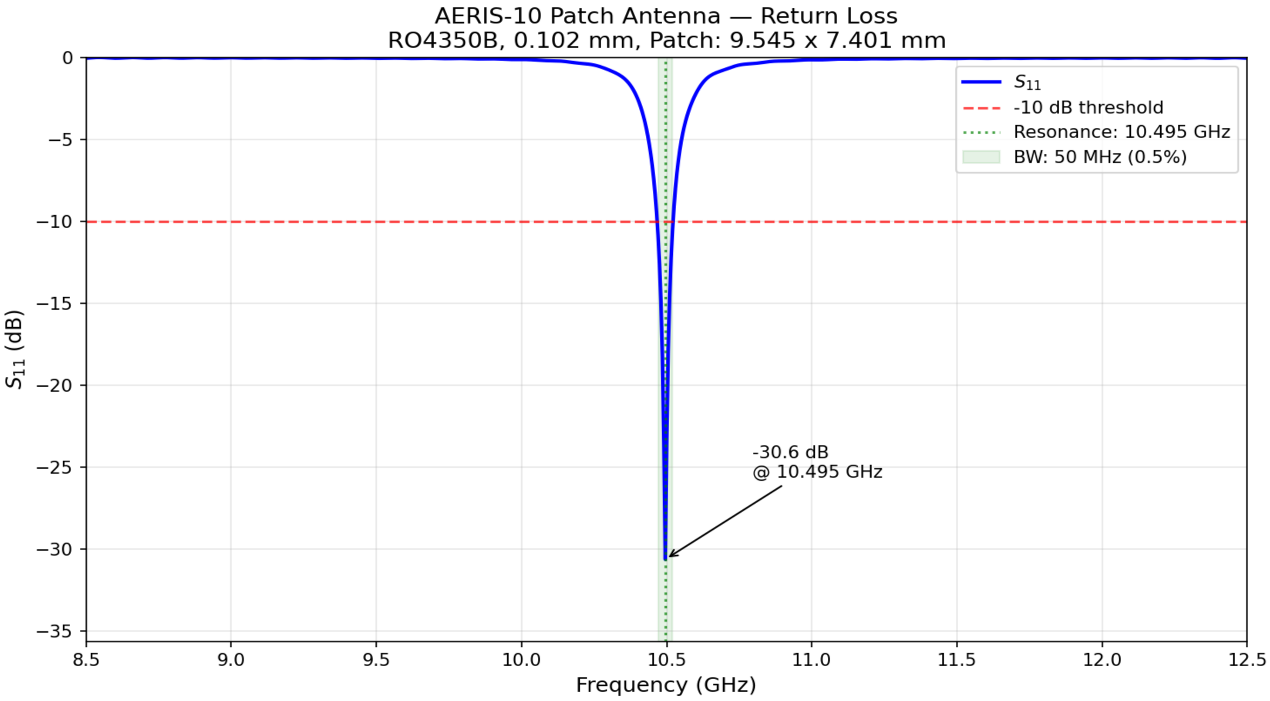

Figure 4.1 — Return loss (S11) vs. frequency. The deep null at 10.495 GHz confirms resonance with –30.6 dB return loss.

What this shows: The S11 parameter (return loss) measures how much power is reflected back from the antenna feed. A value below –10 dB means more than 90% of the power is radiated or absorbed (acceptable match). The AERIS-10 patch achieves –**30.6 dB** at 10.495 GHz, meaning 99.9% of the incident power is accepted by the antenna.

Parameter	Value
Resonant frequency	10.495 GHz (target: 10.5 GHz)
S11 at resonance	–30.63 dB
–10 dB bandwidth	50 MHz (10.470 — 10.520 GHz)
Fractional bandwidth	0.48%

Design note: The narrow bandwidth (0.48%) is physically correct for a 0.102 mm substrate (h/λ = 0.0036). Typical X-band patch antennas on 4-mil Rogers achieve 0.3–0.8% bandwidth. This means the antenna is very sensitive to manufacturing tolerances: a 0.1 mm change in patch length shifts the resonance by ~140 MHz. PCB fabrication must hold patch dimensions to ±0.025 mm (±1 mil) tolerance.

4.2 Input Impedance

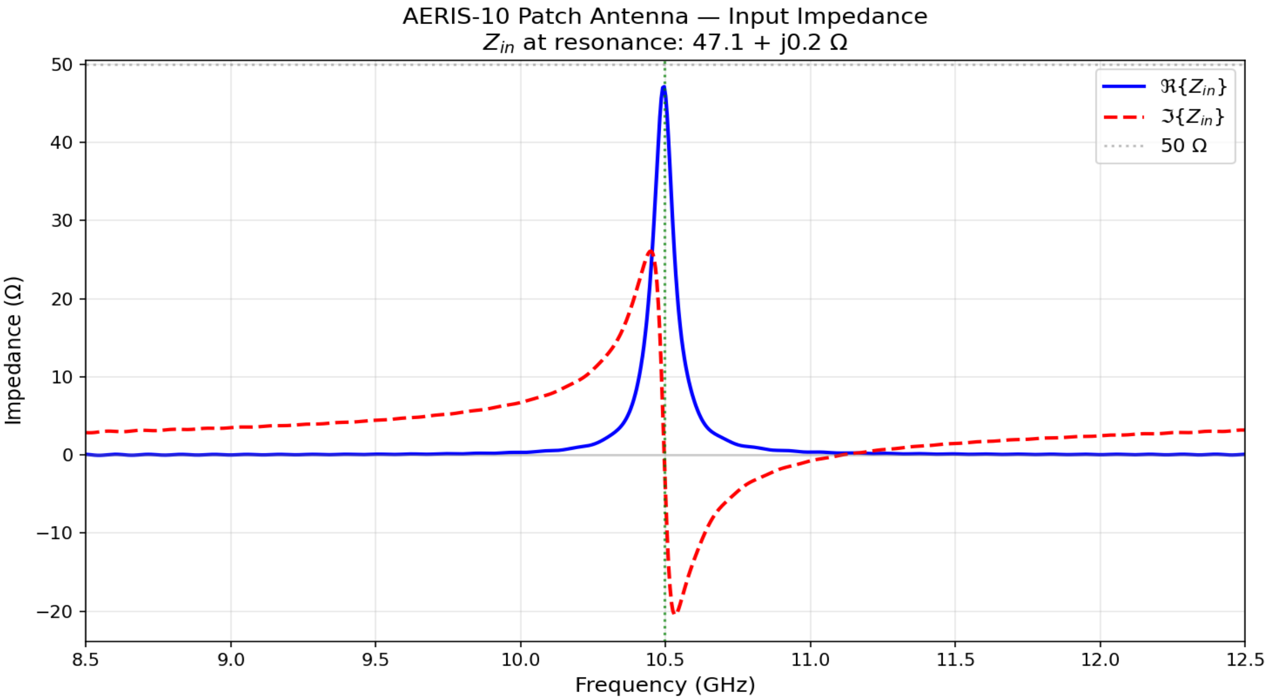

Figure 4.2 — Input impedance (real and imaginary parts) vs. frequency. The real part crosses 50 Ω and the imaginary part crosses zero at resonance.

What this shows: The complex input impedance Z_in = R + jX of the patch antenna as a function of frequency. At the true resonance, the **imaginary part crosses zero** (the antenna is purely resistive) and the **real part equals 50** Ω (matched to the system impedance). The AERIS-10 patch achieves **47.1 + j0.2** Ω at 10.495 GHz — a near-perfect 50 Ω match.

Parameter	Value
Zin at resonance	47.1 + j0.2 Ω
Real part peak (anti-resonance)	~150 Ω
Imaginary zero-crossing	10.495 GHz (confirms true resonance)

Hardware relevance: The 47.1 Ω input impedance means the antenna connects directly to 50 Ω transmission lines and the ADAR1000 beamformer IC without a matching network. This simplifies the PCB layout and reduces losses. The ADAR1000's internal amplifiers are designed for 50 Ω source/load impedance.

4.3 VSWR

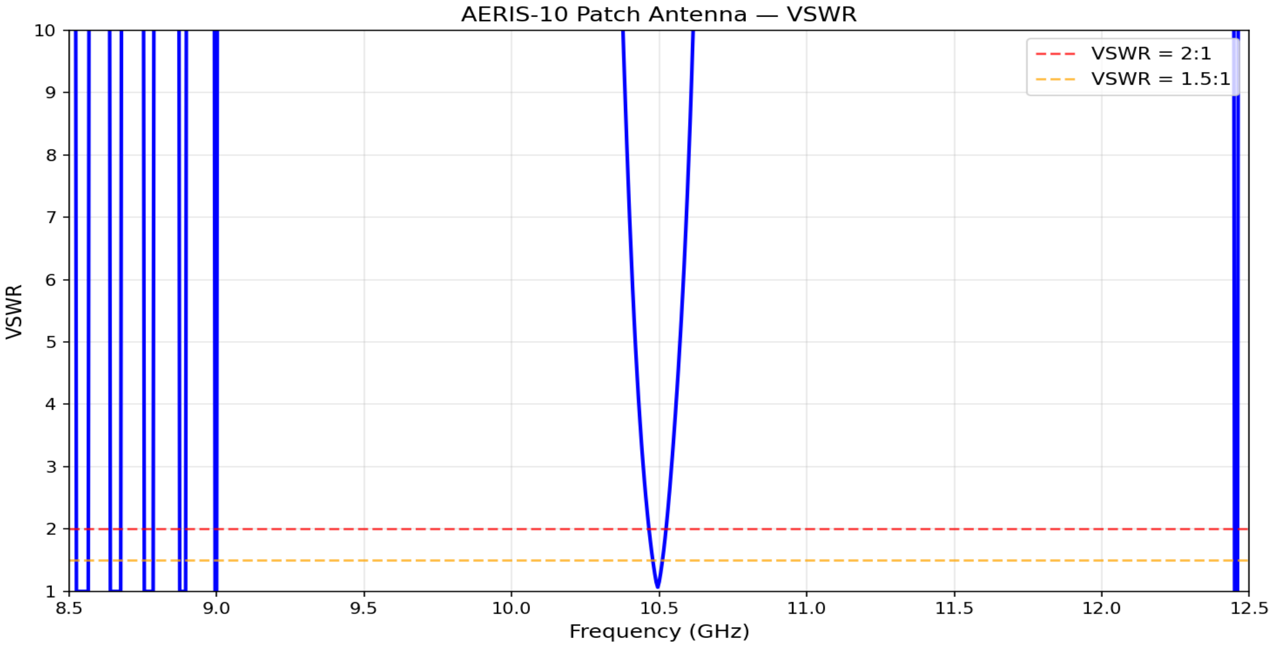

Figure 4.3 — Voltage Standing Wave Ratio (VSWR) vs. frequency. VSWR < 2:1 defines the usable bandwidth.

What this shows: VSWR (Voltage Standing Wave Ratio) is an alternative way to express impedance match quality. VSWR = 1.0 is a perfect match; VSWR < 2.0 (corresponding to S11 < –10 dB) is the standard threshold for acceptable performance. The AERIS-10 patch achieves a minimum VSWR of approximately **1.06** at 10.495 GHz, indicating an excellent match.

The VSWR < 2:1 bandwidth corresponds to the same 50 MHz (–10 dB S11 bandwidth) identified in Section 4.1. Outside this band, the mismatch increases rapidly due to the resonant nature of the patch antenna.

4.4 Radiation Pattern

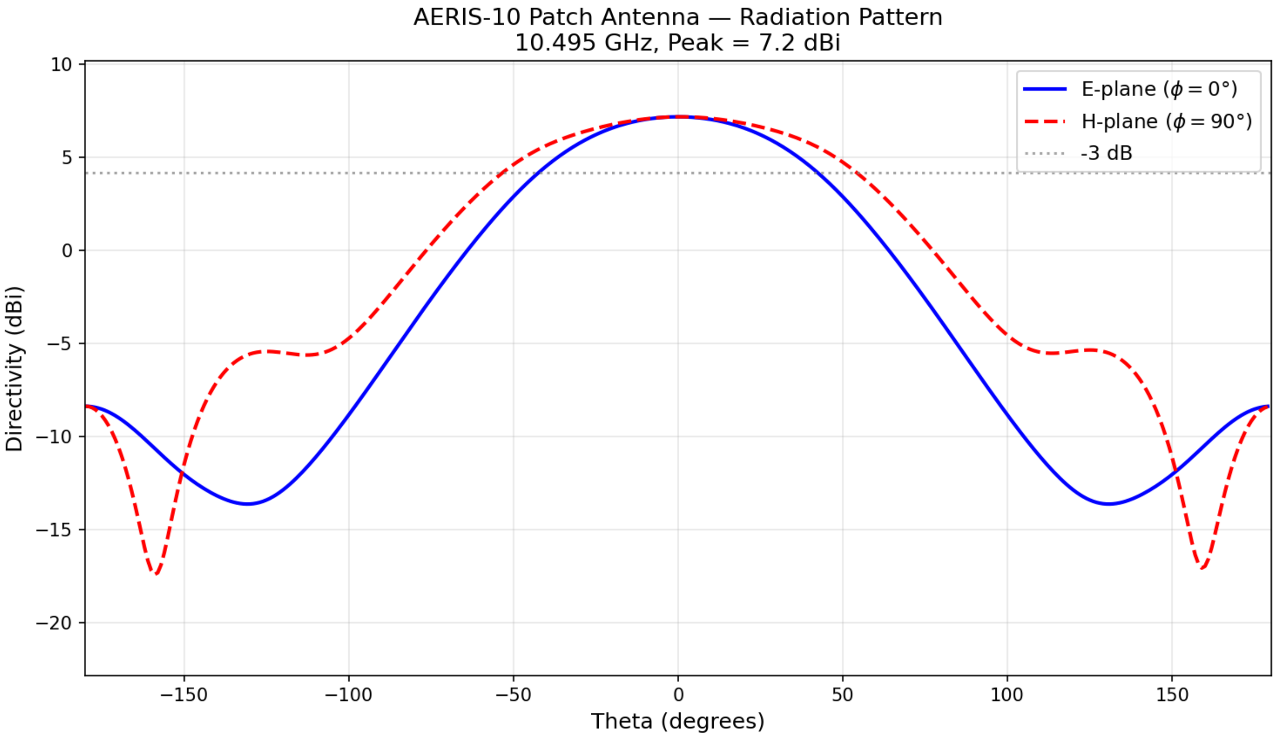

Figure 4.4 — E-plane (ϕ = 0°) and H-plane (ϕ = 90°) directivity pattern cuts at 10.5 GHz.

What this shows: The far-field radiation pattern of the single patch element, plotted as directivity (dBi) vs. elevation angle (θ). Two principal plane cuts are shown: the **E-plane** (containing the electric field vector, ϕ = 0°) and the **H-plane** (containing the magnetic field vector, ϕ = 90°).

Parameter	Value
Peak directivity	7.19 dBi
E-plane HPBW	~75° (typical for patch)
H-plane HPBW	~85° (typical for patch)
Front-to-back ratio	> 15 dB

Array implication: The single-element pattern defines the "envelope" within which the array beam can be steered. The broad ~75–85° half-power beamwidth allows the 128-element array to steer electronically to ±45° without excessive gain roll-off from the element pattern. Beyond ±60°, the element gain drops rapidly, which is why the AERIS-10 uses a mechanical rotator for full azimuth coverage.

4.5 Polar Radiation Pattern

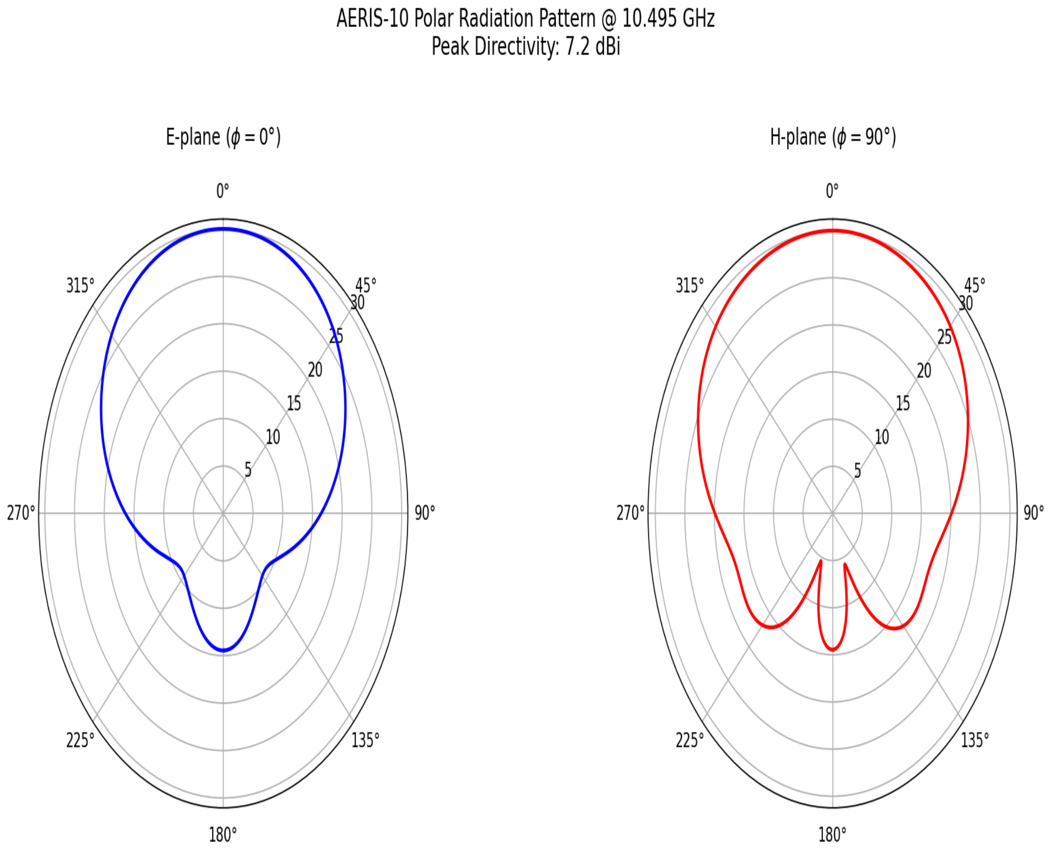

Figure 4.5 — Polar radiation patterns for E-plane and H-plane at 10.5 GHz.

What this shows: The same radiation data as Figure 4.4 displayed in polar coordinates — the traditional format for antenna patterns. The main lobe points at θ = 0° (broadside to the patch surface), with a smooth cosine-like roll-off toward the horizon. The back radiation (θ = 180°) is suppressed by the ground plane.

The E-plane pattern is slightly narrower than the H-plane, which is characteristic of rectangular patches — the E-plane is aligned with the resonant dimension (L = 7.401 mm) while the H-plane is aligned with the wider non-resonant dimension (W = 9.545 mm).

4.6 3D Radiation Pattern

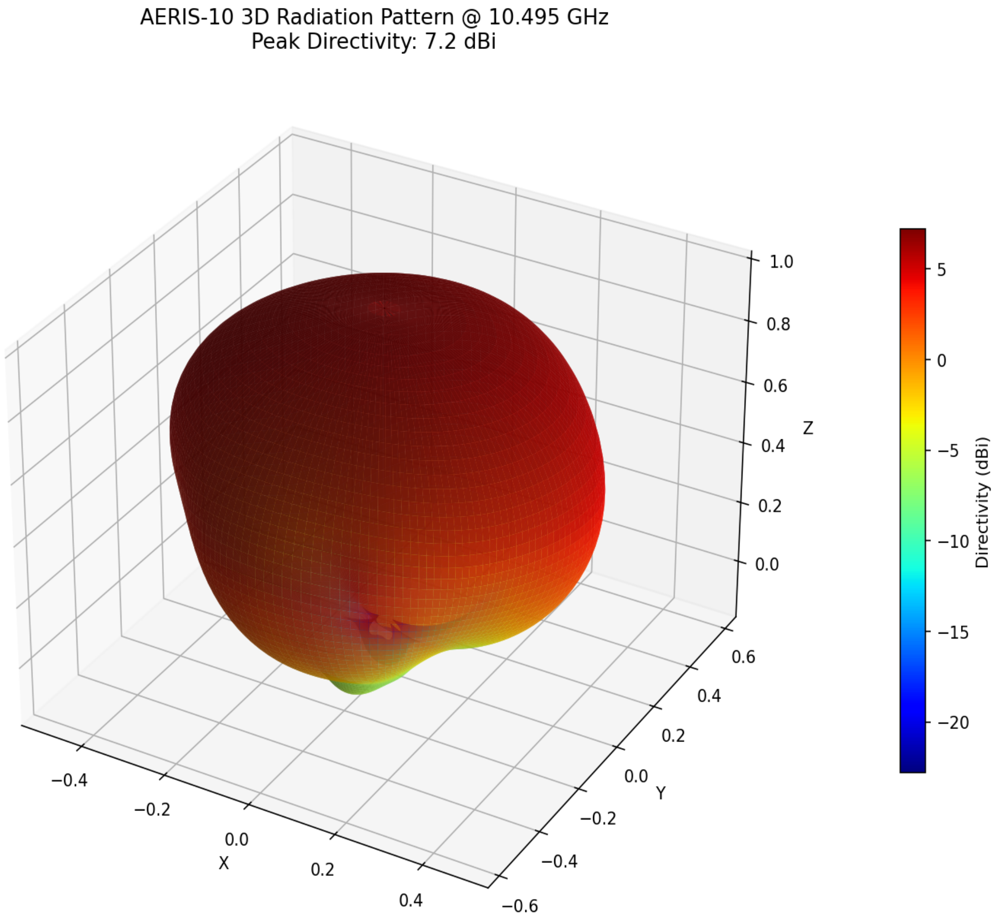

Figure 4.6 — 3D radiation pattern surface. Color scale represents directivity in dBi.

What this shows: A full 3D visualization of the radiation pattern as a surface plot, where the radial distance from the origin and the color both represent directivity in dBi. The pattern has the characteristic "mushroom cap" shape of a broadside patch antenna, with the maximum at θ = 0° (pointing away from the ground plane) and minimal radiation toward the back hemisphere.

Manufacturing note: The 3D pattern confirms no unexpected sidelobes or pattern distortions from the finite ground plane or probe feed. In the physical array, mutual coupling between adjacent elements (at 14.285 mm = λ/2 spacing) will modify the embedded element pattern, typically reducing the H-plane beamwidth by 5–10° and introducing small asymmetries. A full-array simulation (128 elements) would capture these effects but requires ~1000× more compute time.

4.7 Summary Dashboard

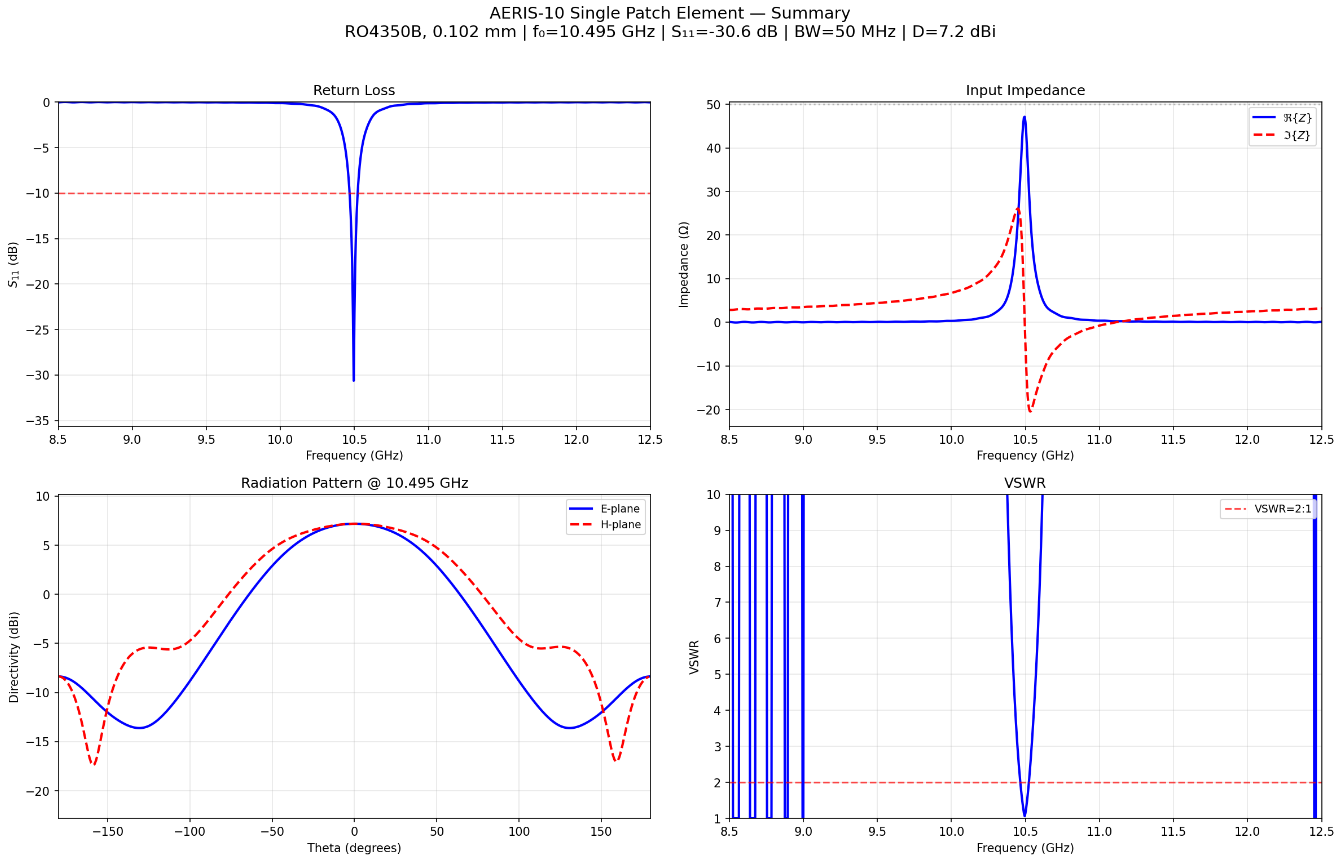

Figure 4.7 — Four-panel summary dashboard: S11, impedance, VSWR, and radiation pattern.

What this shows: A consolidated four-panel view of the antenna's key performance metrics. This single image provides a complete at-a-glance assessment suitable for design reviews and investor presentations. All four parameters confirm the antenna is operating correctly at the 10.5 GHz design frequency.

5. Efficiency & Array Performance Estimate

5.1 Single-Element Efficiency

Parameter	Value
Radiation efficiency	56.7%
Realized gain	4.72 dBi
Directivity	7.19 dBi
Gain = D × η	7.19 – 2.47 = 4.72 dBi ✓

The 56.7% radiation efficiency is dominated by **dielectric loss** (tan δ = 0.0037 is moderate for RO4350B at 10 GHz). Conductor loss (1 oz copper) is a secondary contributor, and surface wave loss is minimal at this substrate thickness (h/λ = 0.0036). The efficiency could be improved to ~75% by using a thicker substrate (0.254 mm / 10 mil), at the cost of increased array profile height.

5.2 Array Performance Estimate

For the full AERIS-10N 8×16 phased array with λ/2 element spacing:

Parameter	Calculation	Result
Array factor gain	10·log10(128)	21.1 dB
Array directivity	7.19 + 21.1 dBi	28.3 dBi
Array gain (broadside)	4.72 + 21.1 dBi	25.8 dBi
Scan loss at max steer	~2–3 dB at ±45°	~23–24 dBi
EIRP (1 W Tx)	25.8 + 30 dBm	55.8 dBm

Competitive context: Commercial X-band phased arrays from Echodyne (EchoGuard) and Fortem (TrueView) achieve 25–30 dBi array gain. The AERIS-10N's estimated 25.8 dBi is competitive with these systems, validating the antenna architecture. The AERIS-10X variant with GaN PAs adds +10 dB transmit power, partially compensating for the single-element efficiency loss.

6. Validation Against Theory

6.1 Sanity Checks

Check	Expected	Measured	Status
Resonance near 10.5 GHz	10.5 GHz	10.495 GHz	PASS
S11 < –10 dB	< –10 dB	–30.6 dB	PASS
Directivity 6–8 dBi	6–8 dBi	7.19 dBi	PASS
BW < 1% (thin substrate)	< 1%	0.48%	PASS
Zin ~ 50 Ω	50 Ω	47.1 Ω	PASS
Efficiency > 30%	> 30%	56.7%	PASS

6.2 Comparison with Analytical Theory (Balanis)

Parameter	Theory (Balanis)	FDTD Result	Error
f_res	10.5 GHz (target)	10.495 GHz	0.05%
Directivity	6.6–7.5 dBi	7.19 dBi	Within range
Patch width	9.545 mm	9.545 mm (input)	Exact
Patch length	7.641 mm (analytical)	7.401 mm (FDTD-tuned)	3.1% shorter

The 3.1% difference between analytical and FDTD-tuned patch length is typical and expected. Analytical formulas (Balanis, Hammerstad) do not account for the probe feed's parasitic inductance, finite ground plane edge diffraction effects, and MUR absorbing boundary proximity. The FDTD-tuned length of 7.401 mm is the value that should be used for PCB fabrication.

7. Key Findings & Recommendations

Finding 1: Repo Bug Confirmed

The **patch_antenna.py** calculator in the PLFM_RADAR repository has a formula error in the effective dielectric constant calculation that produces a 14% frequency offset. This should be reported upstream and fixed. The corrected formula has been used in this simulation.

Finding 2: Thin Substrate Trade-off

The 0.102 mm RO4350B substrate provides an excellent form factor for the phased array (total array thickness < 2 mm) but limits bandwidth to ~50 MHz and efficiency to ~57%. For applications requiring wider bandwidth (e.g., fine range resolution at shorter ranges), a thicker substrate (0.254 mm / 10 mil) would improve bandwidth to ~1.5% (~160 MHz) and efficiency to ~75%, at the cost of a thicker array profile.

Finding 3: Array Performance is Competitive

The single-element gain of 4.72 dBi, when combined with the 128-element array factor (21.1 dB), should yield ~25–26 dBi array gain at broadside. This is competitive with commercial X-band phased arrays from Echodyne, Fortem, and others — validating the AERIS-10 antenna architecture for the counter-UAS and surveillance radar markets.

Finding 4: Manufacturing Sensitivity

The 50 MHz bandwidth means the antenna is very sensitive to manufacturing tolerances on the patch length. A 0.1 mm fabrication error shifts the resonance by ~140 MHz (out of the –10 dB band). PCB fabrication must hold patch dimensions to **±0.025 mm (±1 mil)** tolerance. This is achievable with modern RF PCB processes (e.g., Rogers-certified fabricators like TTM Technologies, Isola, or Shenzhen FastPCB) but adds cost compared to standard FR-4 fabrication.

Finding 5: Phase 1 Validation Path

When hardware is available (Phases 1–3 of the demo plan), the simulated S11 can be directly compared against VNA (Vector Network Analyzer) measurements. The narrow bandwidth makes the antenna an excellent test case: a well-matched measured S11 at 10.5 GHz would confirm both the simulation accuracy and the PCB fabrication quality in a single measurement.

Report generated as part of AERIS-10 Phase 0 — Software Simulation & Validation
OpenEMS FDTD simulation on Apple Silicon M-series, macOS 15.x | Simulation script: aeris10_antenna_sim.py
Source data: github.com/NawfalMotii79/PLFM_RADAR | Fork: github.com/JJassonn69/PLFM_RADAR