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WHITE PAPER | ELECTROMAGNETIC AND THERMAL

Steady, Low-Sidelobe Beams for Satcom and Radar Antenna Teams

How the temperature gradient across an air-cooled active array tile changes its beam, which errors a single temperature sensor can correct, and when per-channel correction or a larger heat sink is needed.

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Method
2D finite-volume thermal model coupled to an array-factor pattern model

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Abstract

Active phased arrays dissipate heat at every element, and the transmit/receive channels drift in phase and gain as they warm. We couple a finite-volume thermal model of an 8 × 8 X-band tile (10 GHz, half-wavelength spacing, 2 W per channel, forced-air heat sink) to an array-factor model of a single tile and of a 4 × 4 array of identical tiles with a 30 dB Taylor taper. With 40 °C inlet air the channel temperatures span 9.2 K from the air inlet to the outlet. The resulting errors are evaluated for phase coefficients from 0 to 1.2°/°C and an amplitude coefficient of −0.015 dB/°C.

Uniform warming relative to a 25 °C factory calibration costs 0.75 dB of gain; one temperature sensor per tile removes it. The gradient barely moves the beam: at 0.5°/°C a single tile points 0.23° off at broadside (1.8 % of its beamwidth). In the large array, however, the same error repeats on every tile and raises tile-periodic lobes: the peak sidelobe rises by 2.8 dB, a one-sensor correction does not change it, doubling the heat sink and airflow recovers 1.2 dB, and per-channel temperature correction recovers all but 0.02 dB. The peak sidelobe stays within 1 dB of design while the phase error spread across a tile is below 2.2°, a threshold any team can check against its own channel coefficient and gradient.

Keywords: active phased array, transmit/receive module, thermal gradient, calibration, sidelobe level, subarray error.

1. Introduction

An active electronically scanned array places a transmit/receive (T/R) channel behind every radiating element. The channels are calibrated so that their phases and amplitudes form the intended aperture distribution, but each channel's insertion phase and gain change with temperature. At full power the channels warm unevenly, because coolant or air warms as it crosses the array and because interior channels are surrounded by neighbors. The array then operates away from its calibrated state.

The effects of excitation errors on array patterns are well understood. Random errors raise an average sidelobe floor and reduce gain in proportion to their variance [3], [6]. Errors that are correlated across the aperture behave differently: a linear phase gradient steers the beam [1], [2], and errors that repeat on each subarray produce periodic lobes at fixed angular spacing [1]. Wang et al. coupled a thermal model to the pattern of an active array and reported gain loss and pointing changes with temperature [5]. What a program team needs in addition is a way to decide, before hardware exists, whether its thermal design or its calibration scheme must change.

This paper builds that link for a representative air-cooled tile. It separates three error types (uniform warming, the gradient within a tile, and the repetition of that gradient across tiles), shows which correction removes each, and gives a design chart in terms of the phase error spread across a tile, the product of the channel phase coefficient and the tile temperature spread.

2. Model and Method

2.1 Thermal Model

The tile (Figure 1, Table 1) is a 120 × 120 mm aluminum spreader carrying 64 channels at 15 mm pitch, one half wavelength at 10 GHz. Each channel dissipates 2 W over an 8 × 8 mm footprint and has a junction-to-spreader resistance of 6 K/W. A finned heat sink is represented by an effective heat transfer coefficient referenced to the footprint. Air enters at one edge at 40 °C and warms as it crosses the tile. In-plane conduction in the spreader is solved on a 1 mm finite-volume grid [8], coupled to one upwind air node per cell with the energy balance $\dot{m}_{row} c_p (T_{a,i} - T_{a,i-1}) = h_{eff} A_{cell} (T_{s,i} - T_{a,i})$ [7]. Edges are adiabatic, as for a tile surrounded by identical tiles.

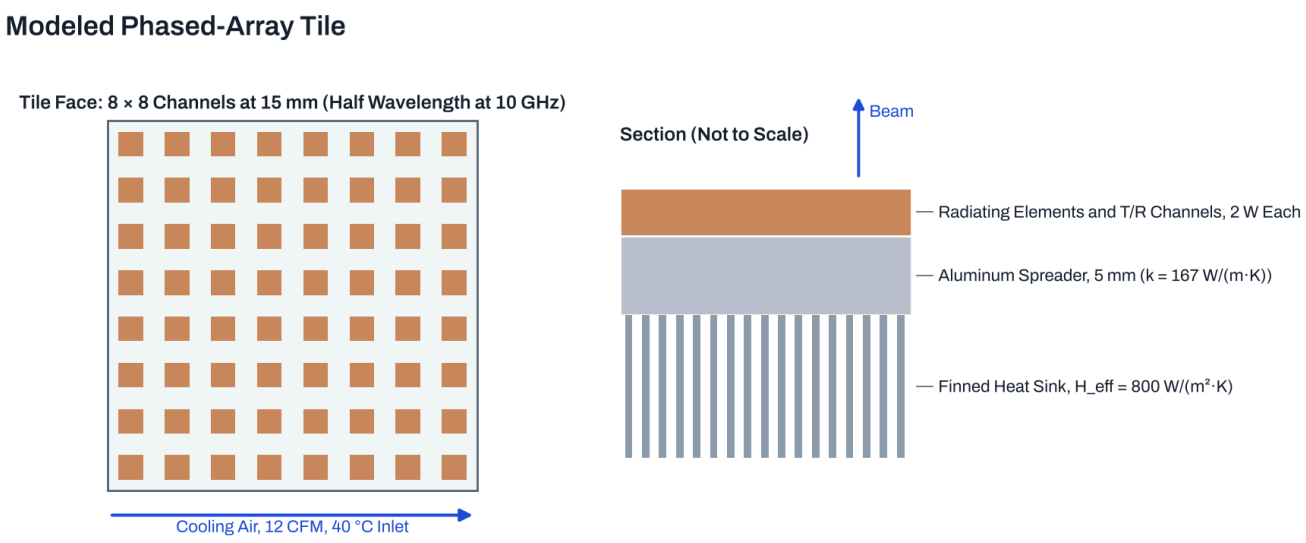


Figure 1. Modeled tile. Left: face with 8 × 8 channels (copper squares are channel footprints) and the airflow direction. Right: section through the element layer, aluminum spreader and finned heat sink. Values are listed in Table 1.

Parameter	Value	Basis
Frequency, element spacing	10 GHz; 15 mm (λ/2)	Representative X band
Channels per tile; array	8 × 8; 4 × 4 tiles (32 × 32)	Representative
Dissipation per channel	2.0 W (128 W per tile)	Representative
Junction-to-spreader resistance	6 K/W per channel	Representative
Spreader	Aluminum 6061, 5 mm, k = 167 W/(m·K)	Handbook value
Heat sink	h_{eff} = 800 W/(m²·K); 12 CFM; 40 °C inlet	Representative forced-air sink
Phase coefficient κ_φ	0 to 1.2°/°C swept; 0.5°/°C illustrative	Design-specific; see Section 2.2
Amplitude coefficient κ_A	−0.015 dB/°C	Consistent with the model of [5]
Calibration temperature	25 °C, uniform	Factory calibration
Taper	Single tile uniform; array 30 dB Taylor, $\bar{n}$ = 4, in both axes	[4]

Table 1. Model inputs. h_{eff} is the heat sink conductance per unit footprint area; CFM is cubic feet per minute; $\bar{n}$ is the Taylor parameter.

2.2 Excitation Errors and Pattern

Each channel's phase and amplitude errors are linear in its temperature difference from calibration, $\delta\varphi_n = \kappa_\varphi(T_n - T_{cal})$ and δA_n [dB] = $\kappa_A(T_n - T_{cal})$. Phase coefficients vary between channel designs and must come from a datasheet or bench test; one published module model gives about 0.03°/°C over 50 to 70 °C [5]. Because the answer scales with the coefficient, we sweep it and report results against the phase error spread across a tile, $\kappa_\varphi \Delta T_{tile}$. Four responses are compared: factory calibration only; one temperature sensor per tile that removes the mean error; per-channel correction from a temperature lookup table with a 10 % residual and 1 °C sensor noise (50 random draws); and a heat sink and airflow both doubled with factory calibration only.

The far field in the plane of the gradient is the array factor

$$F(u) = \Sigma_m \Sigma_n a_m a_n g_{mn} e^{j\delta\varphi_{mn}} e^{jkd\, m\, (u - u_0)}, \quad u = \sin\theta \tag{1}$$

with taper a, amplitude error $g = 10^{\delta A/20}$, element spacing d and steering direction u_0 [2]. It is evaluated on 80,001 points in u. Element patterns are omitted; they are common to all channels and do not change the relative effects. Pointing is the peak location refined by a parabolic fit; the peak sidelobe is the largest value outside the first nulls of the ideal pattern.

3. Verification

Check	Reference	Result
Thermal energy balance	Heat into air equals 128 W	Relative error 3e-13
Air outlet temperature	40 °C + P/($\dot{m}c_p$)	59.915 °C against 59.915 °C
Thermal grid 1.0 and 0.5 mm	Finer grid	Hottest channel 78.94 and 78.93 °C; spread 9.25 and 9.27 K
Pointing from a linear phase gradient	$\Delta u = -s/(kd)$, s = fitted slope per element [1]	Model -0.2253° and -0.3178° against -0.2253° and -0.3178° (0° and 45° steering)
Random phase errors, 5° rms, 32 elements, 2,000 trials	Mean error power $(2 - 2e^{-\sigma^2/2})\Sigma a^2/(\Sigma a)^2$ [3], [6]	-35.58 dB against -35.55 dB
Ideal Taylor pattern	30 dB design sidelobe level [4]	30.24 dB below peak

Table 2. Verification of the thermal and pattern models.

4. Results

4.1 Temperatures

The air warms by 19.9 K across the tile. Channel junction temperatures range from 69.7 °C at the inlet edge to 78.9 °C at the outlet edge, a spread of 9.2 K, and are uniform across the airflow (Figure 2). The spreader carries part of the heat upstream, so the channel spread is less than half the air temperature rise. Doubling both the heat transfer coefficient and the airflow lowers the hottest channel to 66.0 °C and the spread to 6.0 K.

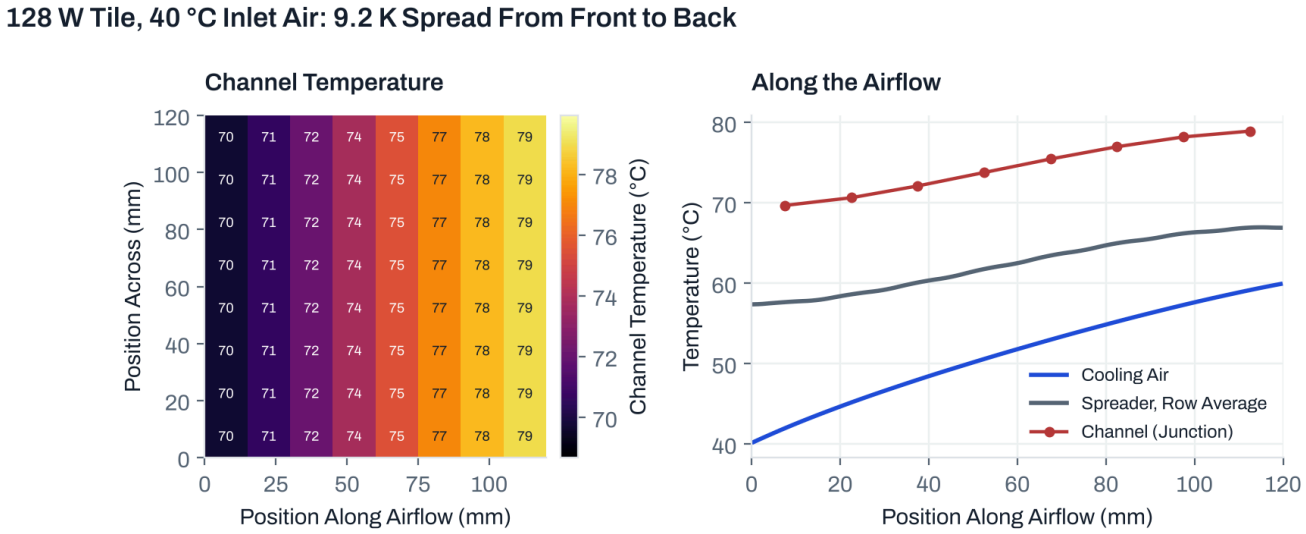


Figure 2. Base case: 2 W per channel, 12 CFM, 40 °C inlet air. Left: junction temperature of each channel (°C). Right: air, spreader and junction temperatures along the airflow; spreader and channel values are averaged across the airflow.

4.2 Single Tile

For one tile with uniform weighting the beamwidth is 12.8° at broadside and 18.4° at 45°. At 0.5°/°C the gradient produces a nearly linear phase error across the tile and moves the beam by 0.23° at broadside and 0.32° at 45°, under 2 % of the beamwidth (Figure 4, right). Uniform warming of 49.5 K above calibration reduces gain by 0.74 dB through

the amplitude coefficient; one sensor per tile removes this. The sidelobes of a uniformly weighted tile change by less than 0.1 dB.

4.3 Array of Tiles

In a 32 × 32 array built from identical tiles, every tile carries the same error pattern. The tile-level beam shift cancels at array level (the array beam moves 0.010° at 45°), but the error now repeats with the tile period and produces lobes at $u_0 \pm k\lambda/D_{tile}$, where $D_{tile} = 4\lambda$ is the tile width [1]. With a 30 dB Taylor taper these lobes set the peak sidelobe: at 0.5°/°C it rises from -30.2 to -27.5 dB (Figure 3).

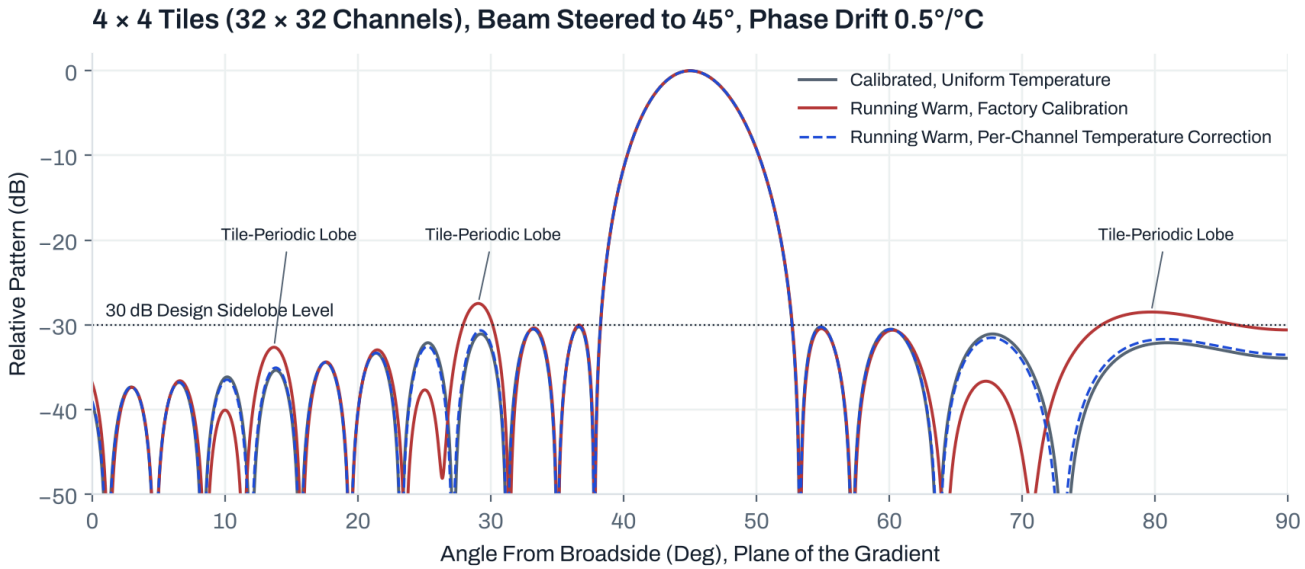


Figure 3. Pattern of the 32 × 32 array (4 × 4 identical tiles, 30 dB Taylor taper) steered to 45° in the plane of the temperature gradient, with phase coefficient 0.5°/°C and amplitude coefficient −0.015 dB/°C. Each curve is normalized to its own peak. Labeled lobes are the tile-periodic lobes at $u_0 \pm k/4$.

Figure 4 gives the general result. The peak sidelobe stays at its design value until the phase error spread across a tile reaches about 1°, rises 0.5 dB at 1.5° and 1 dB at 2.2°, and reaches -23.9 dB at 11°. For the 9.2 K spread of this tile, those spreads correspond to phase coefficients of 0.17°/°C and 0.23°/°C.

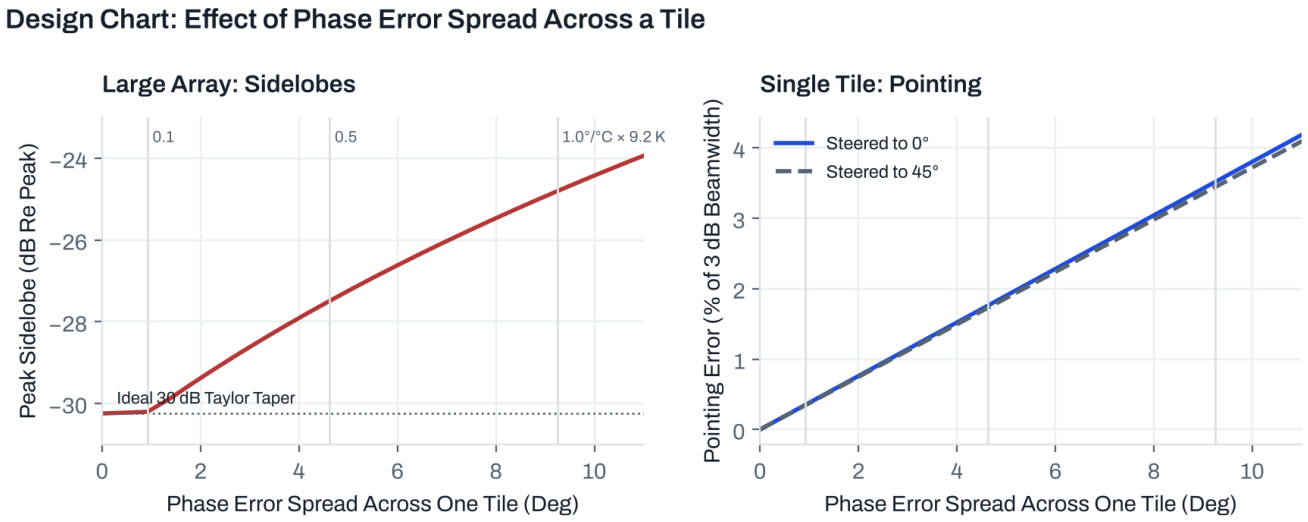


Figure 4. Design chart against the phase error spread across one tile (phase coefficient times tile temperature spread). Left: peak sidelobe of the 32 × 32 array at 45° with a 30 dB Taylor taper; the dotted line is the ideal level. Right: pointing error of a single uniformly weighted tile as a percentage of its 3 dB beamwidth. Vertical lines mark 0.1, 0.5 and 1.0°/°C for the 9.2 K spread of this tile. Amplitude errors are excluded.

4.4 Corrections Compared

Figure 5 compares the four responses for the array at 45°. One sensor per tile restores gain but leaves the sidelobe rise unchanged, because the gradient, not the mean, causes it. Per-channel correction restores both, leaving 0.02 dB of sidelobe rise from the residual model error (95th percentile of 50 sensor-noise draws: 0.03 dB). Doubling heat sink conductance and airflow cuts the temperature spread by 36 % and the sidelobe rise to 1.58 dB, and reduces the gain loss only to 0.57 dB because the array still runs above its calibration temperature.

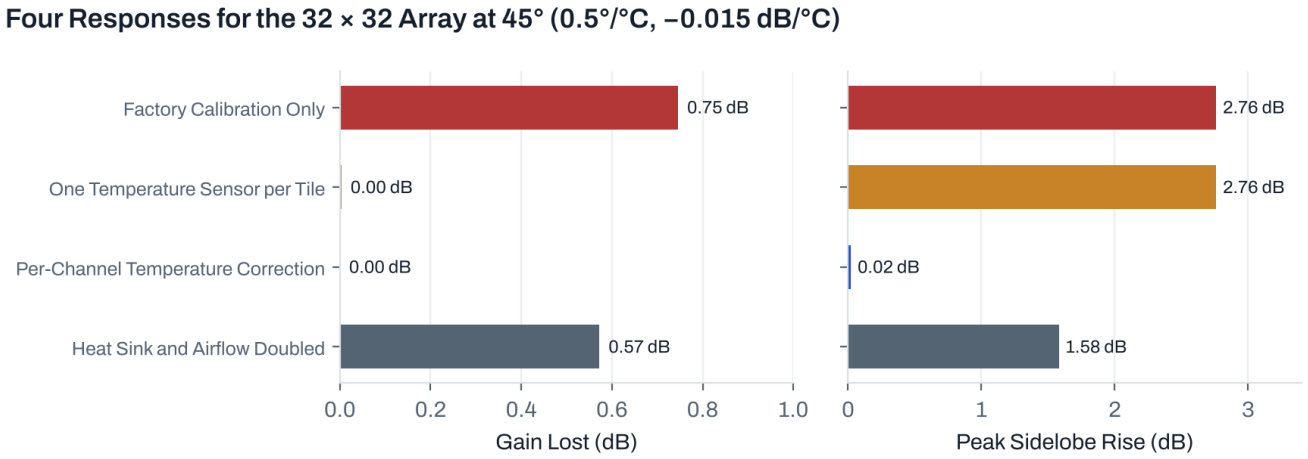


Figure 5. Gain lost and peak sidelobe rise relative to the calibrated array for four responses: 32 × 32 array steered to 45°, 0.5°/°C and −0.015 dB/°C. Per-channel correction assumes a 10 % residual model error; the sensor-noise case is reported in the text.

5. Discussion

For a program team the results separate cleanly. Gain loss is a uniform-temperature effect and is the cheapest to fix: one sensor per tile and a gain table recover it. Beam pointing is not a thermal problem for a tile cooled this way, even at the upper end of the coefficient range. The sidelobe rise in a large array is the effect that drives design decisions, and it is set by the phase error spread across one tile. If the channel coefficient times the tile temperature spread stays below

about 2.2°, factory calibration plus one sensor per tile is enough for a 30 dB array. Above it, per-channel temperature correction is far more effective than a larger heat sink: doubling the sink removes about 43 % of the sidelobe rise at the cost of size, weight and fan power, while per-channel correction removes nearly all of it with sensors that many channel designs already include.

The same chart applies to other cooling layouts. A liquid cold plate with counterflow, or a tile that is hot in the center, gives a different spread and shape; a center-hot (quadratic) error mainly widens the beam and fills nulls rather than creating a single dominant lobe. Staggering or rotating tiles breaks the periodicity and spreads the lobe energy, a known subarray technique [1].

Limitations. Linear temperature coefficients; identical tiles; steady state; isotropic elements and no mutual coupling; principal-plane cut only; air-side heat transfer represented by a single effective coefficient. The phase coefficient is the controlling input and must come from the channel design.

6. Conclusions

1. With 2 W per channel and 40 °C inlet air, the modeled tile has a 9.2 K temperature spread along the airflow.
2. Warming relative to a 25 °C calibration costs 0.75 dB of gain; one temperature sensor per tile removes it.
3. Thermal gradients move a single tile's beam by under 2 % of its beamwidth at 0.5°/°C; pointing is not the limiting effect.
4. In a large array of identical tiles, the gradient raises tile-periodic lobes. The peak sidelobe stays within 1 dB of a 30 dB design while the phase error spread per tile is below 2.2°.
5. Above that, per-channel temperature correction recovers nearly all of the sidelobe rise; doubling the heat sink and airflow recovers about 43 %.

References

1. R. J. Mailloux, *Phased Array Antenna Handbook*, 3rd ed. Boston: Artech House, 2017.
2. C. A. Balanis, *Antenna Theory: Analysis and Design*, 4th ed. Hoboken: Wiley, 2016.
3. R. C. Hansen, *Phased Array Antennas*, 2nd ed. Hoboken: Wiley, 2009.
4. T. T. Taylor, "Design of line-source antennas for narrow beamwidth and low side lobes," *IRE Transactions on Antennas and Propagation*, vol. AP-3, no. 1, pp. 16–28, 1955.
5. Y. Wang, C. Wang, P. Lian, S. Xue, J. Liu, W. Gao, Y. Shi, Z. Wang, K. Yu et al., "Effect of temperature on electromagnetic performance of active phased array antenna," *Electronics*, vol. 9, no. 8, art. 1211, 2020. doi:10.3390/electronics9081211
6. J. Ruze, "Antenna tolerance theory: a review," *Proceedings of the IEEE*, vol. 54, no. 4, pp. 633–640, 1966.
7. T. L. Bergman, A. S. Lavine, F. P. Incropera and D. P. DeWitt, *Fundamentals of Heat and Mass Transfer*, 7th ed. Hoboken: Wiley, 2011.
8. S. V. Patankar, *Numerical Heat Transfer and Fluid Flow*. Washington: Hemisphere, 1980.

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