Identifiability of 3D Attributed Scattering Center Features from Sparse Nonlinear Apertures

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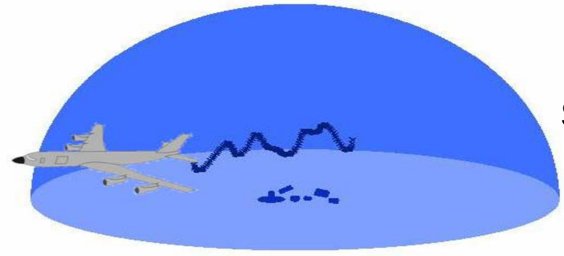
Research Overview

Goal: Study identifiability of 3D canonical features from complex phase history data collected over sparse linear/nonlinear apertures.



Sparse nonlinear sampling of 3D aperture

- "Confusion Matrix" of 6 canonical feature shapes
- Some canonical shapes easily confused due to native similarities in scattering response
- Feature discrimination from:
  - Phase history response versus aspect/elevation
  - Peak radar cross section
  - Polarization

Parametric Scattering Models

$$S_m = M_m(f, \theta_t, \phi_t, \theta_r, \phi_r; \vec{\Theta}_m) \exp\left(jk\Delta R(\vec{\Theta}_m)\right)$$

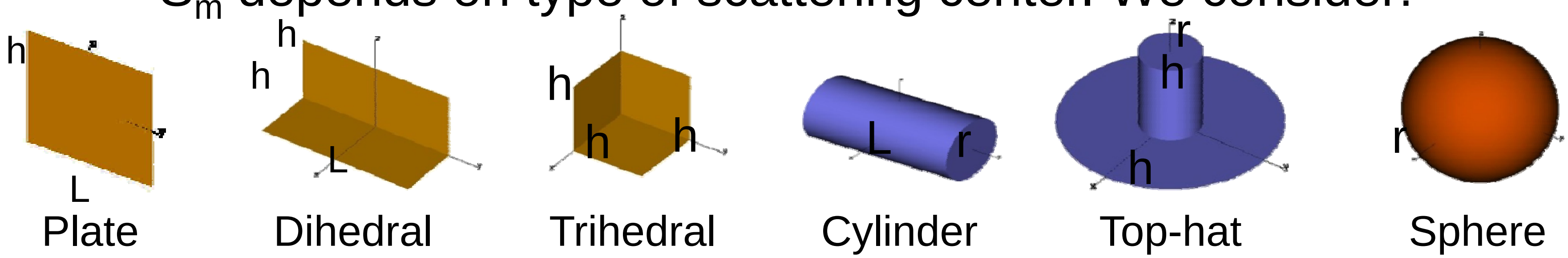
Frequency, Aspect,
and Polarization Dependence

Location Dependence

$\vec{\Theta}_m$:

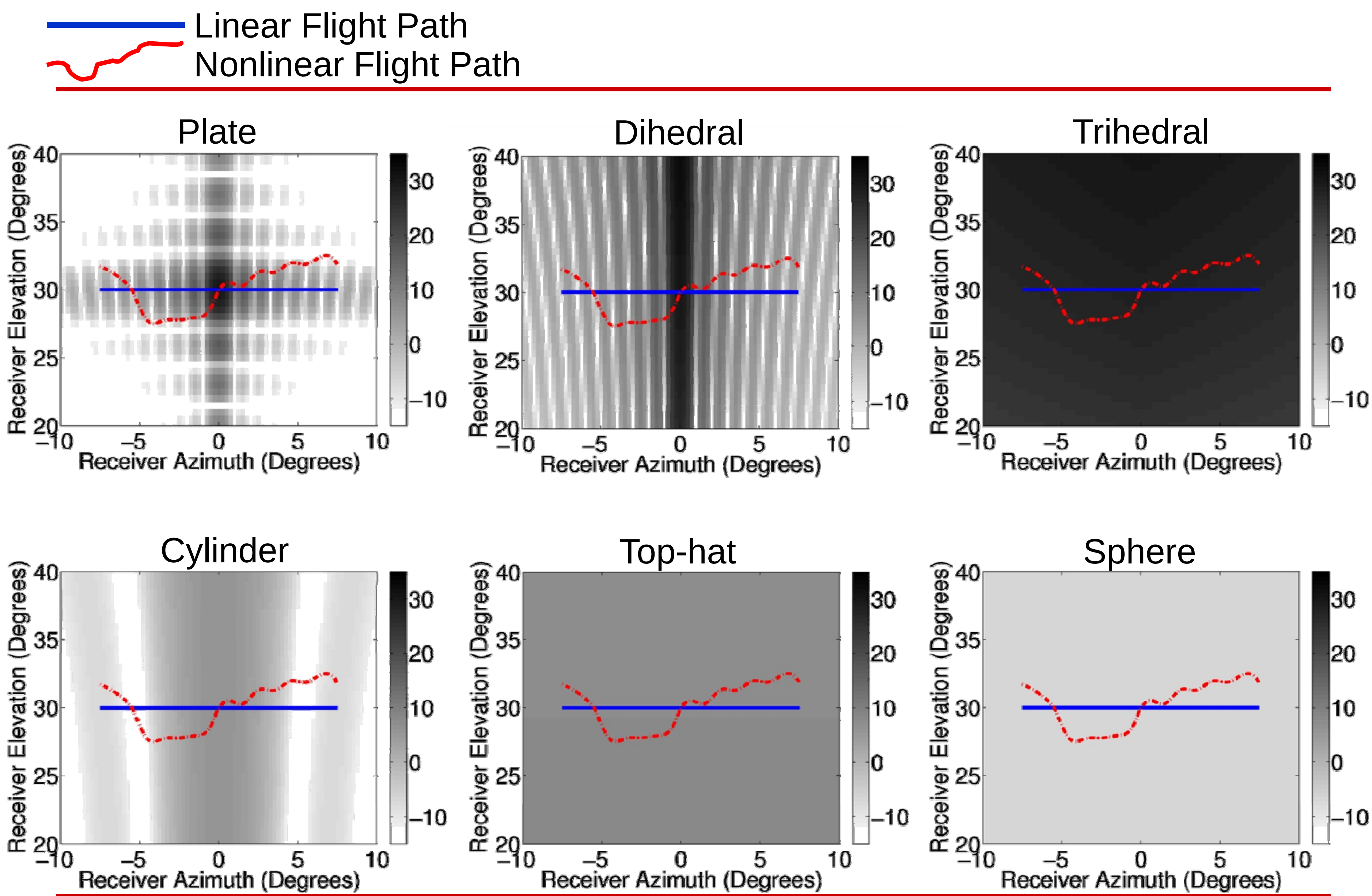
Complex Amplitude	$A_r + jA_i$
Roll, Pitch, Yaw	$(\psi_m, \theta_m, \phi_m)$
Location	(X, Y, Z)
Size parameters	(L, H, r)

S_m depends on type of scattering center. We consider:



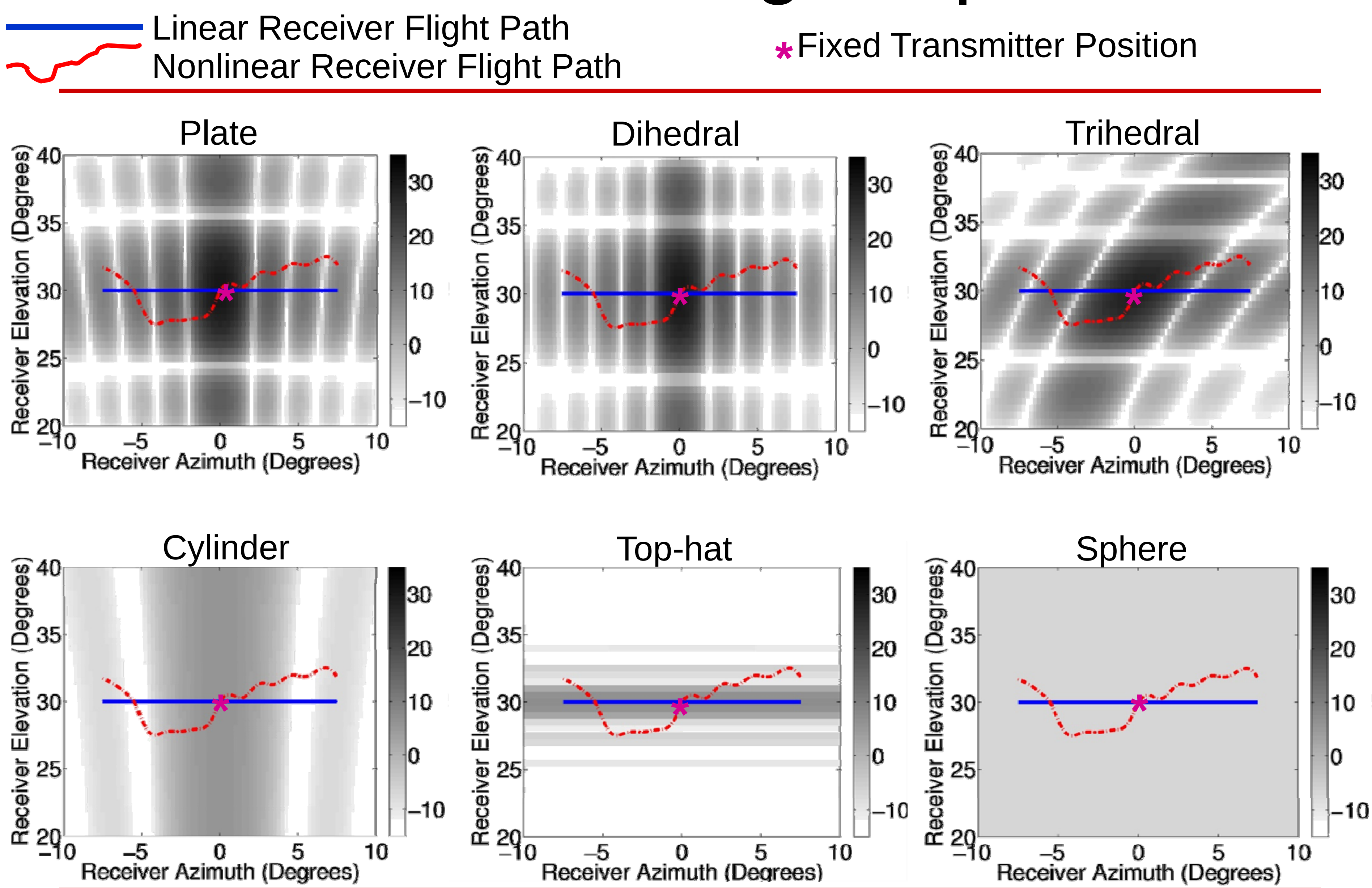
Rigling's (SPIE 2004) bistatic parametric scattering models modified to account for object radius and amplitude scaling to radar cross section

Monostatic Scattering Amplitudes



50 dB dynamic range – all on same scale

Bistatic Scattering Amplitudes



50 dB dynamic range – all on same scale

Least Squares Model Fit

- Compute complex phase history Y_n for each shape
  - Xpatch
  - Single channel (VV pol)
  - f_c=10.16 GHz, BW=3.96 GHz
  - Monostatic, linear and nonlinear flight paths
  - Bistatic, nonlinear receiver flight path

- Fit all models S_m, m=1,…,6 to observed data Y_n

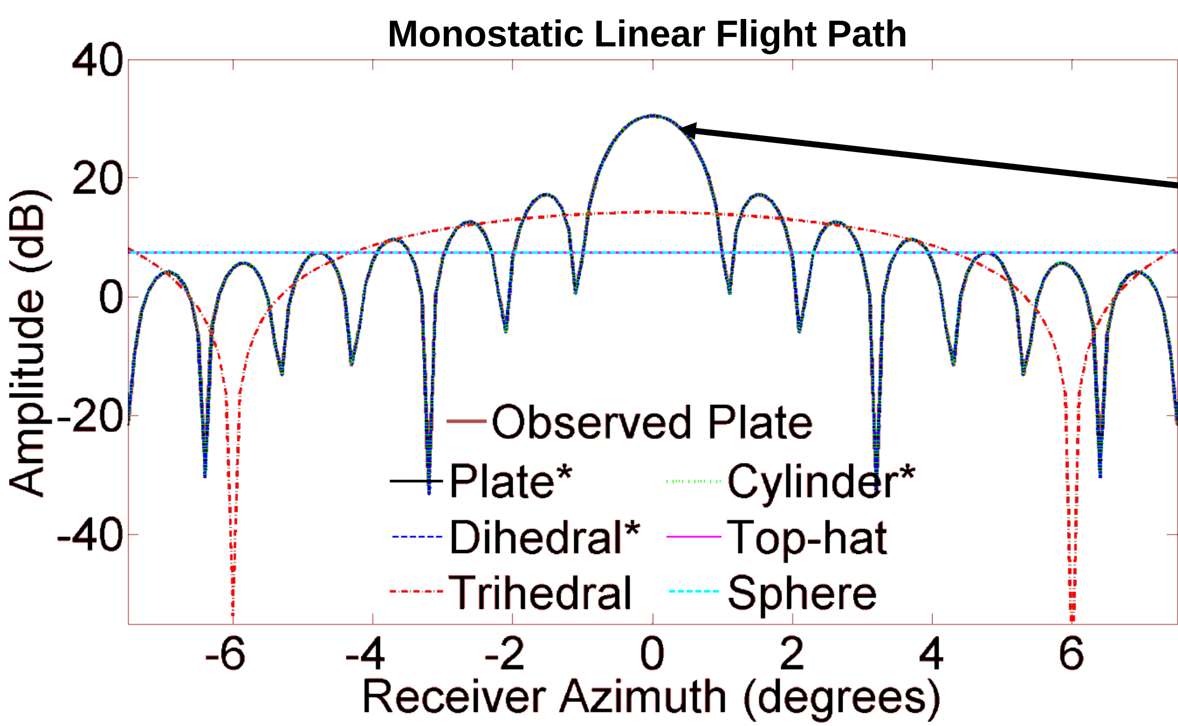
$$\hat{\Theta}_{m,n} = \arg\min_{\vec{\Theta}_m} \|Y_n - S_m(\vec{\Theta}_m)\|^2$$

Feature Identification Results

Easily confused best-fit features

True Signal	Model Fit Errors (dB)					
	Plate	Dihedral	Trihedral	Cylinder	Top-hat	Sphere
Plate	-43.0668	-42.3765	15.1250	-41.6044	15.6085	15.6083
Dihedral	-16.9800	-16.9292	15.1074	-19.7509	15.6003	15.6001
Trihedral	-14.5679	-14.6323	-26.6534	-20.3218	1.0707	6.3117
Cylinder	-25.9517	-29.6208	-15.2579	-29.6863	-5.8281	-5.8310
Top-hat	-13.7339	-15.4873	-14.7378	-11.8658	-15.6206	-14.5147
Sphere	-16.0719	-37.9948	-28.3642	-38.0509	-33.1546	-38.3475

Multiple models may fit well to the observed feature



e.g. Plate, Cylinder, and Dihedral all have length-dependent sinc responses

Other Model Discriminators

- Polarization
  - Even bounce vs. Odd bounce

- Consistency of estimated object size with its peak RCS
  - Calibrated radar: peak scattering intensity matches RCS

$$\max \|S_m\|^2 = \text{RCS}$$

  - Object dimensions estimated independently of amplitude

→ Compute RCS from table, estimated dimensions and check consistency with max $\|S_m\|^2$

Canonical Shape	Peak RCS	Example Dimensions	Example RCS $\lambda = 0.0295$ cm
Rectangular Plate	$\frac{4\pi L^2 H^2}{\lambda^2}$	$L = 36$ in. $H = 12$ in.	1119.6 m^2
Dihedral	$\frac{8\pi L^2 H^2}{\lambda^2}$	$L = 36.0$ in. $H = 12$ in.	2239.2 m^2
Square Trihedral	$\frac{\pi}{2}\frac{12\pi H^4}{\lambda^2}$	$H = 15$ in.	1431.2 m^2
Cylinder	$\frac{2\pi}{\lambda} rL^2$	$r = 5$ in. $L = 15$ in.	3.9 m^2
Top-hat	$\frac{2\pi r H^2}{\lambda\sqrt{2}}$	$r = 6$ in. $H = 18$ in.	4.8 m^2
Sphere	πr^2	$r = 10$ in.	0.2 m^2

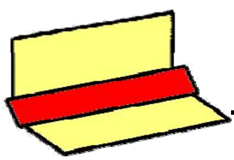
Large Range of RCS values for objects of similar size helps to discriminate features

e.g. 15” Trihedral ~ 70’ Sphere

RCS Consistency Examples

RCS consistent | RCS not consistent | Monostatic Nonlinear Path

True Signal	Estimated Signal Radar Cross Section (dB)											
	Plate		Dihedral		Trihedral		Cylinder		Top-hat		Sphere	
	Amp.	Dim.	Amp.	Dim.	Amp.	Dim.	Amp.	Dim.	Amp.	Dim.	Amp.	Dim.
Plate	32.058	32.063	31.463	—	9.247	—	31.221	-112.092	9.615	—	6.525	-267.676
Dihedral	32.049	19.098	32.033	—	33.697	—	31.976	13.550	11.797	—	8.194	-40.671
Trihedral	29.878	-22.209	29.933	—	29.988	—	29.883	-65.902	29.277	—	27.938	-99.649
Cylinder	6.597	-5.857	7.479	—	-9.773	—	7.482	6.694	-6.587	—	-9.222	-12.952
Tophat	9.136	6.993	8.053	—	10.077	—	8.049	-28.471	8.152	—	6.723	-12.237
Sphere	-14.285	2.079	-4.968	—	-4.961	—	-5.495	-41.429	-7.915	—	-6.935	-6.931



Est. Plate: L = 35.46", H=2.75"
Est. Dihedral L = 35.46", H=indeterminate
True Dihedral: L = 36", H = 12"

} RCS consistency check discards incorrect feature

Assume radar calibrated and determine height from measured RCS:

Estimated Top-hat: r = 1.2", RCS = 29.277dB
→ H=40.7 feet
True Trihedral: H = 15"

} Estimated dimensions may be unreasonable for the scene

Feature Identifiability

True Shape	Best-fit Confuser Shapes Monostatic Linear	Monostatic Nonlinear	Bistatic Nonlinear
Plate	dihedral cylinder		
Dihedral	plate cylinder	plate cylinder	plate
Trihedral			plate, dih, cyl, top-hat
Cylinder	plate dihedral	plate dihedral	dihedral trihedral
Top-hat	plate, dih., trih., cyl., sphere	dihedral, cylinder, sphere	plate, dihedral, trihedral
Sphere	dihedral cylinder		dihedral, top-hat

Model fit only

Feature Identifiability

True Shape	Best-fit Confuser Shapes: Monostatic Linear	Monostatic Nonlinear	Bistatic Nonlinear
Plate	~~dihedral~~ cylinder		
Dihedral	~~plate~~ ~~cylinder~~	~~plate~~ ~~cylinder~~	~~plate~~
Trihedral			plate, ~~dih~~, cyl, ~~top-hat~~
Cylinder	plate ~~dihedral~~	plate ~~dihedral~~	~~dihedral~~ trihedral
Top-hat	~~plate~~, dih., ~~trih.~~, ~~cyl.~~, ~~sphere~~	dihedral, ~~cylinder~~, ~~sphere~~	~~plate~~, dihedral, ~~trihedral~~
Sphere	~~dihedral~~ cylinder		~~dihedral~~, ~~top-hat~~

Struck-through entries: Polarization inconsistency

Feature Identifiability

	Best-fit Confuser Shapes		
True Shape	**Monostatic Linear**	**Monostatic Nonlinear**	**Bistatic Nonlinear**
Plate	dihedral ~~cylinder~~		
Dihedral	~~plate~~ ~~cylinder~~	~~plate~~ ~~cylinder~~	plate
Trihedral			plate, dih, ~~cyl~~, ~~top-hat~~
Cylinder	~~plate~~ dihedral	~~plate~~ dihedral	dihedral ~~trihedral~~
Top-hat	~~plate~~, dih., trih., ~~cyl~~, ~~sphere~~	dihedral, ~~cylinder~~, ~~sphere~~	plate, ~~dihedral~~, trihedral
Sphere	dihedral ~~cylinder~~		~~dihedral~~, ~~top-hat~~

— RCS inconsistency

Feature Identifiability

True Shape	Best-fit Confuser Shapes		
	Monostatic Linear	Monostatic Nonlinear	Bistatic Nonlinear
Plate	~~dihedral~~ ~~cylinder~~		
Dihedral	~~plate~~ ~~cylinder~~	~~plate~~ ~~cylinder~~	~~plate~~
Trihedral			plate, ~~dih~~, ~~cyl~~, ~~top-hat~~
Cylinder	~~plate~~ ~~dihedral~~	~~plate~~ ~~dihedral~~	~~dihedral~~ ~~trihedral~~
Top-hat	~~plate~~, dih., ~~trih.~~, ~~cyl.~~, ~~sphere~~	dihedral, ~~cylinder~~, ~~sphere~~	~~plate~~, ~~dihedral~~, ~~trihedral~~
Sphere	~~dihedral~~ ~~cylinder~~		~~dihedral~~, ~~top-hat~~

Polarization inconsistency   RCS inconsistency

Summary

- Studied identifiability of canonical scattering features for various apertures
  - Monostatic linear and nonlinear
  - Bistatic nonlinear
- Characterized feature “confusion matrix”
  - Anisotropic scattering shape only
  - Polarization
  - RCS consistency
- Useful information for higher level reasoning about scene content or object recognition