RF Signature Modeling and Analysis – Lessons Learned

Presented at
MATRIX 2005

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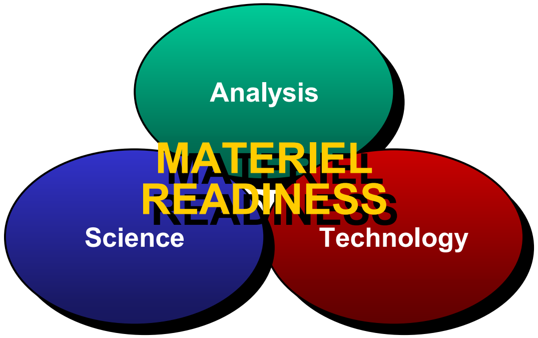

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RF Signature Modeling and Analysis – Outline

- Background Beginning in 1999
  - ✓ CAD Models – Resolution and Fidelity
  - ✓ Ground Vehicles at *X*-Band – Lessons Learned
  - ✓ Approximate Codes – Not Always Appropriate
- Modeling Uncertainties Increase with Frequency
  - ✓ Model Fidelity Issues and Examples
  - ✓ Analysis Examples
  - ✓ Simulation Fidelity Issues and Examples
- Advanced Tools Are Available When Needed
- Lessons Learned Summary – Target, Results Required, & Cost Determine Tools & Procedures

Overview of Lessons Learned

- Good Results at X-Band, but
  - ✓ Must Use Tools Appropriate to the Target
  - ✓ Good Target Model Fidelity is Required
  - ✓ Simulation Requirements are Application Specific
- K_a-Band is More Problematic
  - ✓ CAD Model/Mesh Issues Become a Limiting Factor
  - ✓ Visualization & Analysis are Important Factors
  - ✓ Simulation Requirements Depend on the Application
  - ✓ Accuracy Requirements & Metrics Depend on the Application
  - ✓ Most Issues are Resolvable Given Sufficient Resources
- *W*-Band Will be Even More Difficult →→ Cost
  - ✓ 3-year Grand Challenge Project
  - ✓ CEM Advances Driven by Applications & Funding

ARL Objective – Support Vehicle Design for Integrated Survivability

Historically, a costly and time consuming process to build survivable vehicles.

design (heavy) vehicle with great ballistic protection

build prototype

turntable measurements

vulnerability assessment

modify design

months to years

Army transformation requires.a better approach

design lightweight, small footprint vehicle

develop mesh for vehicle from CAD vehicle design

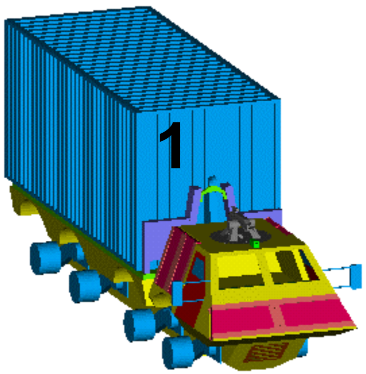
run model

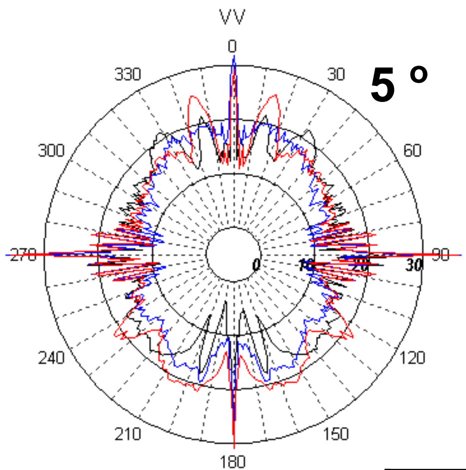
vulnerability assessment

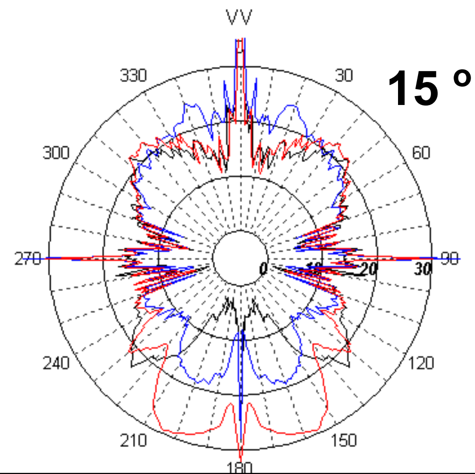
modify design to reduce signature

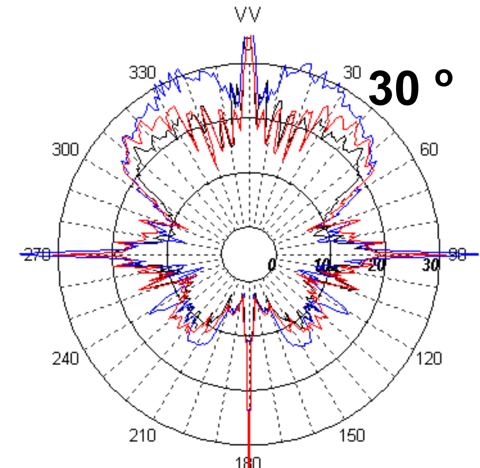
days to weeks

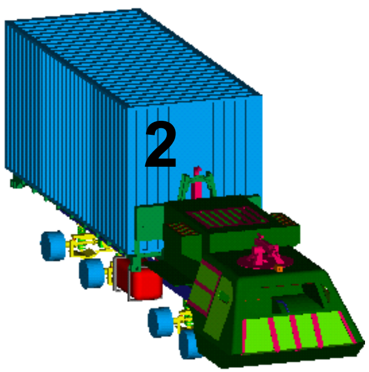
Design Concepts Example – Xpatch Results at *X*-band

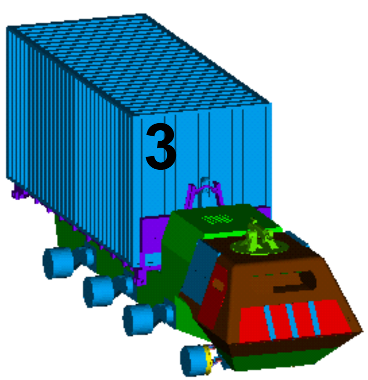












	Concept1		Concept2		Concept3	
Angle (degrees)	Mean (dBsm)	Median (dBsm)	Mean (dBsm)	Median (dBsm)	Mean (dBsm)	Median (dBsm)
5°	17.1	16.4	16.8	15.5	18.1	16.6
15°	16.9	15.8	18.2	15.6	20.6	17.6
30°	18.0	11.6	22.0	14.1	18.6	13.4

We are Establishing a Rapid Turnaround Capability.

RF Signature Modeling – Background

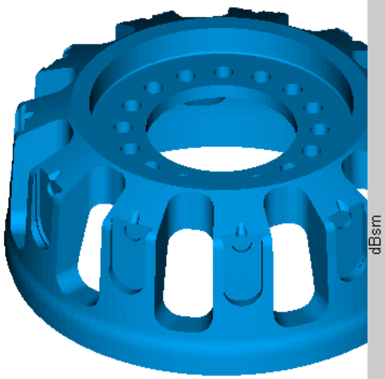
- ARL has developed an end-to-end signature measurement and model prediction capability to support US Army objectives
- ARL leveraging past and current research in CEM
  - ✓ NATO Research Study Groups (pre-1999 to present)
  - ✓ DoD HPCMO Grand Challenge Project (2001)
  - ✓ ARL Directors Research Initiative (2002)
  - ✓ TARDEC/ARL Signature Management for FCS STO transitioned to Integrated Survivability ATD (2003)
  - ✓ Army HPC Research Center
  - ✓ Collaborations & DoD WGs (2004)
  - ✓ SBIR Code Development (end 2006)
  - ✓ Current Grand Challenge Project

Software Development and Rapid Prototyping and Assessment

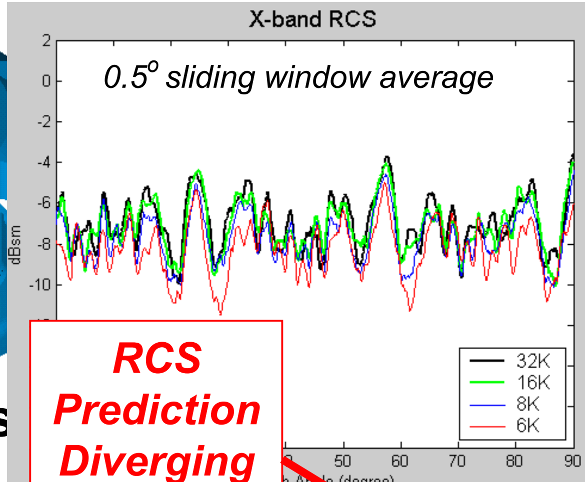
Measurements

Materials Research

Background – Resolution vs. Accuracy



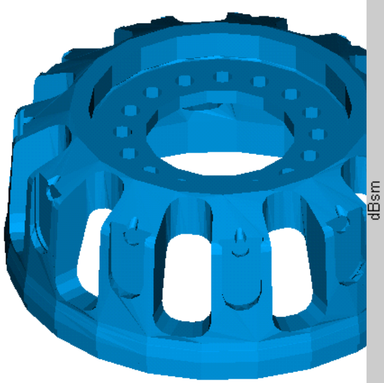
32K Facets



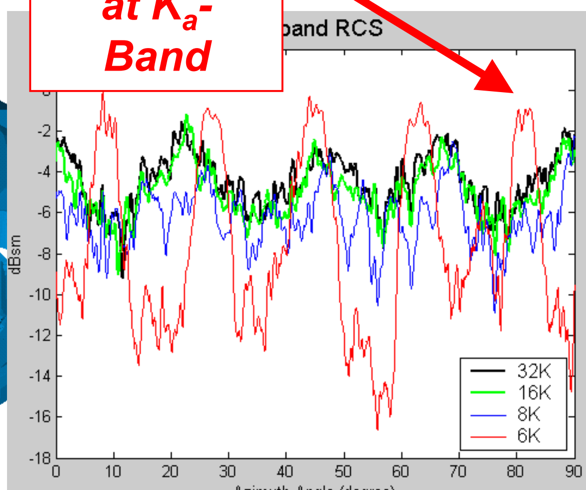
16K Facets

22.4” diam. x 9.4” height

RCS Prediction Diverging at K_a-Band



6K Facets



8K Facets

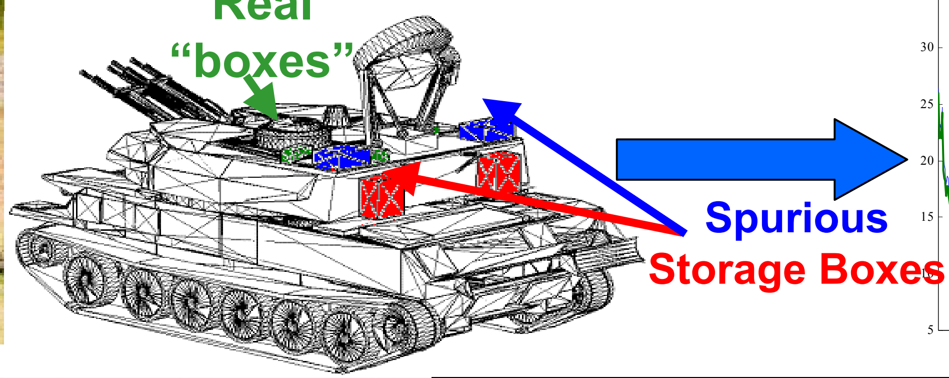
ProE Facet Output at Various Levels, We See that the RCS Prediction Begins to Fail at K_a-Band with Coarser Resolution where Upper Limit is Based on CAD Fidelity

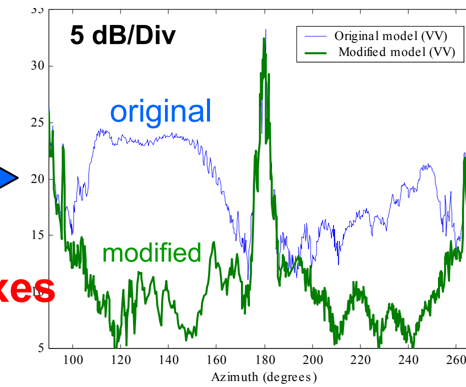
- **Facet Model Resolution**
  - How Well Does The Facet Model Resolve The CAD Surfaces?
- **Virtual Target Model Fidelity**
  - How Well Does The CAD Model Represent The Real Surfaces?

Resolution & Accuracy Requirements are Relative to λ

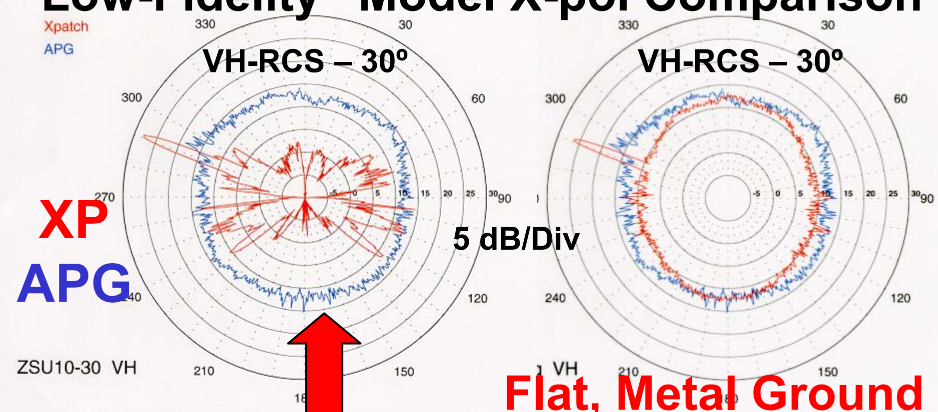
Background
Improvements at X-Band

1999 "Low-Fidelity" → Modify Model



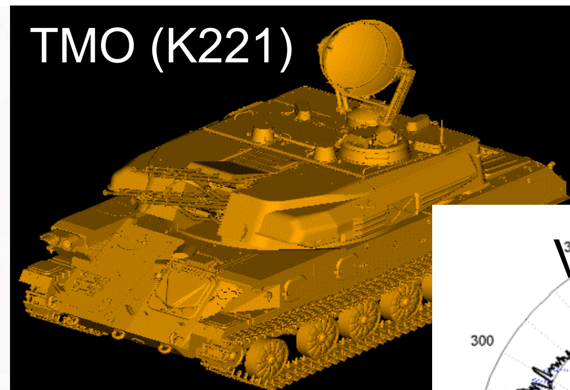


"Low-Fidelity" Model X-pol Comparison

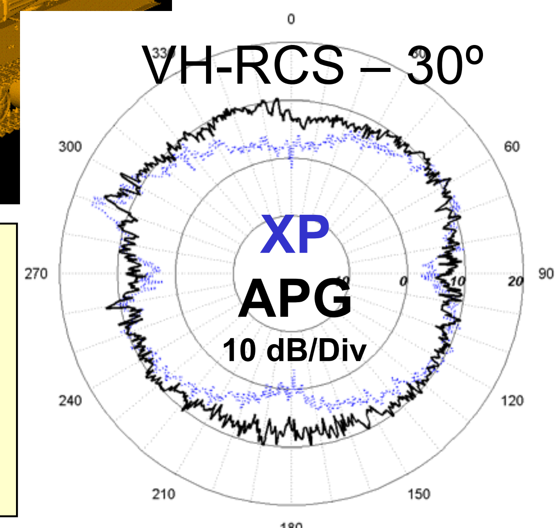


Free-space Inadequate Due to 10.2° Radar Beamwidth

R. Chase, H. B. Wallace and T. Blalock, "Numerical Comparison of the RCS of the ZSU-23-4, ARL-MR-430 (April **1999**).

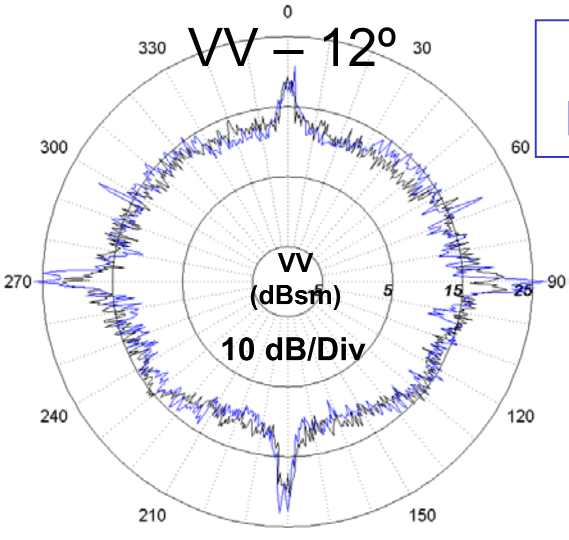


2002 "High-Fidelity"



But Fidelity Depends On λ & Application Determines Affordability

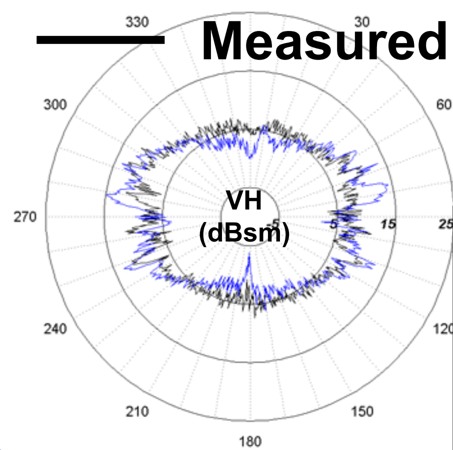
Background – Lessons Learned at *X*-Band

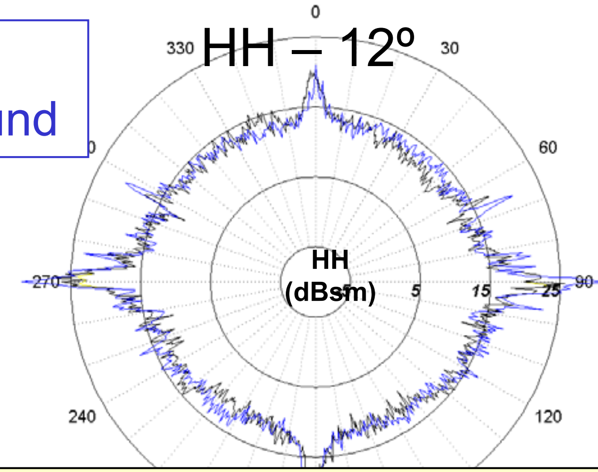


Better Agreement at Low Depression Angles with Ground

Xpatch

Measured





Best Comparison Achieved by Careful Treatment of Ground Plane (ε_r = 8) and "High Fidelity" CAD Model

Difference in Mean RCS (dB) at 12º/30º Depression

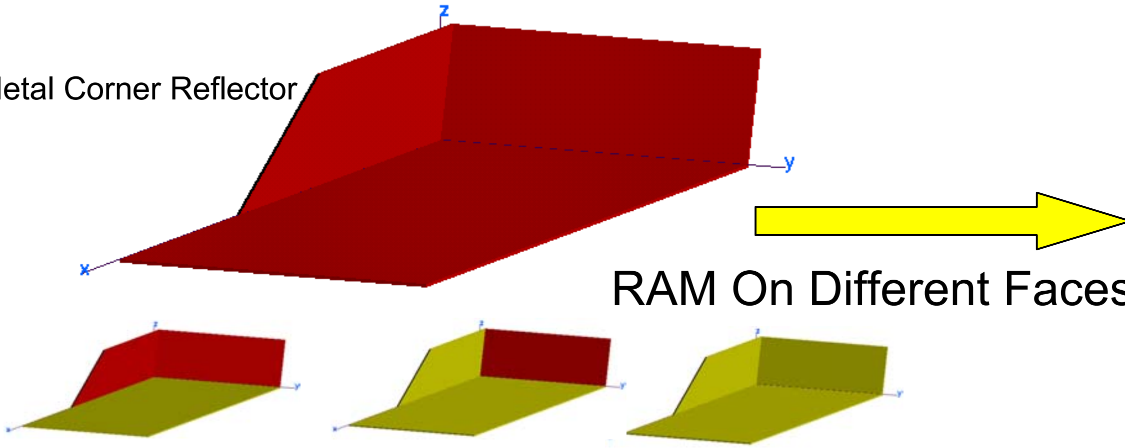
1999 — 2.0/2.7

2003 — 0.2/1.5

Two ZSU-23s Were Carefully Measured at the Range at APG. By Using an Accurate (but All-metal) CAD Model of the Test Vehicles from TMO and Carefully Characterizing the Test Environment, Good Agreement Between Models and Measurements Were Achieved at *X*-Band

Lossy, Composite Materials Must be Included if Present

All Metal Corner Reflector

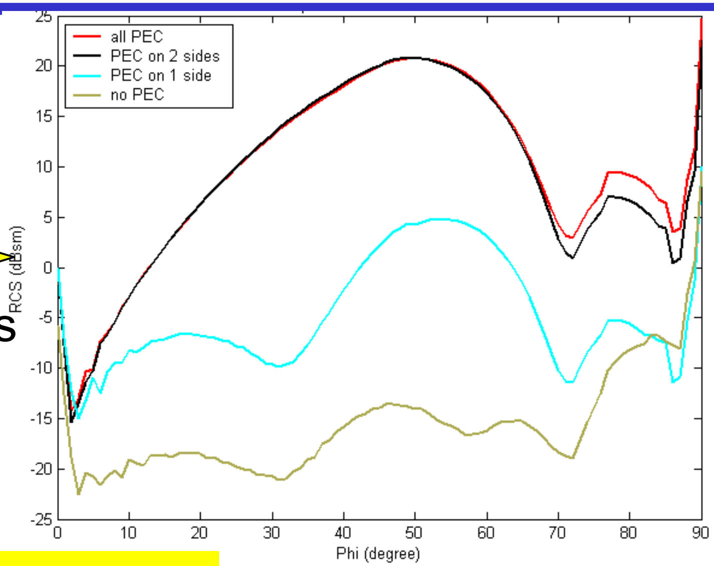


RAM On Different Faces

PEC on 2 sides

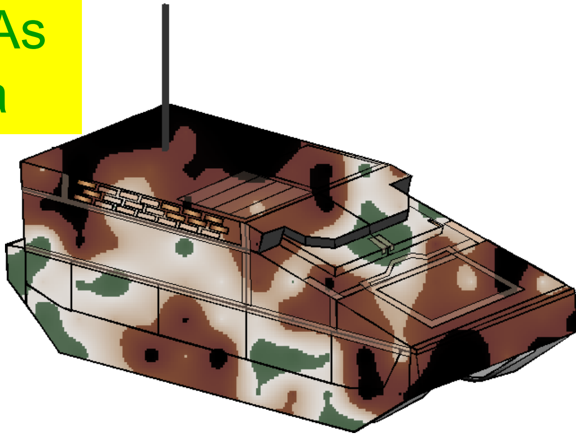
PEC on 1 side

No PEC



Numerical Results Are Only As Accurate As The Input Data

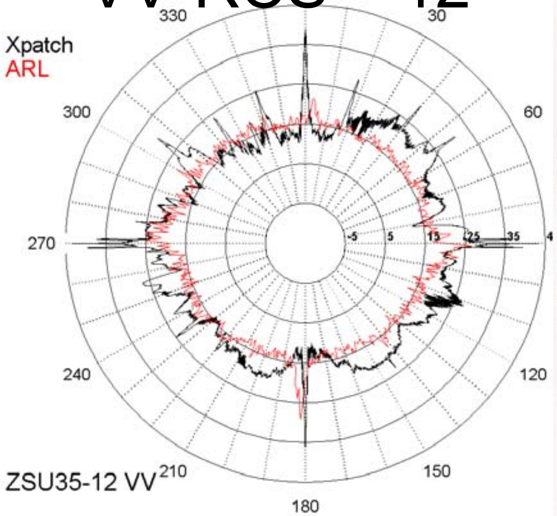
Good CAV *X*-band Results Using Model & Material Layers Provided



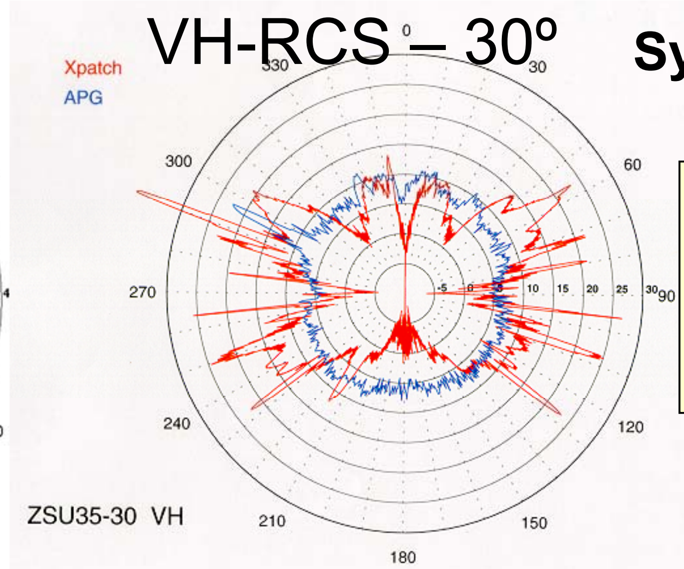
Xpatch and Other Approximate and Highly Accurate Solvers Allow Complex, Laminated Structures to be Modeled – However, the Result is Highly Dependent Upon the Material Electrical Characterization & Thickness

Background – Poor Xpatch Comparisons at K_a-Band

VV-RCS – 12º



VH-RCS – 30º



Synthetic Data (1999) Mean RCS Difference > 3dB

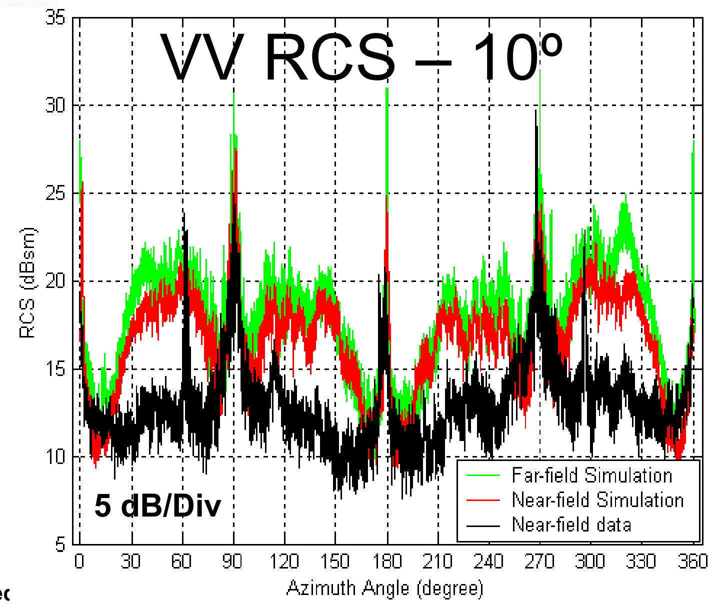
Range 8 Ground Model is Not Needed with 8.5° Beamwidth,

Only A Small Difference for Near-field Simulation

Synthetic Data (2003) Mean RCS is Closer but Still > 3dB

Virtual Target Fidelity To A Specific Test Vehicle Is A Limiting Factor At K_a-band For Comparison To Measured Data

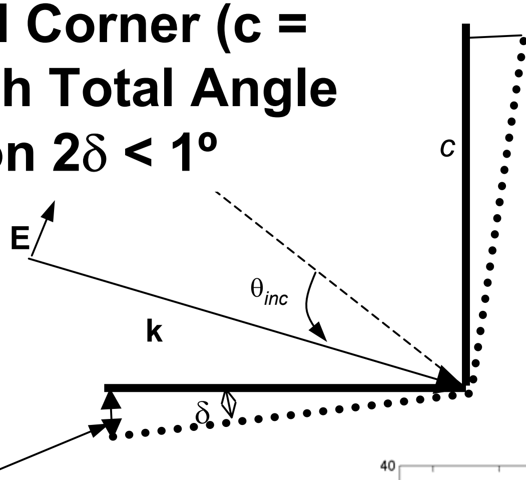
VV RCS – 10º



Model Fidelity Issues – “Pristine” Corner Effects

Non-orthogonal Dihedral Corner (c = 1-ft) with Total Angle Deviation 2δ < 1º

An Orthogonal Corner (Solid) Compared To A More Realistic Corner (Dashed) Having Deflection Δ = 40 – 160 mils

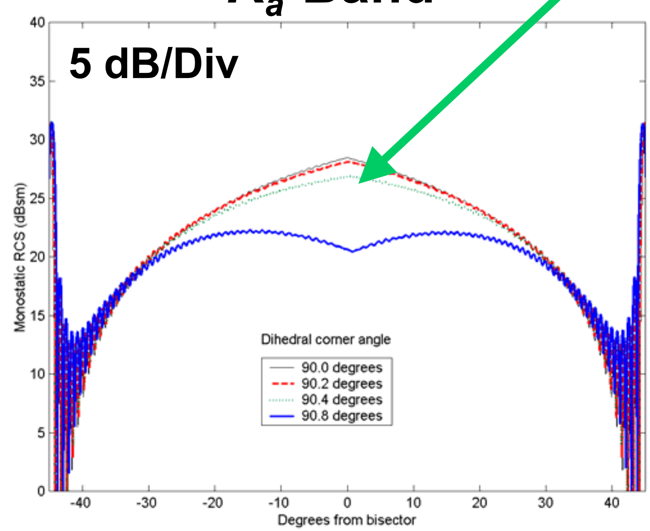


Deflection from “Flat” Depends On Corner Size

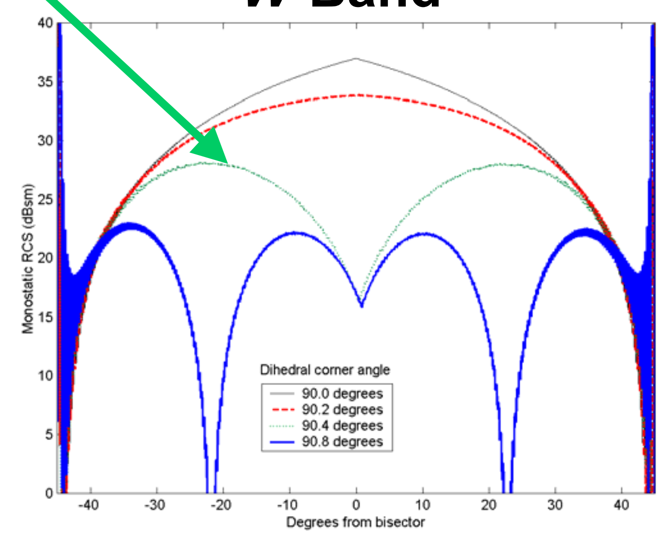
Δ = ctanδ

2δ = 0.4º Is a Negligible Deviation at K_a-Band but not at *W*-Band

K_a-Band



***W*-Band**

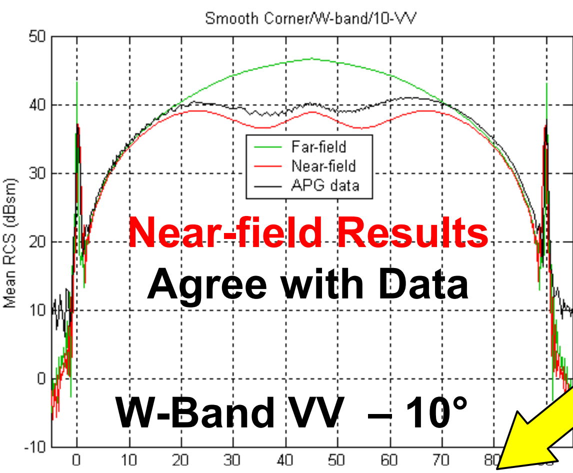


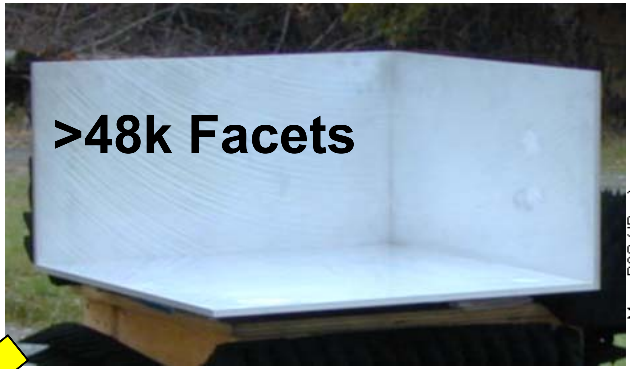
Orthogonal Dihedral Requires Fabrication Tolerance ~ λ/2

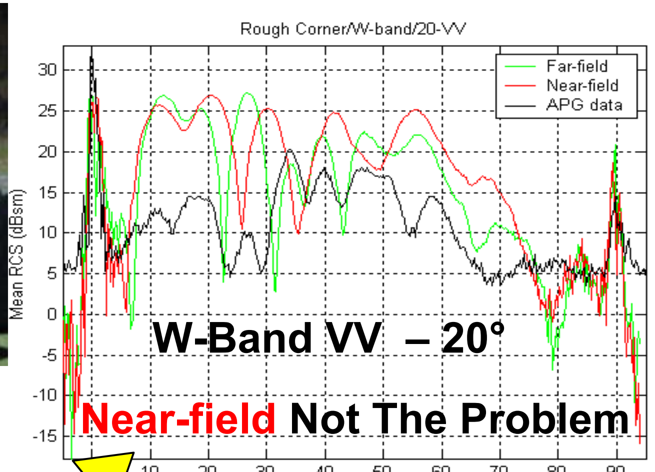
Model Fidelity Examples – "Pristine" Corner Effects

A Smooth, Well-built Corner Can Be Accurately Modeled. **Far-field** RCS Scales As Expected With Frequency

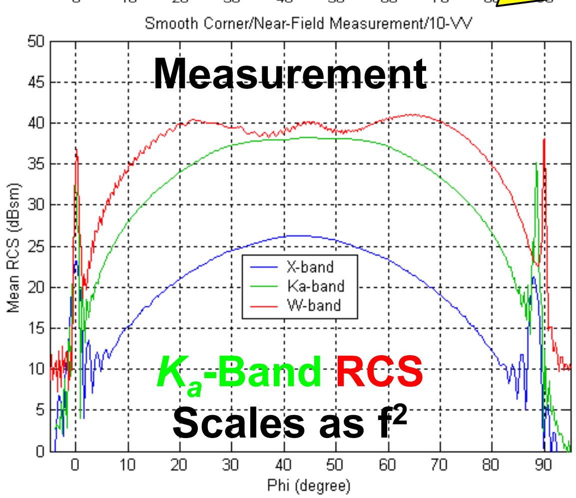
A Rough, Poorly-built Corner Is More Difficult to Model. **Far-field** RCS Doesn't Scale With Frequency

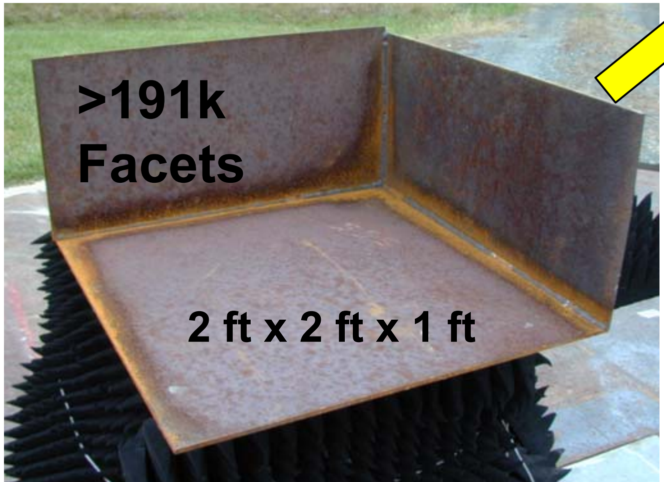


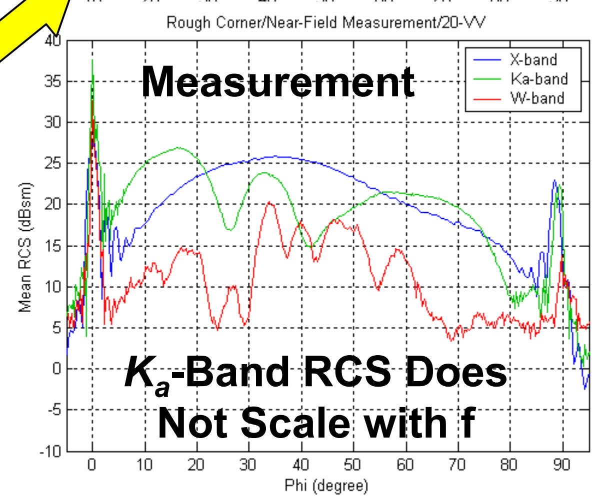




Laser Scanned Facet Files

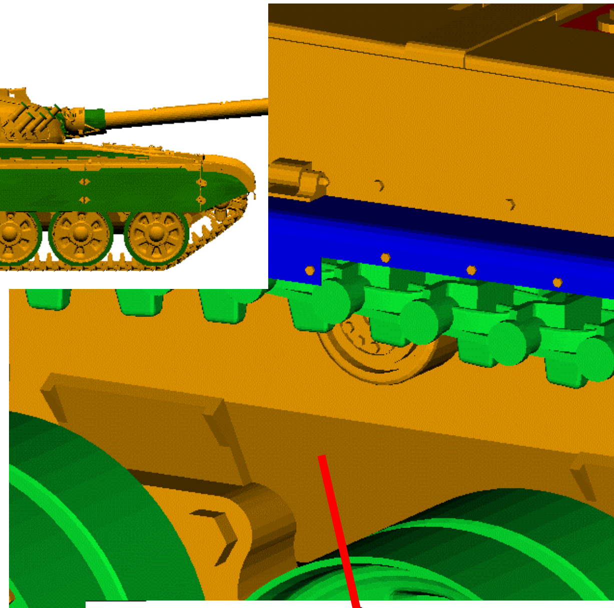




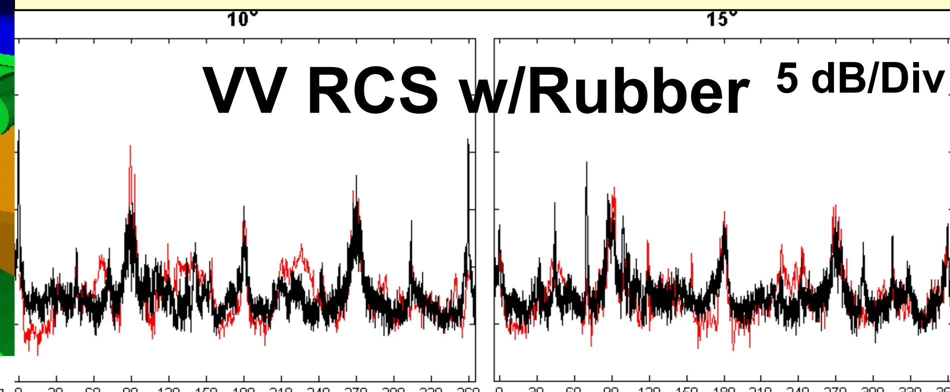


Model Fidelity Examples – "Pristine"
Corner Effects if Materials Removed

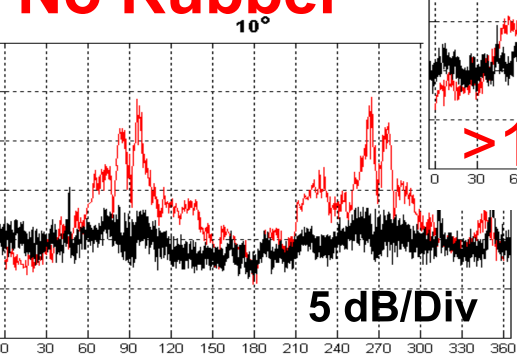
T72M1 Without Materials

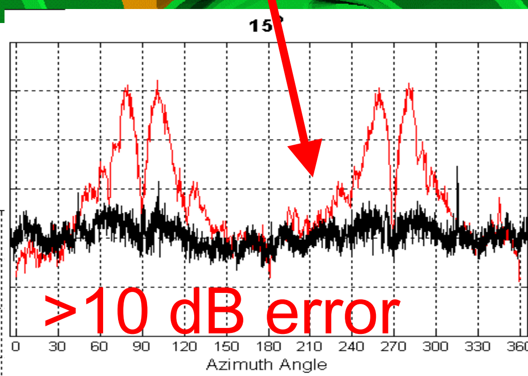


Rubber Tires/Skirts Required on T72M1 to Avoid Multi-Bounce Between "Pristine" Hull/Wheels

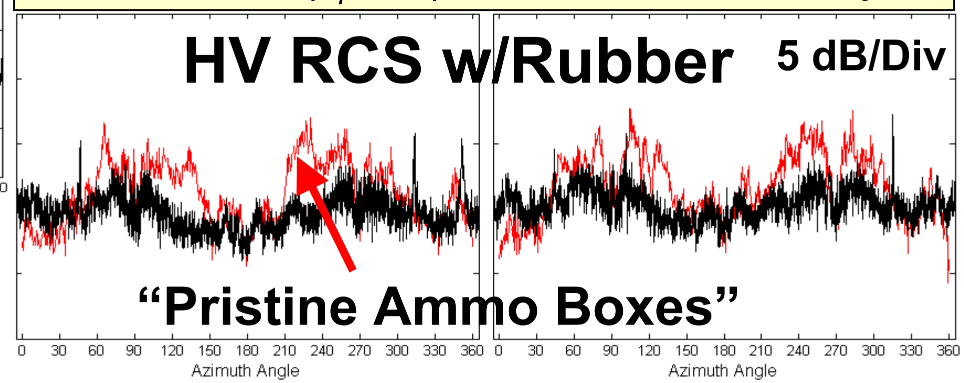


HV RCS – No Rubber

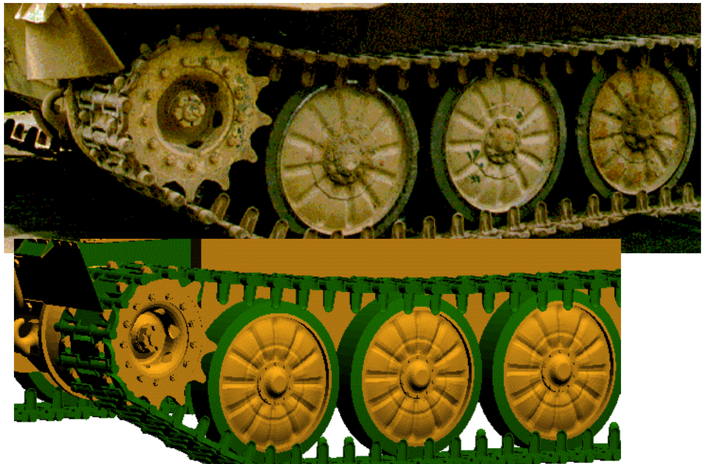




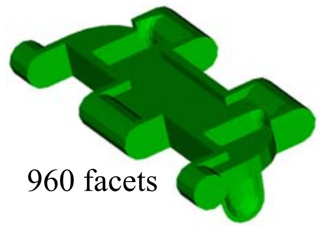
Better Agreement using Absorbing Tracks & Rubber ($\varepsilon_r = 4$) but x7 Time Penalty



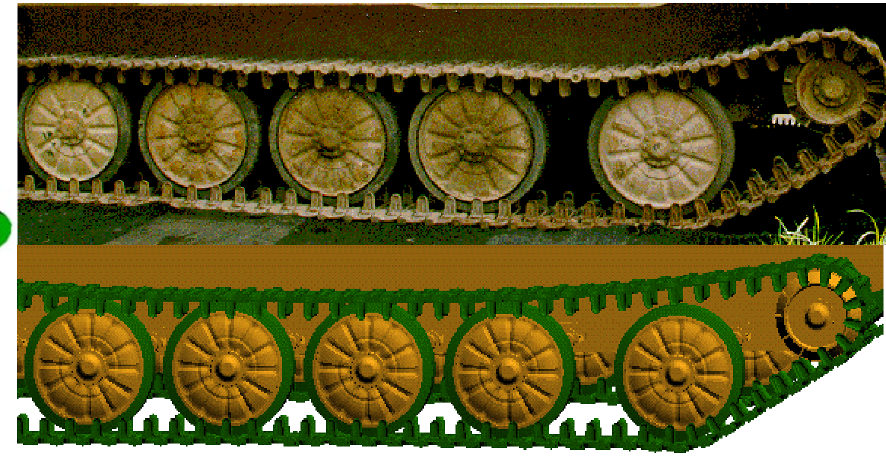
Model Fidelity Examples – Replication of Idealized Parts



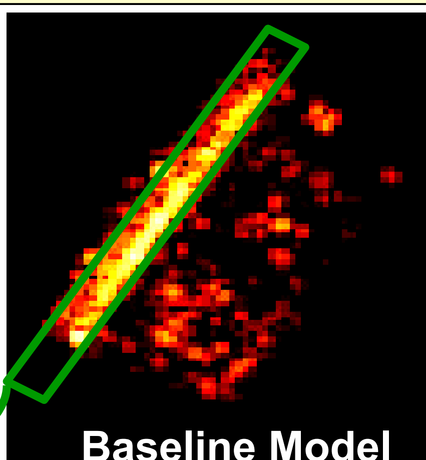
ZSU-23-4



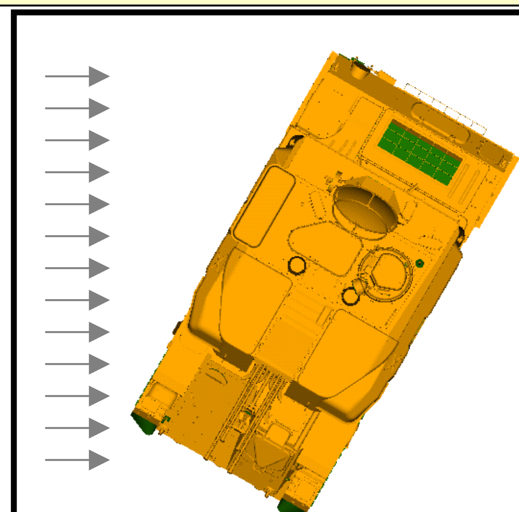
Replicated Parts (186)

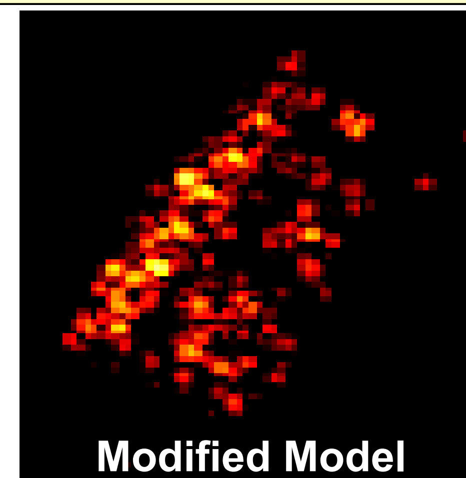


Tracks Made Absorbing After Analyzing Multi-Bounce Returns
→→ Even High-Fidelity CAD Models Can Have Unrealistic Features



Materials Removed (e.g., radome, tires, etc.) or Replaced With Absorber (e.g., glass lenses)

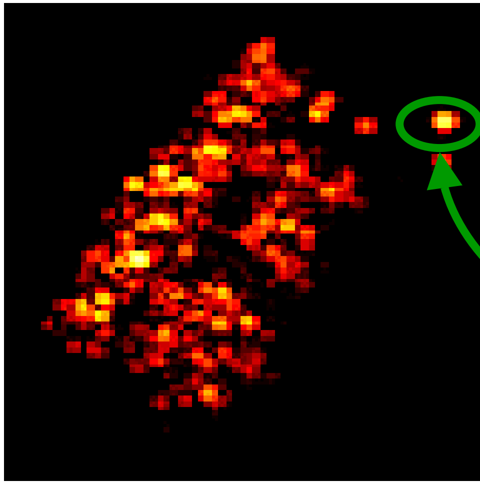




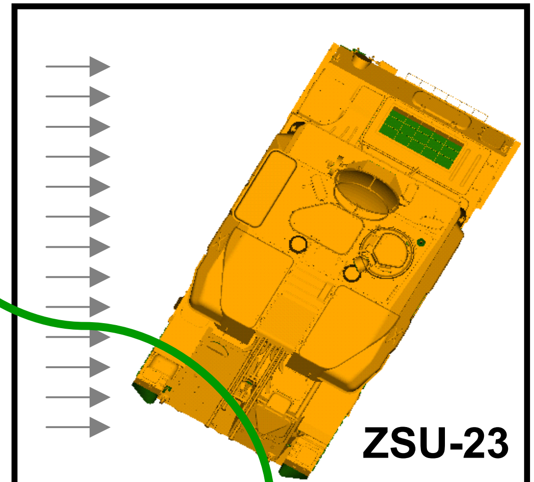
Baseline + Absorber Tracks

Analysis Examples – Artificial Multi-Bounce Paths

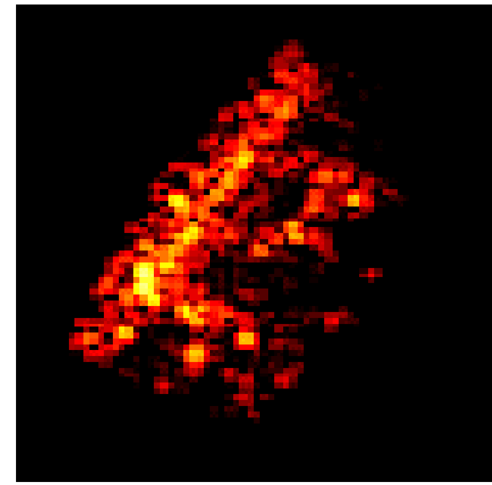
Xpatch Prediction



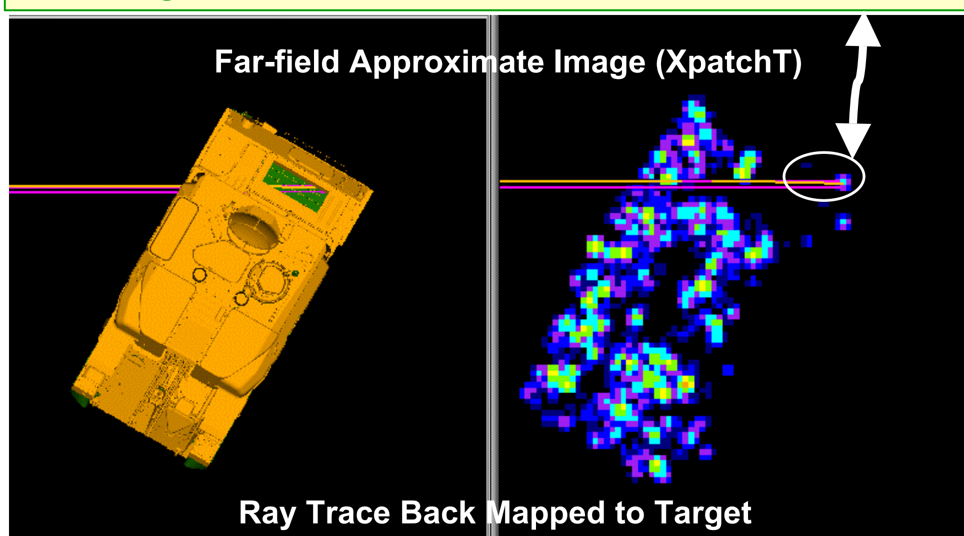
10° depression angle



Measurement



Delayed Return In Prediction But Not In The Measured Signature

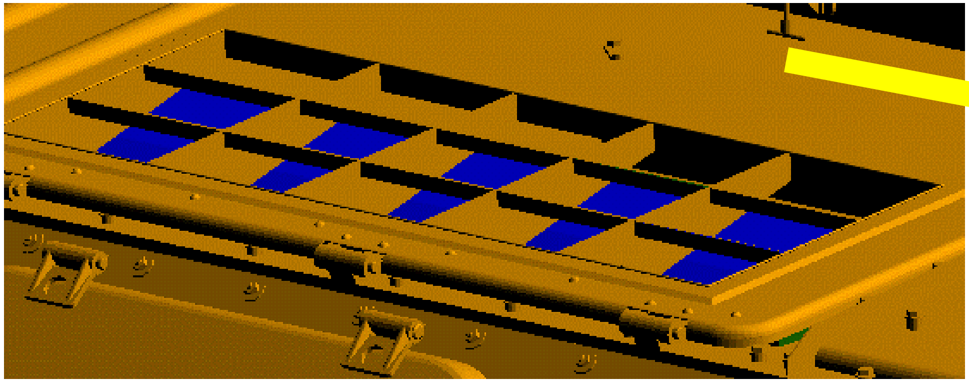


Only Observed at Certain Angles – Analysis with Ray Trace Back from an Approximate Image

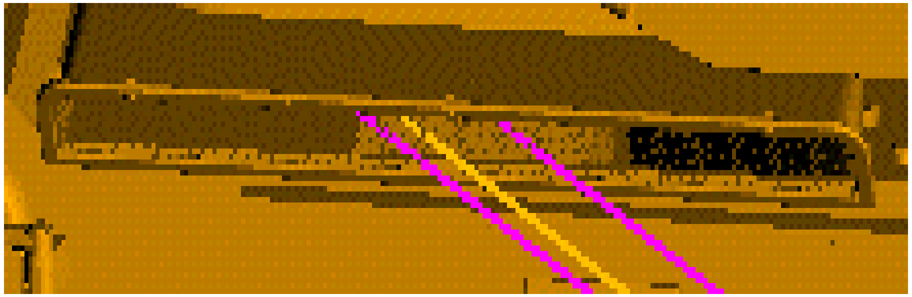
Some Analysis is Always Required and a Visualization Capability Is Critical

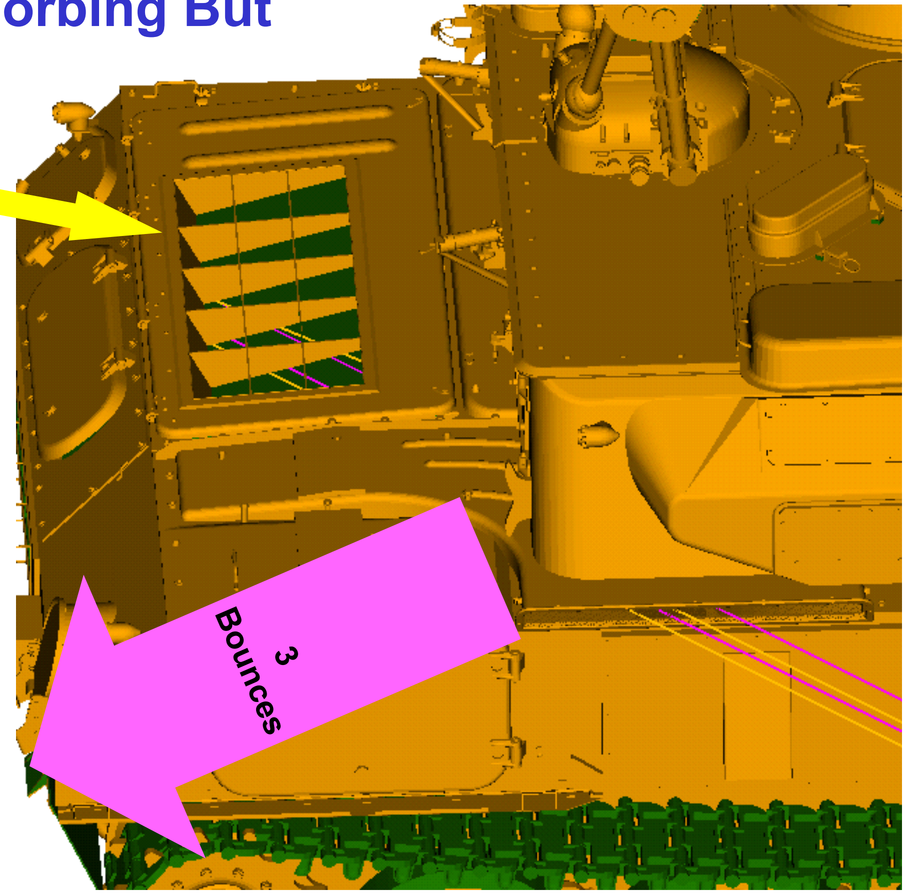
Analysis Examples –
Target Interior with Unknown Accuracy

The Engine (Flat Facets) is Made Absorbing But Interior Multi-Bounce is Still Possible



A Metal Grill Will Not Stop SBR At MMW

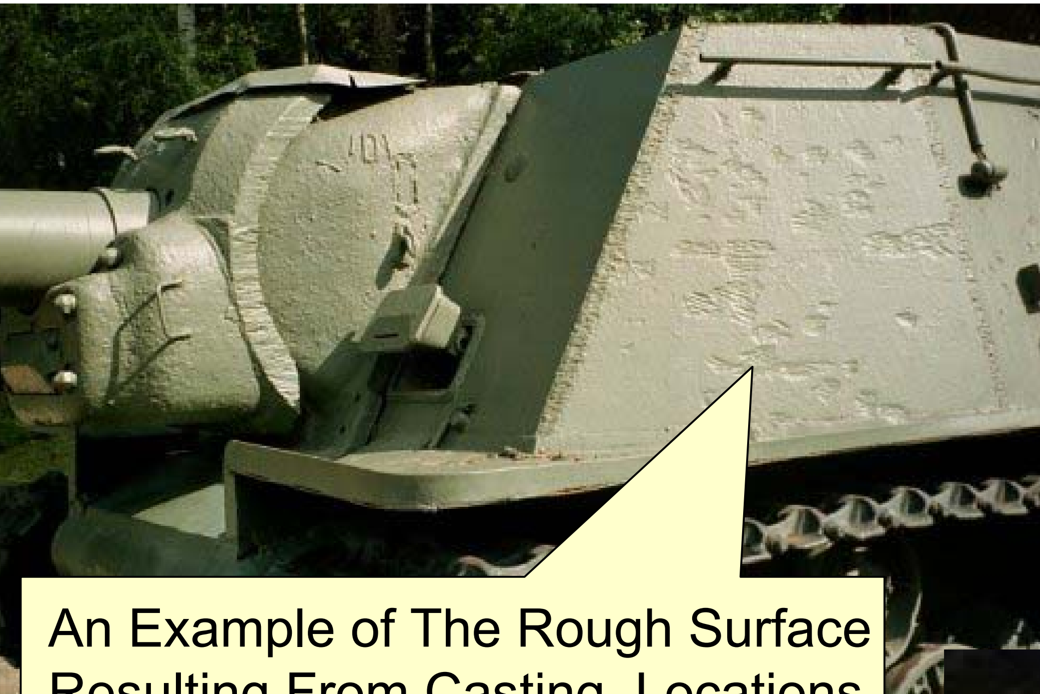




Vent Allows Retro-Reflection Paths → Make Interior Facets Absorbing

A Monostatic Cavity Return Would be Rare for the Small Openings and Complex Interior of Armored Vehicles

Surface Condition Begins to Matter at MMW Frequencies



An Example of The Rough Surface Resulting From Casting. Locations are Variable and Not Random

Typical Average Roughness Measured on Test Vehicles:

Smooth Al Parts, R_a < 1 mil
Painted RHA Parts, R_a < 3 mil
Rusted RHA Parts, R_a ~ 5 mil
Waviness is much larger

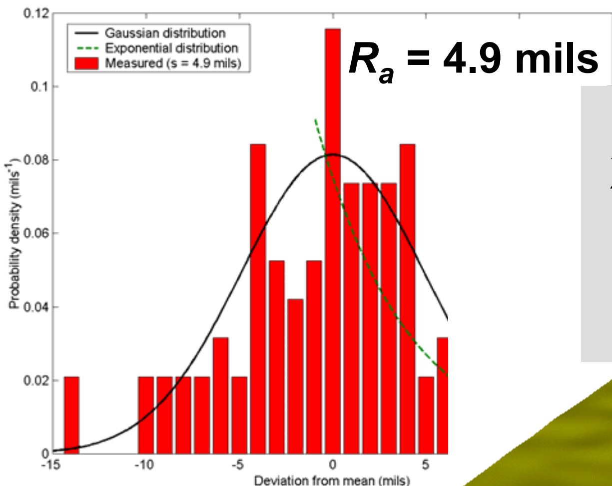
"Weathered" RHA Plates:

R_a = 3 – 5 mil

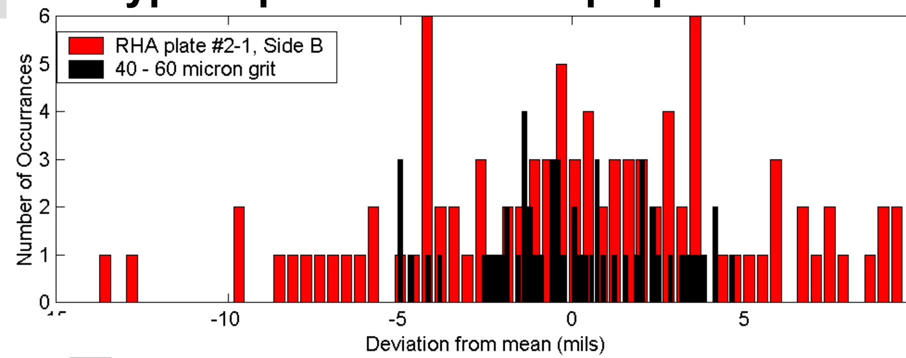
Waviness ~ 15 mil over 6-in

Surface Roughness
Measurements and Analysis

Measured RHA Surface Height Distribution with Coordinate Measurement Machine (CMM)



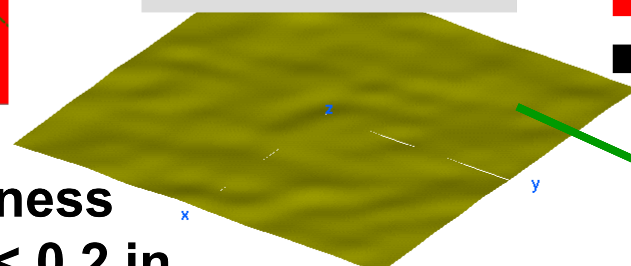
Before & after grit blast statistics for typical painted surface preparation

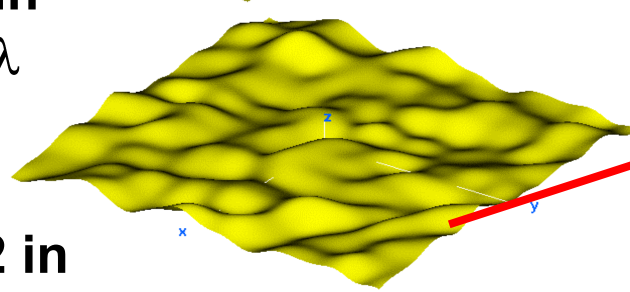


Rolled Homogeneous Armor (**R_a = 4.9 mils**)

After 40 – 60 μm Grit Blasting (**R_a = 2.5 mils**)

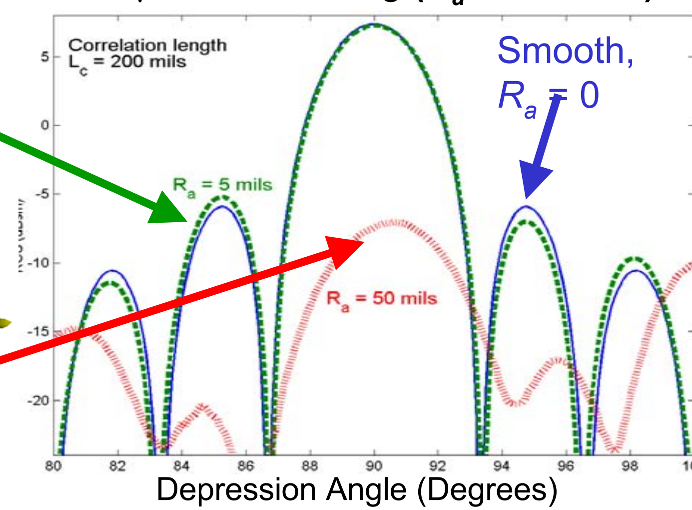
Model With Xpatch – Single Realization of a Random Rough Surface





Typical Roughness
R_a < 5 mils, L_c < 0.2 in
So $R_a \ll \lambda$ and $L_c \sim \lambda$

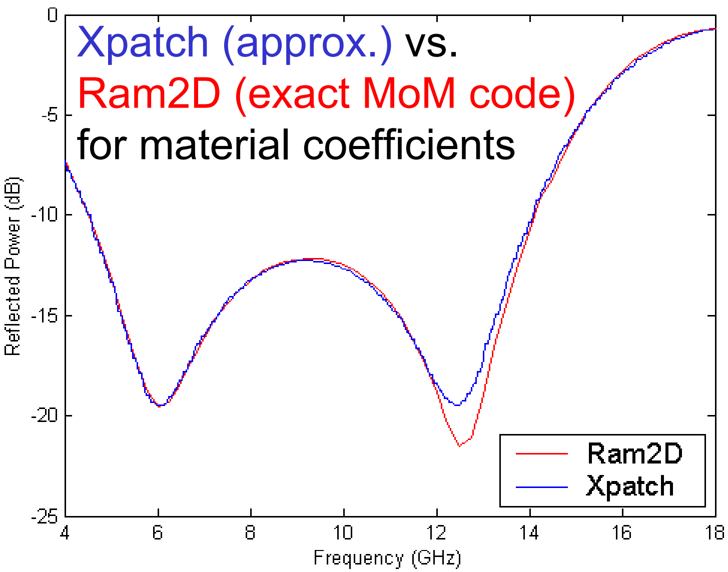
Extreme Case
R_a = 50 mils, L_c = 0.2 in



Typical Roughness Has A Negligible Effect On K_a-band RCS

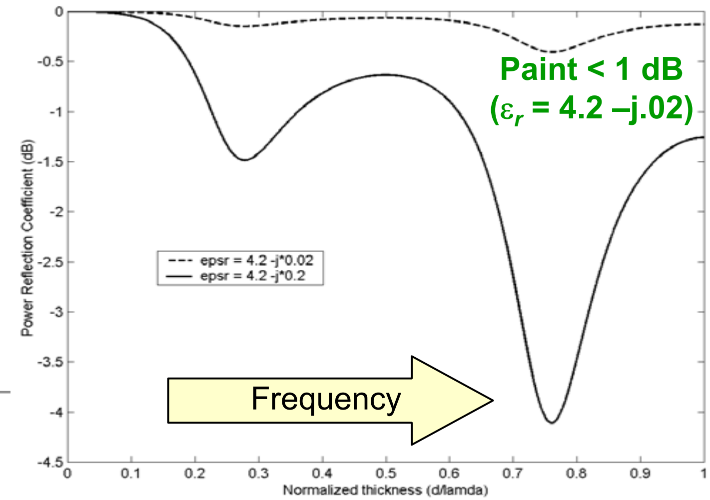
Surface Coatings
Numerical and Theoretical Analysis

Jaumann Absorber

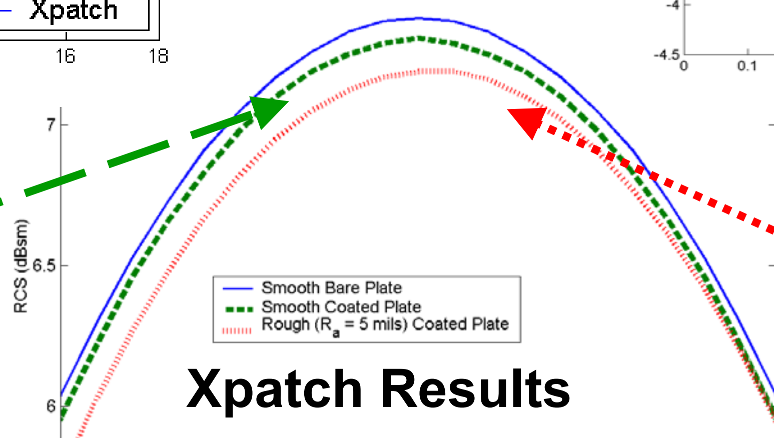


Codes Are Only As Accurate As The Input Data

Thick (Or Lossy) Coatings May Effect RCS



Typical CARC (d = 0.6 mm) Is Negligible (~0.1 dB) At K_a-band

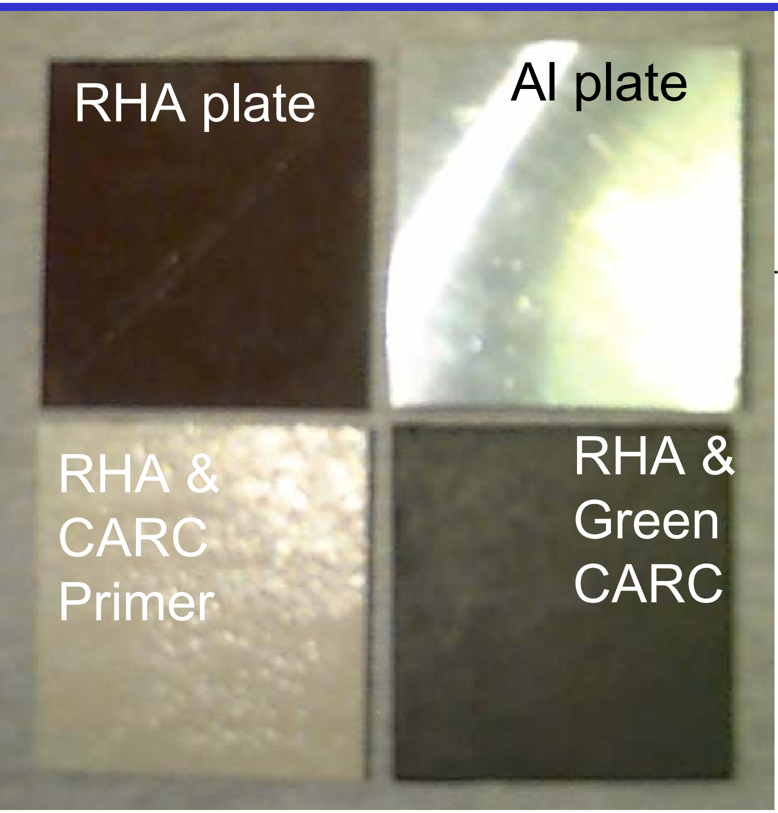


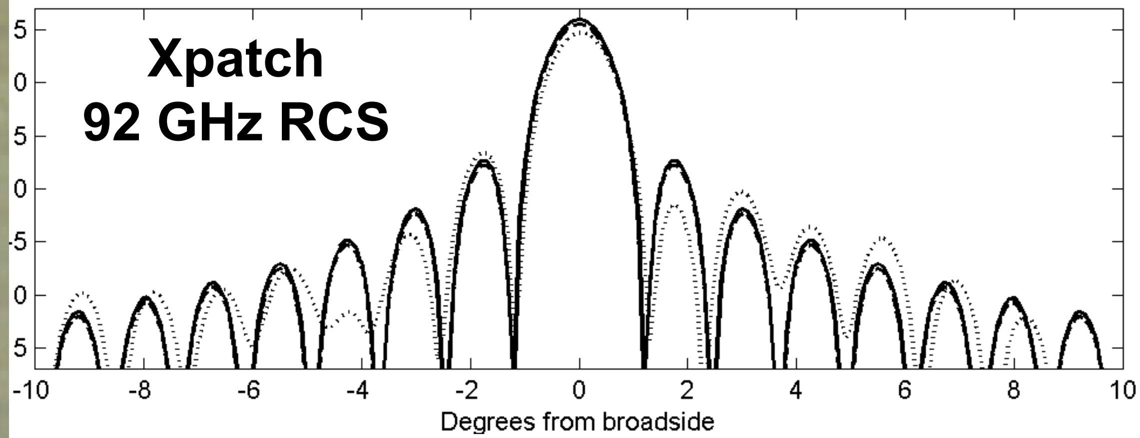
Xpatch Results

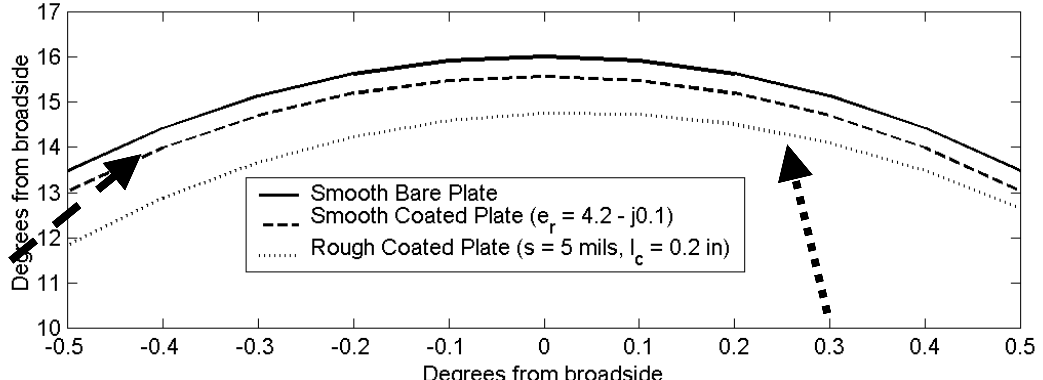
Typical Roughness with CARC Is Negligible (~0.2 dB) At K_a-band

Measured Reflection Coefficients vs. Frequency are Preferred Otherwise the Layer Thickness Must be Known Accurately

Surface Characterization – Effects May Not Be Negligible at *W*-Band







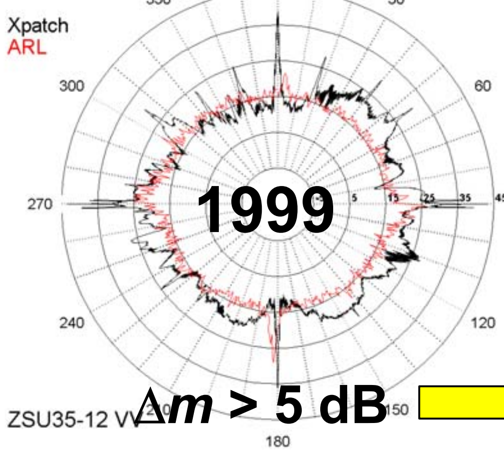
Typical CARC Is Negligible (~0.5 dB) At *W*-band

Typical Roughness with CARC May Not be Negligible (~1.3 dB) At *W*-band

A Complete Characterization of the Target May Be Required at W-Band Depending on the Accuracy Requirements

K_a-Band Lessons Learned – Single ZSU-23-4

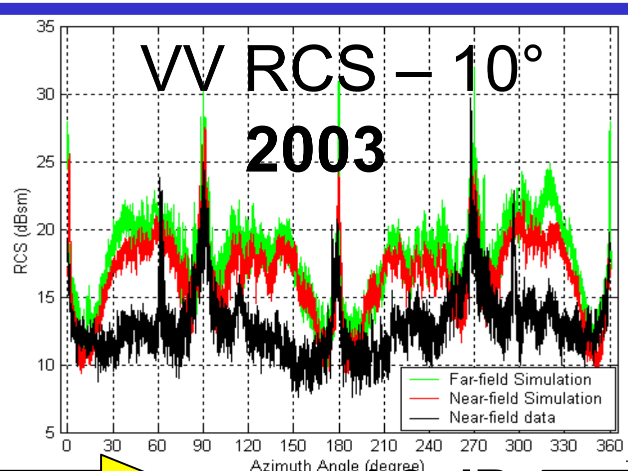
VV-RCS – 12°



Δm > 5 dB

VV RCS – 10°

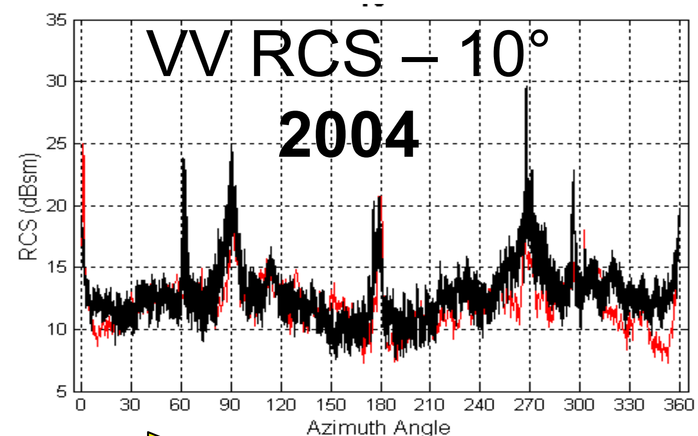
2003



Δm = 4.9 dB

VV RCS – 10°

2004



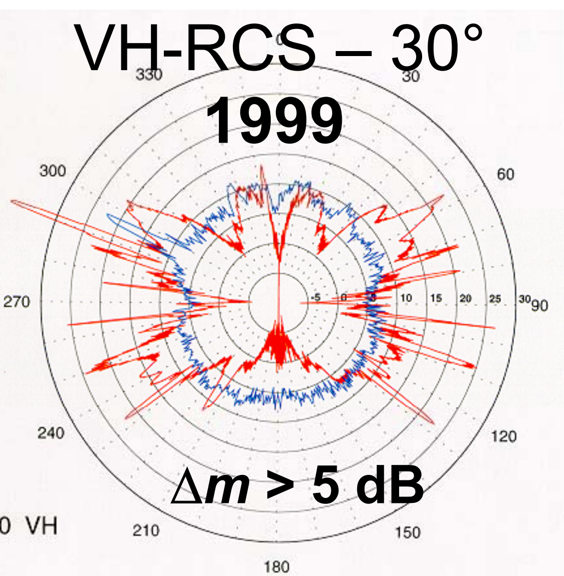
Δm = 1.1 dB

Improved Model & Simulation Fidelity

Modified Model Avoids Ideal Track

VH-RCS – 30°

1999

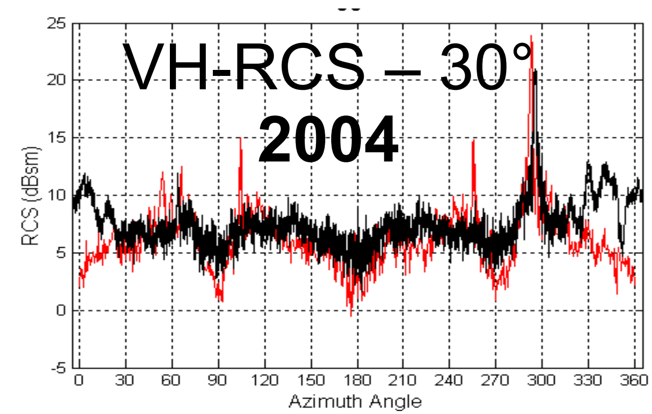


Δm > 5 dB

RCS Comparisons Are Improved ~ 3 dB & Identified Modeling Issues.

VH-RCS – 30°

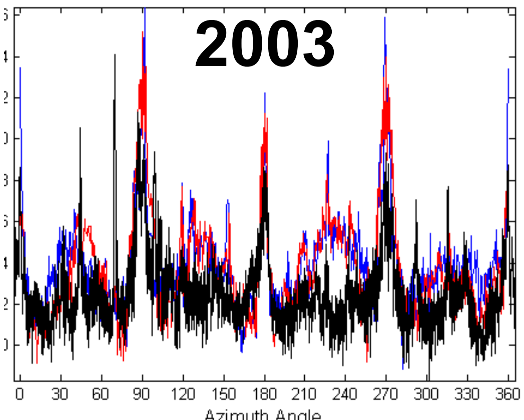
2004



Δm = 0.2 dB

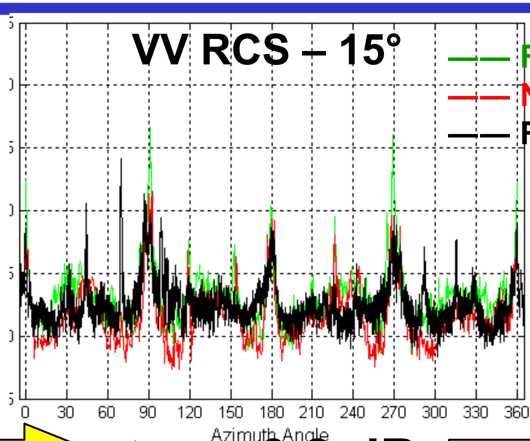
K_a-Band Lessons Learned – Single T72M1

VV RCS at 15°



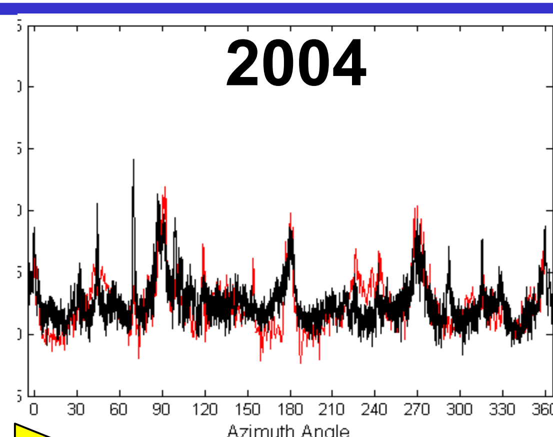
Δm = 1.7 dB

Like ZSU with RAM tracks



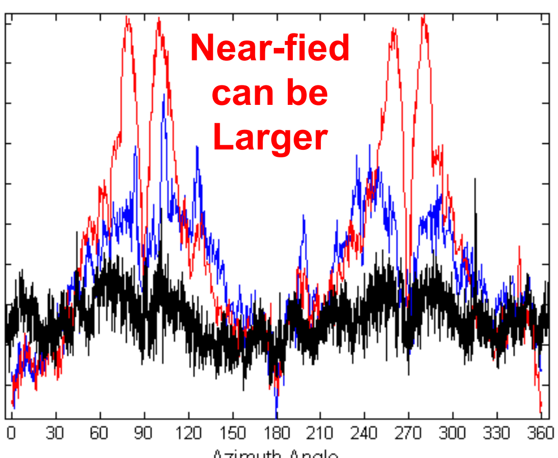
Δm = 0.8 dB

Tracks & Rubber Parts as RAM



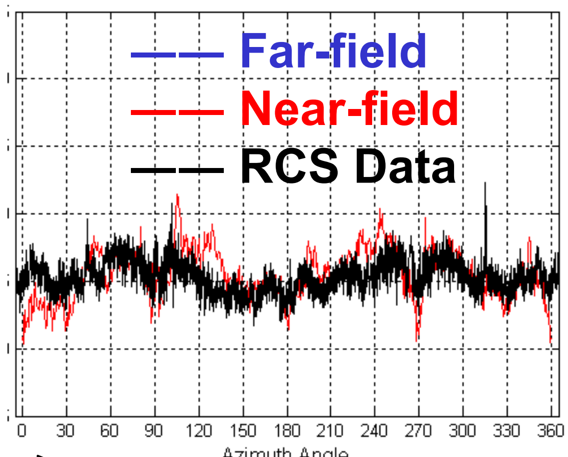
Δm = 0.1 dB

RAM Tracks & Rubber Parts

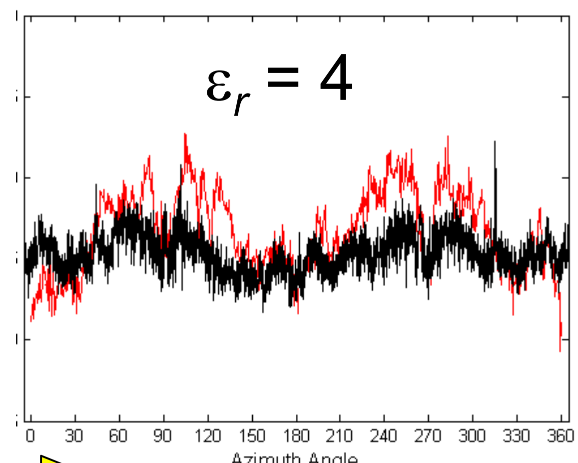


Δm = 3.0 dB

HV RCS at 15°



Δm = 0.4 dB



Δm = 1.9 dB

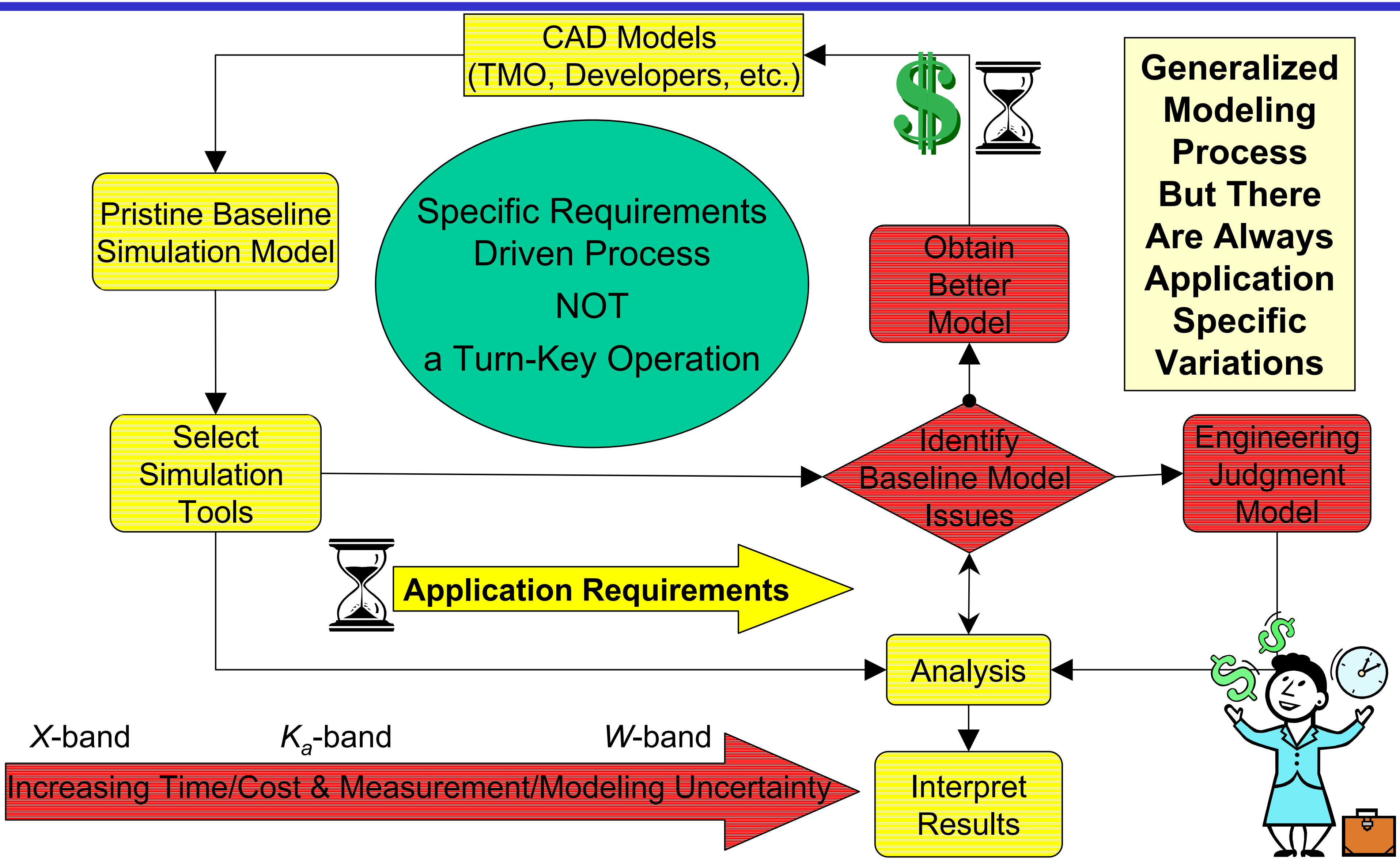
Modeling Issues Identified by Parametric Study & Analysis

K_a-Band – Target Model Lessons Summary

- Seal All Openings Caused by Transparent Facets
  - Glass Lenses & Rubber Seals Replaced: RAM is Better than Metal
  - Retains Correct Shadows but Avoids Cavities (Usually Artificial)
- Consider the Effect of any Remaining Cavities (e.g., Vents)
  - Realistic Interior? (ZSU Engine Compartment Example)
  - Cavity Contributions Possible/Important on Real Target? (e.g., FTTS)
- Contribution of Unrealistic Parts (e.g., Tracks, Corners, etc.)
  - Correct Shadow Boundaries Needed but Beware Pristine Parts
  - Analysis to Identify Issues (T72M1 Hull Ex. at Low Depression Angles)
- Material Descriptions for Non-Metal Parts, Coatings, etc.
  - Only as Accurate as the Input – Thickness is a Critical Parameter
  - Deleted/Incorrect Parts Change Multi-Bounce Returns (Ex. T72M1)
- Accurate Simulation of Test for Single Target Comparisons
  - Target Configuration & Articulation (Ex. Target Variability Issues)
  - Include the Radar Parameters and Test Geometry As Required

Model & Simulation Fidelity Based on Available Information

K_a-Band – Modeling Lessons Summary



RF Signature Modeling and Analysis – Summary

- Tool Kit Established With Known Issues/Limitations
  - ✓ Xpatch Advances and Hybrids
  - ✓ SBIR Codes And Brute Force Hybrid Techniques
  - ✓ New Advances Driven By Applications & Funding
- Choose The Optimum Tool To Fit The Job
  - ✓ Dominant Scattering Mechanisms and Important Physics
  - ✓ CAD Model & Mesh Quality Limitations →→ Time/Cost
- Modeling Requirements Still Based On Wavelength
  - ✓ Approximate Codes Are Often The Only Practical Tools
  - ✓ Practical Limitations of Model Fidelity & Resolution
  - ✓ Input Data Accuracy And Simulation Fidelity
  - ✓ Accuracy Required Depends on How Results Are Used

As Usual the Bottom Line is Cost

RF Signature Modeling and Analysis – Lessons Learned

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This paper was received as a PowerPoint presentation without supporting text.

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