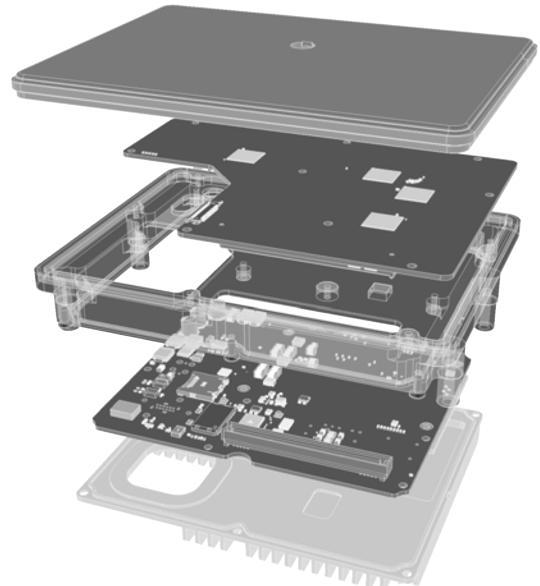
Rugged Packaging Solutions for Radar Sensors in Diverse Applications and Environments

Mo Emadi, CEO and David Wu, Head of Hardware:
Zadar Labs

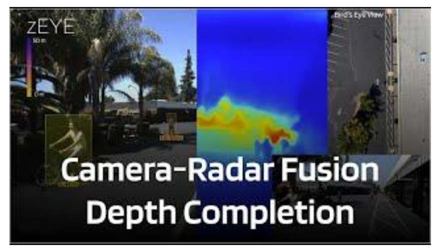


Radar History

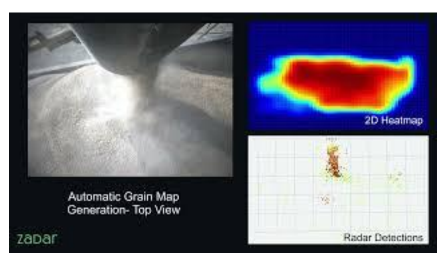
	1940s-1950s	1960s-1970s	1980s-1990s	2000s-2010s	2020+
Frequency	< 4GHz	< 12 GHz	< 24 GHz	< 80GHz	< 240 GHz
Technology	**Vacuum tubes Cavity magnetron** Doppler shift Bistatic Radars,MTIs	**Solid state radars** LFM pulse compression; **Advanced modular design** Phased array DSP	**Integrated circuits** pulse coded Advanced DSP SAR Phased array; **SMT** Advanced DSP Adaptive antenna Active electronically scanned array	**3D Packaging & SiP** Wideband and dual polarized; **Low power SiGe/CMOS** ML and AI , DBF, 3D radars	**CMOS-SOP** Radar networking, massive MIMO, quantum radars, ultra small and low power
Size	Large buildings to big trucks	Large cabinets; Suitcase-sized	Handheld devices	Palm-sized	Wearable
Packaging	Rubber seals and gaskets, traditional construction; Epoxy and other sealant	Advanced polymers. Enhanced thermal management; Heat sinks and fans in radar packaging	Hermetic sealant; Miniaturization	Cost reduction	Flexible packaging
Application	Air defense, moving ground troops and vehicles; Air traffic control, weather radars	Space exploration, Ballistic missile defense; Marine radars, geological exploration	Airborne radar; Drone radar	Automotive radar; Autonomous vehicles, drone detection	Everywhere

Outdoor mm-Wave Radar Applications – public safety

- RF emission and safety – FCC/ETSI 60 GHz
- EMC and interference – IEC 61000
- IP rating – IP67
- Impact Resistance (IK8)
- UV and corrosion – ISO 4892-2



Outdoor mm-Wave Radar Applications – agriculture , mining



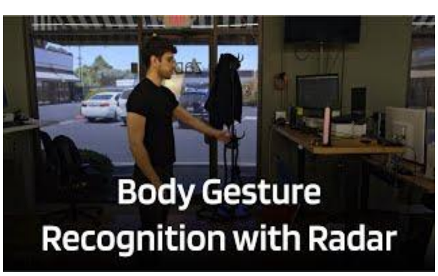
- RF emission and safety – FCC/ETSI – 76-81 GHz
- EMC and interference – IEC 61000
- Dust and water ingress- IP68 and 6K9K
- Temperature and humidity- MIL-STD-810
- Impact resistance (IK10)
- Explosion protection- IECEx
- UV and corrosion – ISO 4892-2
- Vibration and shock Resistance: ISO 16750

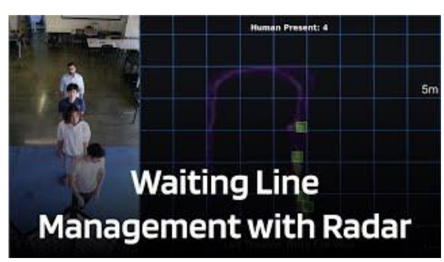
Outdoor mm-Wave Radar Applications - automotive

- RF emission and safety - FCC/ETSI - 76-81 GHz
- EMC and interference - CISPR 25 and ISO 11452
- Dust and water ingress- IP rating - IP67 or 69k
- Corrosion resistance - ASTM B117
- Temperature and humidity- MIL-STD-810
- Functional safety: ISO 26262
- Electrical safety: ISO 7637 and ..
- Vibration and shock Resistance: ISO 16750
- Quality management - IATF 16949
- Reliability testing - SAE J1211

Indoor mm-Wave Radar Applications - public safety

- RF emission and safety - FCC/ETSI - 60 GHz
- Dust and water ingress- IP rating - IP20
- Electrical safety: IEC 60950-1
- Material safety: ISO 10993

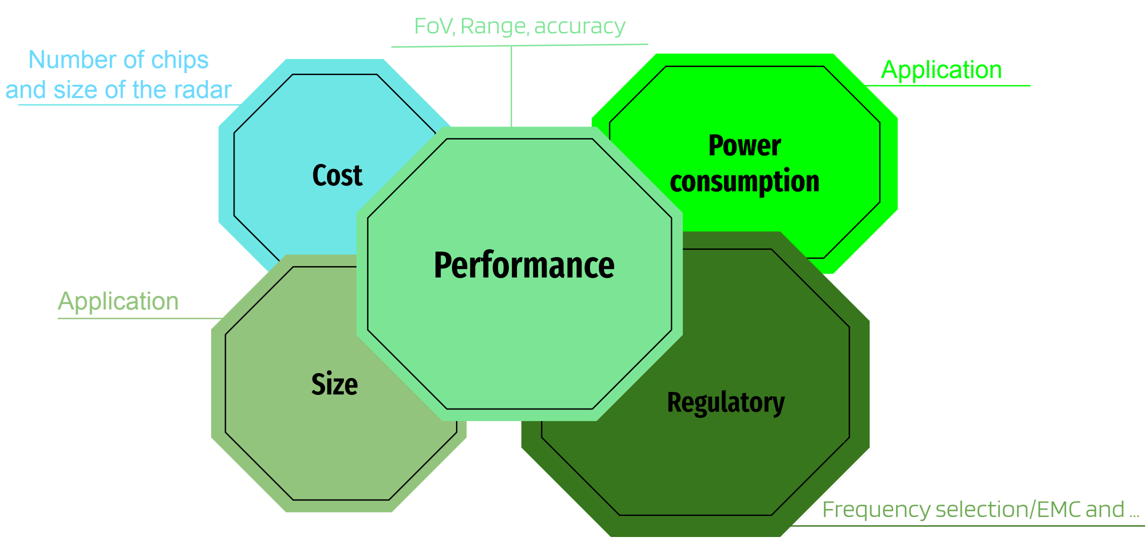




Indoor mm-Wave Radar Applications- wearable devices

- FCC or ETSI
- RF exposure: IEC/IEEE 62209 or guidelines from International Commission on Non-Ionizing Radiation Protection (ICNIRP)
- Biocompatibility: ISO 10993, avoid allergic reactions or skin irritation
- Electrical safety: IEC 60601-1
- IP67
- MIL-STD-810

Market Needs and Tradeoffs



- Form Factor vs Performance
- FCC & Regulatory
- Ruggedness and Reliability
- PCB Material and Design
- Ingress Protection
- Thermals
- Radome Effects on Antenna Pattern
- Calibration
- Near Field Coupling
- RX Saturation and Phase Noise

Packaging Challenges

Two Radars: a Case Study

Application	Long-range, high performance radar for autonomous perception. Meant to be installed on a vehicle or on a building	Consumer, close-range, wearable radar for low-latency classification of gestures at distances < 1m
Architecture	?	?

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Frequency Selection

Application	Frequency (GHz)	TX Power (FCC)	Notes
ISM	24-24.25		FCC Part 15 Subpart E
Vehicular radar	76-81	50dBm EIRP	FCC Part 95 Subpart M
Airport operations (fixed or mobile)	76-81	50 dBm EIRP	
Stationary radar, outdoor	57-64	14dBm peak EIRP	FCC § 15.255 Subject to duty cycle limitation
Indoor radar	57-64	20 dBm peak EIRP	
Drone/airborne radar	60-64		

- Frequency selection is largely guided by regulatory requirements
- In the U.S, the FCC allowed bands are 24, 60, and 77GHz
- These high frequencies pose unique challenges when it comes to packaging and interconnect design

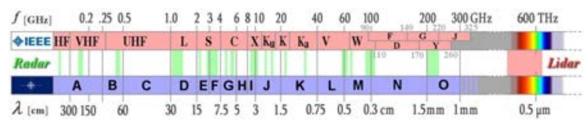
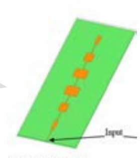


Photo source: https://www.radartutorial.eu/07waves/Waves%20and%20Frequency%20Ranges.en.html

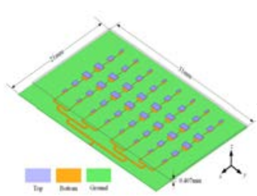
Why Can't All Radars be Small?

Small, cheap, high performance: pick two!

~5dBi

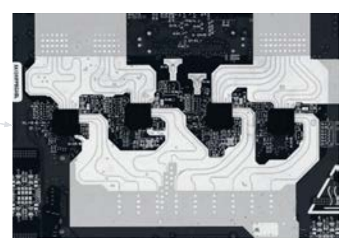


~13dBi



~22dBi

4TX, 4RX: ~8°



12TX, 16RX: ~2°

Increasing Detection Range:

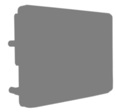
- High-gain antennas
- Multi-antenna arrays
- For a constant TX power, greater range means increased radar size

Increasing Spatial Resolution:

- Increase aperture size by spacing out elements
- Increase aperture size by adding elements

Photo source: https://www.researchgate.net/figure/Conventional-and-two-layered-series-fed-microstrip-patch-antenna-array_fig1_347979880
https://www.ti.com/tool/AWR2944EVM
https://www.ti.com/tool/MMWCAS-RF-EVM

Two Radars: a Case Study



Application	Long-range, high performance radar for autonomous perception. Meant to be installed on a vehicle or on a building	Consumer, close-range, wearable radar for low-latency classification of gestures at distances < 1m
Architecture	4-Chip Cascade @ 77GHz	Single-Chip @ 60GHz
Packaging Considerations	?	?

EMC/EMI: Packaging for Regulatory

What about out-of-band emissions?

- The more integrated the architecture, the less you will need to worry about spurious emissions at high frequencies
- Cascaded architectures require a high frequency LO (e.g. 20GHz), and emissions at this frequency are a problem
- Designs with very low integration are a challenge to package and shield properly- one company spent years certifying one of these designs
- Co-design your RF, antenna, and packaging to ensure you can pass regulatory requirements

Fully-shielded design using metallized 3D waveguide antenna

Photo source: https://fcc.report/FCC-ID/OAYARS5A/5047733.pdf

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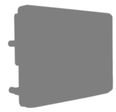
Two Types of Radar: a Case Study



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Regulatory	- Cascade design will have a 20GHz LO that can produce unwanted emissions, this will need to be shielded	- Single-chip design helps reduce chance of unwanted emissions, allowing for less shielding

Radar Ruggedness vs Reliability

Reliability: will the sensor survive after exposure to lifetime environmental shock & vibration?

Ruggedness: will the sensor perform well under these difficult conditions?

Luckily, phased array radars are completely solid state and have high levels of reliability and ruggedness.

Radars have a long history of deployment in aviation, military, and automotive applications

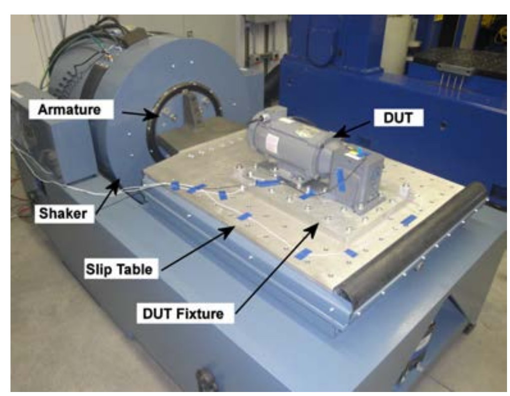


Photo source: https://www.desolutions.com/blog/wp-content/uploads/2015/08/Fig2-Slip.jpg

Shock and Vibe Testing

	Automotive Vibe	Pothole Shock	Closure Shock	Heavy Equipment Shock
Amplitude	3G RMS	25G	40G	100G
Shape	10-1000Hz	10ms half-sine	6ms half-sine	11ms half-sine
Direction	3 axes	3 axes, 6 directions	3 axes, 6 directions	3 axes, 6 directions
Duration	8 hours per axis	400 shocks	1,500 shocks	Thousands
Test	IEC 60068-2-64	60068-2-27		

Ingress Protection Packaging

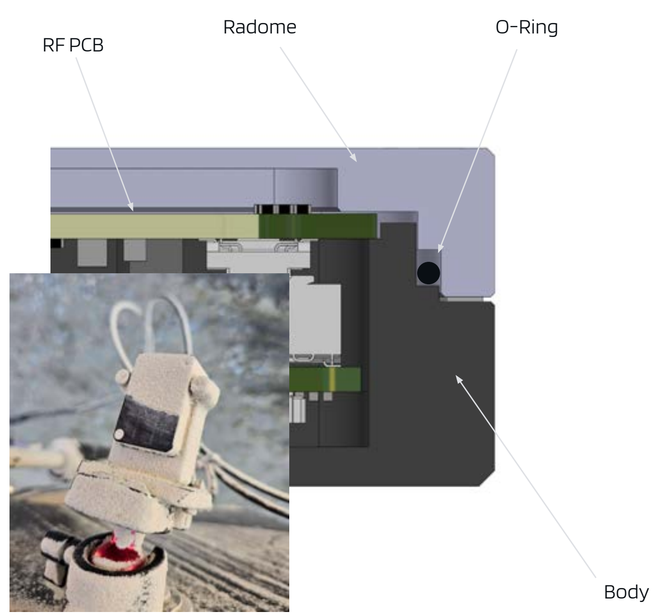
Radars are typically packaged in a multi-part enclosure that fully seals to protect against water ingress.

A seal can be achieved with o-rings, gaskets, or adhesives.

- Passive cooling is required, fans cannot be used

Long-term thermal cycling with a sealed enclosure can cause a “pumping” effect that draws moisture past seals into the enclosure

- ePTFE environmental vents allow moisture to escape while keeping out liquids



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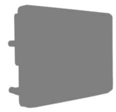

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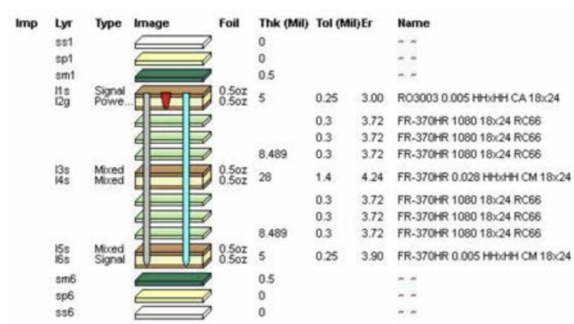
Sealing	- Outdoor design will require full sealing considerations, with a co-designed radome - Antennas and RF ICs will need solid mechanical support to prevent shock/vibe failures	- Consumer product has less stringent shock/vibe requirements

PCB Design: Material Selection

Interconnect design is critical when optimizing range performance of a radar.

At high frequencies, loss becomes a significant impact to the link budget. Low-loss materials are desirable for long range applications and extensive simulation is needed to optimize loss.

Short-range, high volume applications can use more conventional FR4 construction.



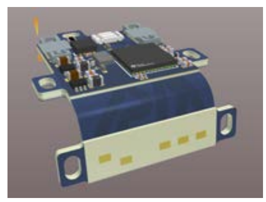
Material	εr	tanδ @ 77GHz	Typical Loss, dB/in @ 77G	Notes
RO3003	3.0	0.001	1.9	Lowest-loss option
RO4830	3.2	0.003	2.2	More affordable
FR408HR	3.7	0.009	>3	Most affordable, conventional FR4 process

PCB Design: Flexible Materials

In certain applications, antenna array area is highly limited due to form factor requirements.

In these applications, flex and rigid-flex PCBs can be used to connect the RF frontend with a "remote" antenna array.

The flex layer adds additional RF design complexity and should be simulated for optimum performance.



< 5mm

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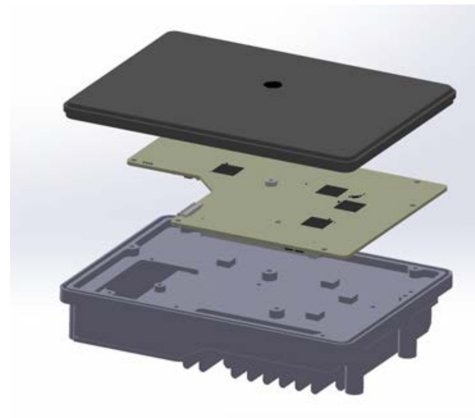
Interconnect	- RO3003 will be used to maximize range	- Rigid-flex substrate will be used to achieve form factor requirements

Thermals

Outdoor applications will experience a huge range of temperatures:

Application	Ambient	Internal Junction
Automotive	-40 to +85C or +105C	-40 to +125 or +140C
Industrial	-40 to +85C	-40 to +105C
Consumer/Indoor	0 to +70C	0 to +85C



RF frontend, linear regulators, and DSP/FPGA will need cooling. High temperatures will degrade RF performance, leading to:

- Reduced SNR
- Reduction of transmitted power
- Phase noise degradation
- Linearity issues

Peak power can be 2-3x idle power during the active chirp time

- RF frontend will be transmitting
- DSP will be performing range FFT

Thermals: Calibration Over Temperature

Modern integrated front-ends have sophisticated calibration procedures to correct for variation over temperature

"Low, mid, high temperature bias"- gain and phase imbalances between TX/RX will be measured and corrected over temperature

Multi-device cascades should aim to minimize thermal variation across front-ends to minimize the errors introduced in calibration switching

Temperature-induced calibration errors will result in:

- Range drift
- Loss of detection
- DoA drift over temperature (phase)

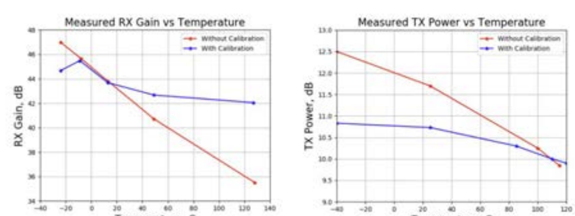
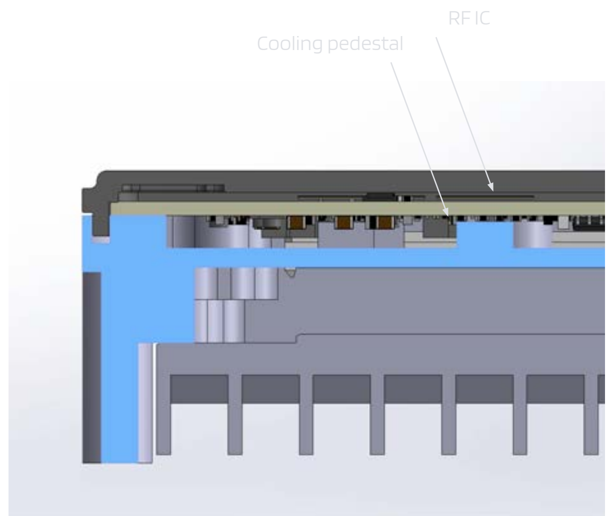


Figure 1-2. RX Gain and TX Power With and Without Calibration

Thermals: Takeaways

- Estimate power consumption to design appropriate cooling (heatsink or active)
- Multimode radars can have radically different power consumption profiles (100:1 or greater)

- Design your radar package to thermally equalize multi-chip cascades. This will help with calibration stability, and thus radar accuracy, over temperature
- Optimal thermal performance is a mix of radar systems design, appropriate layout, and packaging/enclosure design



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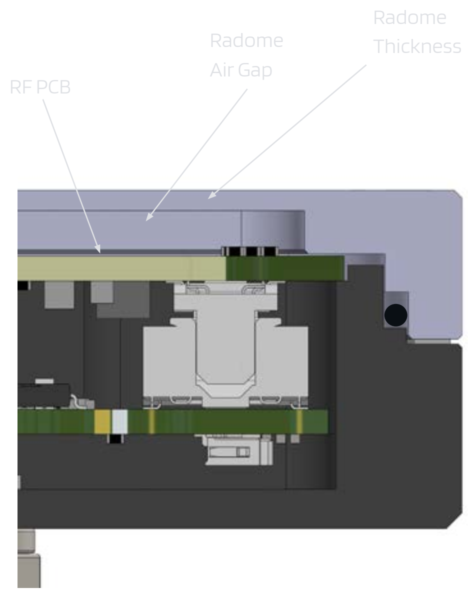
Sealing	- Outdoor design will require full sealing considerations, with a co-designed radome - Antennas and RF ICs will need solid mechanical support to prevent shock/vibe failures	- Consumer product has less stringent shock/vibe requirements
Interconnect	- RO3003 will be used to maximize range	- Rigid-flex substrate will be used to achieve form factor requirements
Thermals	- Aluminum enclosure with careful heatsinking and thermal equalization	- Low duty cycle and power requirements mean that additional cooling is not required

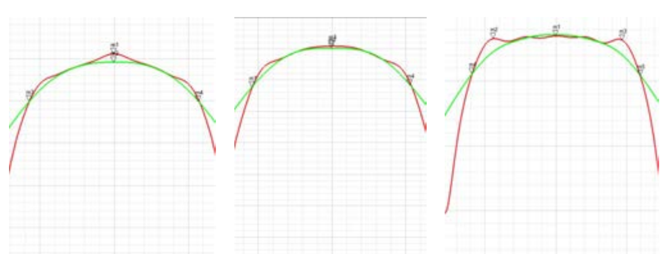
Radome Effects on Antenna Pattern

- Radomes are a critical part of a successful radar design and they are an integral part of the overall package
- The radome covers the sensitive antenna components and provides a radio transparent window that keeps the electronics sealed
- Typical materials are plastics
- Key parameters: material, thickness, air gap



Radome Effects on Antenna Pattern

- Radomes can shape the radiated antenna pattern
  - Lens behavior: ↓ FOV and ↑ gain, or ↑ FOV and ↓ gain
  - Usually designed to be transparent, with minimal effect on the radiated pattern
- A specific radome design is not necessary broadband- this causes ripples in the antenna pattern as you move away from the design frequency
- Material itself introduces loss, depending on the thickness and the tangent loss, Radome can easily introduce 1-3dB loss in the link budget



Green: Antenna pattern without Radome
Red: Antenna pattern after adding Radome

Radome Selection and Design

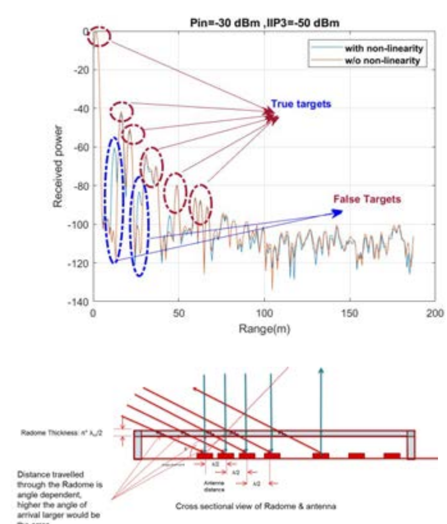
Material Selection (see TI) (see Preperm)

- Manufacturability- moldable vs CNC
- Chemical compatibility- solvents, etc.
- Thermal & dimensional stability- radome thickness
- Dielectric constant variation over frequency and temperature
- Dissipation factor (affecting loss)

Material	εr	tanδ @ 77GHz	Manufacturing	Notes
Polycarbonate	2.9	0.012	Moldable	Acceptable loss, low Dk -> easy to design with
ABS	2.0-3.5	< 0.02	Moldable	Susceptible to solvent damage (e.g. gasoline)
PEEK	3.2	0.005	Moldable	Expensive
PTFE	2	< 0.0002	CNC	Expensive, very soft -> subject to deformation
Ceramic	9.8	0.0005	-	Expensive, high Dk -> sensitive to tolerances
PBT + GF	3.5-4.2	0.03	Moldable	Relatively high loss, very affordable -> an automotive favorite
PEI	3.1	0.003	Moldable	Expensive
Proprietary Materials	2-3	0.003	Moldable	e.g. Preperm, based off PPE for special radome usage

Near Field Coupling Effects:

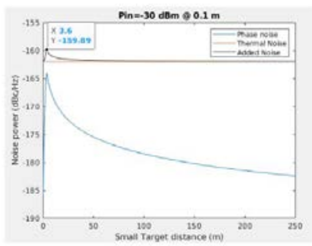
- Radiated signal can reflect back by the radome and result in:
    - Receiver saturation (Tx. to Rx. Coupling)
        - Generate nonlinearity -> generates harmonics (False targets)
    - Increase the antenna to antenna coupling (Rx. to Rx. coupling), this can also happen via the direct coupling of the antennas
        - Results in angle error: During calibration, the antenna coupling can be estimated and compensated to some extent
    - The reflections from the radome surface, travels different at different angles and can causes disturbance on the antenna pattern and add error in accuracy of angle estimation

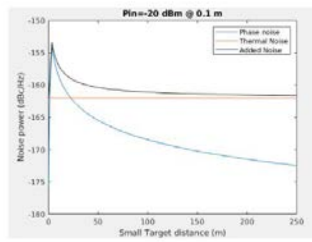


see TI

Close Range Reflections and Phase noise effect:

- Injection of a high power signal to the receiver can degrade detection sensitivity at long range due to the Phase noise:
  - The tail of the phase noise due to reflection from a close range target can increase the noise floor at long range and degrade the detection performance at long range
    - Simulation results for a target at 10cm, this target reflects back the power and causes -30dBm / -20dBm at the input of the receiver.

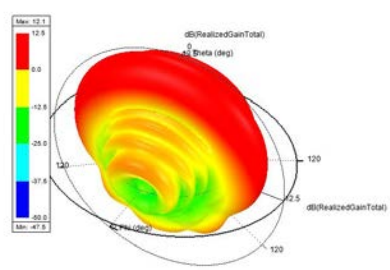


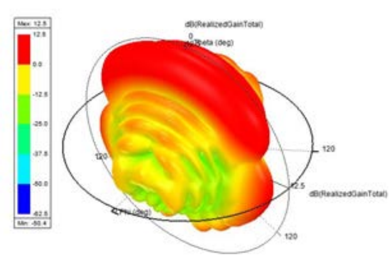


Radome Takeaways

Radome thickness, spacing, and material heavily affect radar performance in terms of RF gain over the field of view.

- What is an acceptable radome loss for my application?
- Will the radar need to survive physical impact to the radome?
- What are my allowable tolerances for thickness and spacing for satisfactory performance?
- Simulation of radome designs is valuable, but materials need to be characterized at the frequency of interest (60+ GHz)





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	zPRIME	zLITE
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Architecture	4-Chip Cascade @ 77GHz	Single-Chip @ 60GHz
Range	1,000m for vehicle detection	
Resolution	0.35°x 0.4° static	
Size	14 x 10 x 3 cm	1 x 1 x 0.2 cm
Power	22 Watts	< 500mW
Packaging	Aluminum/Polycarbonate/RO3003 with careful thermal management and rigid construction	Flexible, high density construction to fit in a small consumer device

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