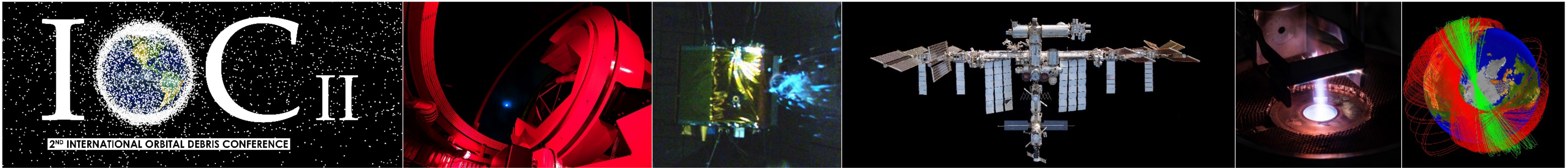
An Approach to Shape Parameterization Using Laboratory Hypervelocity Impact Experiments

John H. Seago

ERC—Jacobs JETS II Contract

NASA Orbital Debris Program Office



SOCIT & DebriSat Impact Experiments

- **Satellite Orbital Debris Characterization Impact Test (SOCIT) hypervelocity impact test series**
  - December 1991 to January 1992
  - Fourth test (SOCIT4) targeted a flight-ready Navy Transit satellite bus
- **Current breakup models like the NASA Standard Satellite Breakup Model (SSBM) use SOCIT4 test results**
  - About 59% of the spacecraft's total mass analyzed
  - ~810 recorded fragments or fragments groups

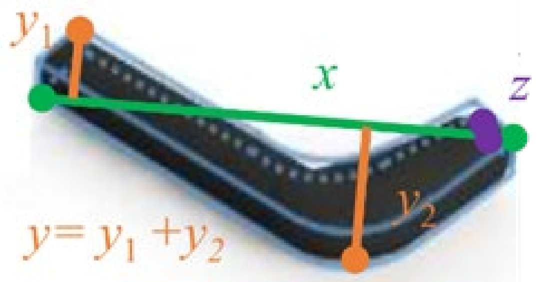
SSBM well represented the major in 2009 on-orbit collision involving Cosmos 2251 – a legacy spacecraft

- **DebriSat experiment builds upon the previous impact test data by utilizing more modern materials typical of low Earth orbit (LEO) satellites today**
  - Better represents evolving materials and technology that may fragment differently
- **DebriSat's post-impact processing targets collection of fragments greater than or equal to 2 mm**
  - 205K+ individual fragments recorded thus far
  - ~60K have mass, dimensions, primary material, shape recorded

High area-to-mass ratio materials not well represented in collisions with *Fengyun*-1C (2007) and Iridium 33 (2009)

SOCIT & DebriSat Fragment Datasets

- **Fragment database records involving shape assessment**
  - Mass, dimensions, volume, primary material, shape designation (from inspection)
- **Estimated size and shape**
  - DebriSat: point-clouds from imagery
  - SOCIT: manually measured with calipers
- **Mutually perpendicular Orthogonal-projection measurements ($x \geq y \geq z$) defined as:**
  - *x* is the longest projected dimension across the fragment
  - *y* is the longest projected dimension orthogonal to *x*
  - *z* is the longest projected dimension orthogonal to the *x*-*y* plane



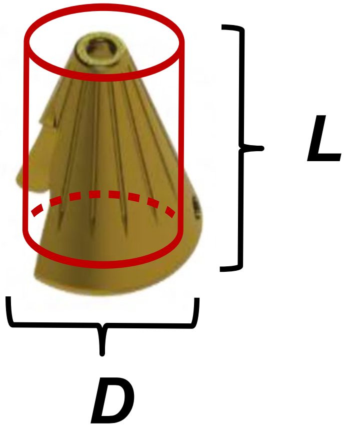
- **Average of these orthogonal projections produces a characteristic length, L_C,**
  - A standard metric of size for space-debris observations
  - Independent of the aspect angle or remotely sensed object

Fragments As Cylindrical Shapes

Rod-like (straight)

Rod-like (bent)

Nugget-like



- **Rod-like**
  - **One "much longer" dimension**
- **Plate-like**
  - **One "much shorter" dimension**
- **Nugget-like**
  - **All dimensions similar**
- **Flexible**
  - **Shape changes or doesn't hold**

Plate-like (straight)

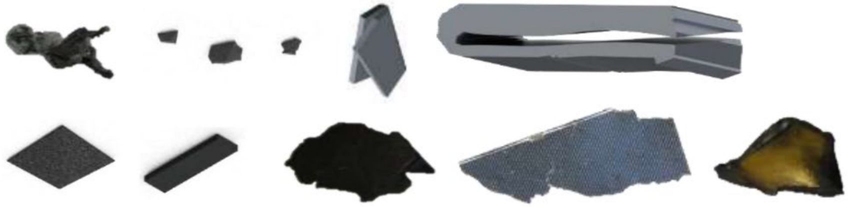


Plate-like (bent)

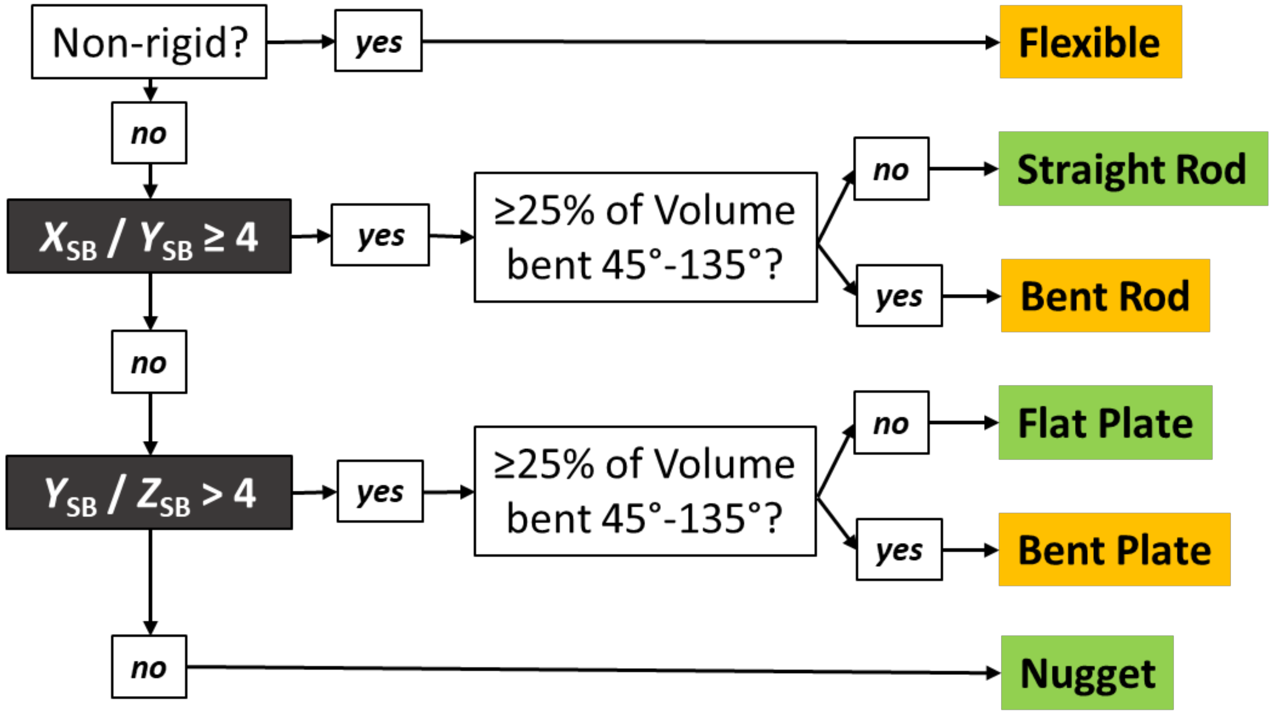
Simplified Shapes Categories

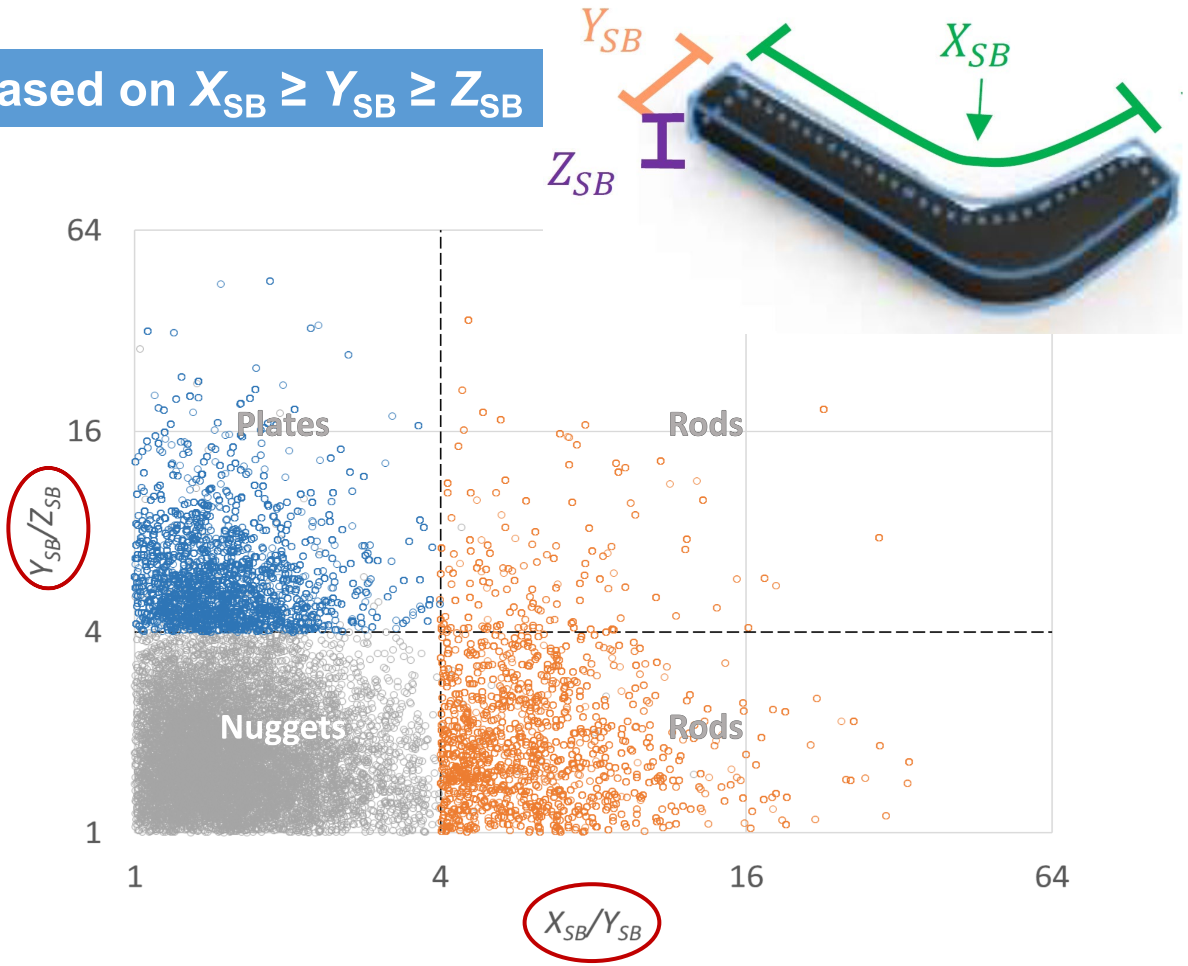
SOCIT		%	DebriSat		%	Simplified
• Flat Plate • Flake	(1%) (13%)	14%	○ Flat Plate	(36%)	36%	**Plate**
• Curled Plate	(1%)	1%	○ Flexible ○ Bent Plate	(1%) (2%)	3%	**Plate** (Bent)
• Box • Sphere • Box & Plate • Nugget • Other	(0.3%) (<0.1%) (<0.1%) (59%) (23%)	83%	○ Parallelepiped/nugget/spheroid	(19%)	19%	**Nugget**
			○ Bent needle/rod/cylinder	(11%)	11%	**Rod** (Bent)
• Rod • Cylinder	(2%) (0.3%)	2%	○ Straight needle/rod/cylinder	(31%)	31%	**Rod**
	(100%)	100%		(100%)	100%	

SOCIT's 10 categories and DebriSat's 6 categories simplified to 3 Right Circular Cylinder (RCC) proportions (plates, nuggets, rods) for intercomparison

Assigning Shapes with Dimensions

Ideal Decision logic for characterizing *DebriSat* shapes based on $X_{SB} \geq Y_{SB} \geq Z_{SB}$



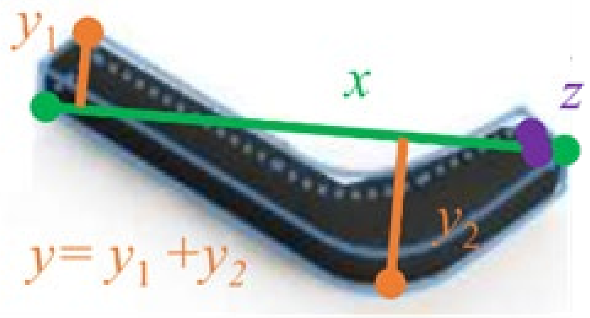


***SOCIT* defined 10 shape categories and mostly relied on individual judgments**

Assigning Shapes with Dimensions

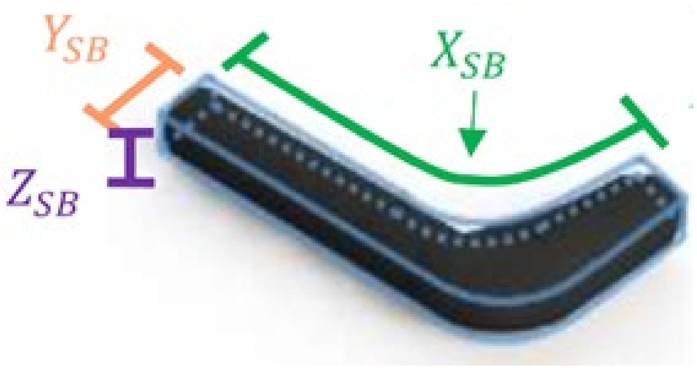
Bent Rod Example

Orthogonal-projections ($x \geq y \geq z$)



Recorded in Database, with $L_C = (x + y + z)/3$

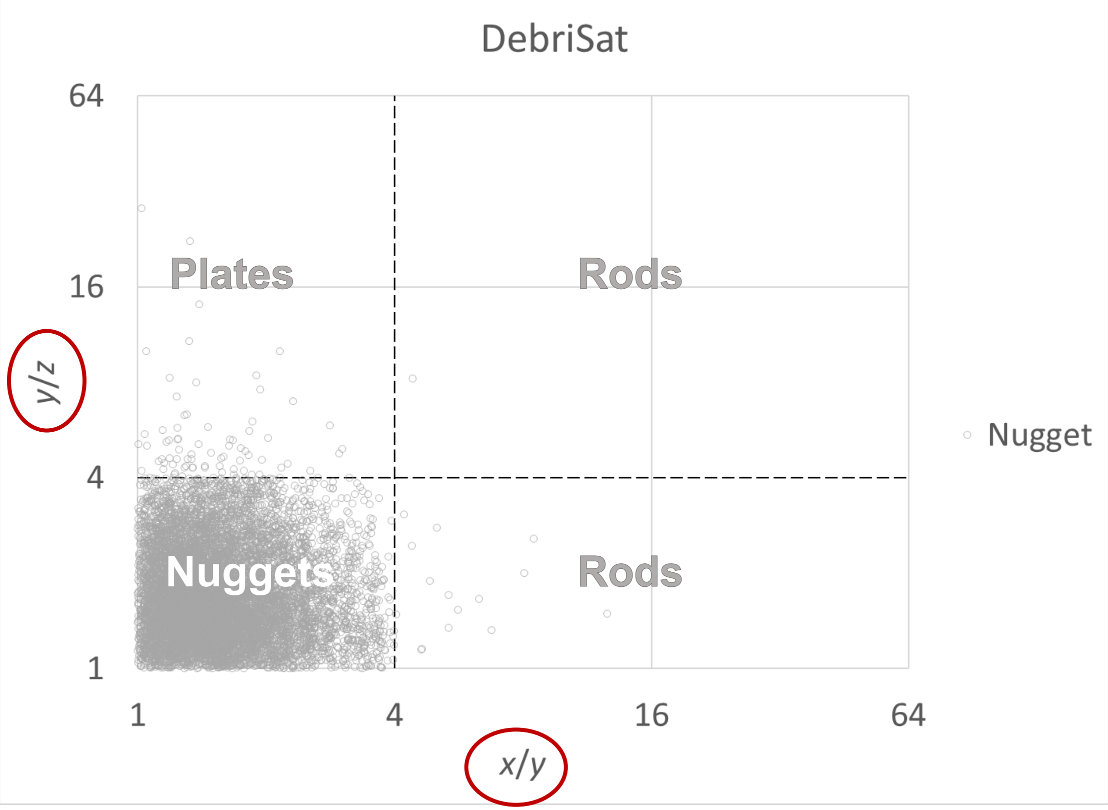
Solid-body dimensions ($X_{SB} \geq Y_{SB} \geq Z_{SB}$)

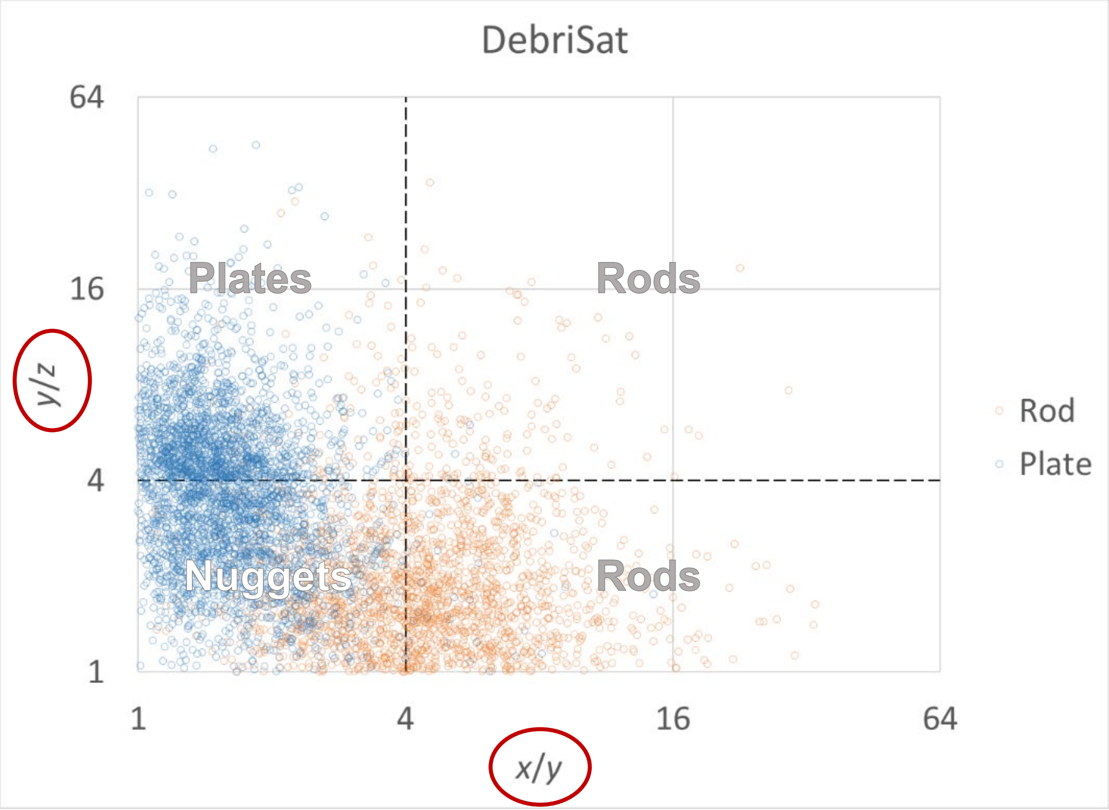


Estimated during inspection, not recorded

Most fragment bending thought to occur during impact with foam catch system

Can Orthogonal Projection Assign Shape?



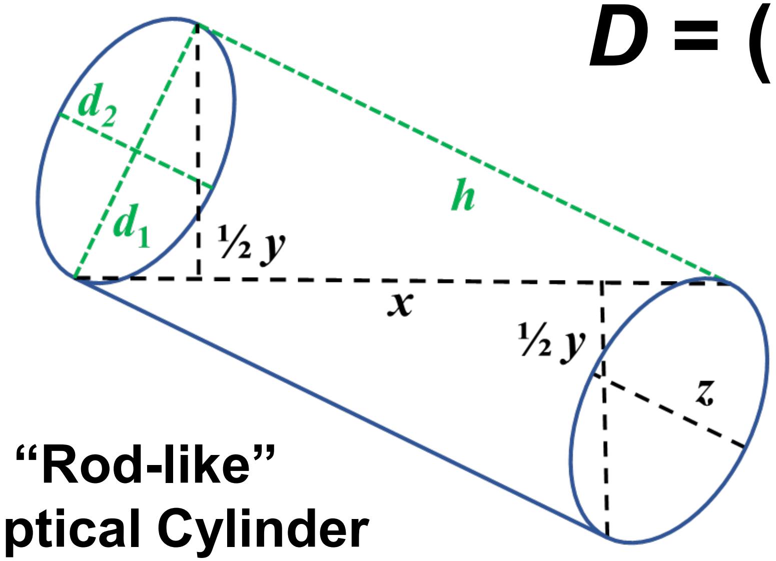


% Agreement	Plates	Nuggets	Rods
SOCIT	43%	94%	69%
DebriSat	76%	99%	67%

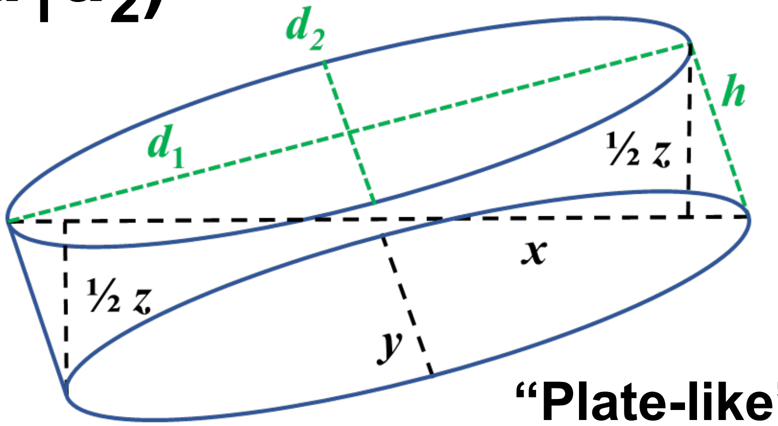
Cylindrical Shape Based on ($x \geq y \geq z$)

Ratio of Length-to-Diameter $\underline{L:D \equiv h \div D}$

$$D = (d_1 d_2)^{1/2}$$



"Rod-like"
Elliptical Cylinder
$h > D = (d_1 d_2)^{1/2}$



"Plate-like"
Elliptical Cylinder
$h < D = (d_1 d_2)^{1/2}$

A cylindrical shape can be imagined to enclose a fragment, then a RCC shape can be characterized by $L:D$

Cylindrical Shape Based on ($x \geq y \geq z$)

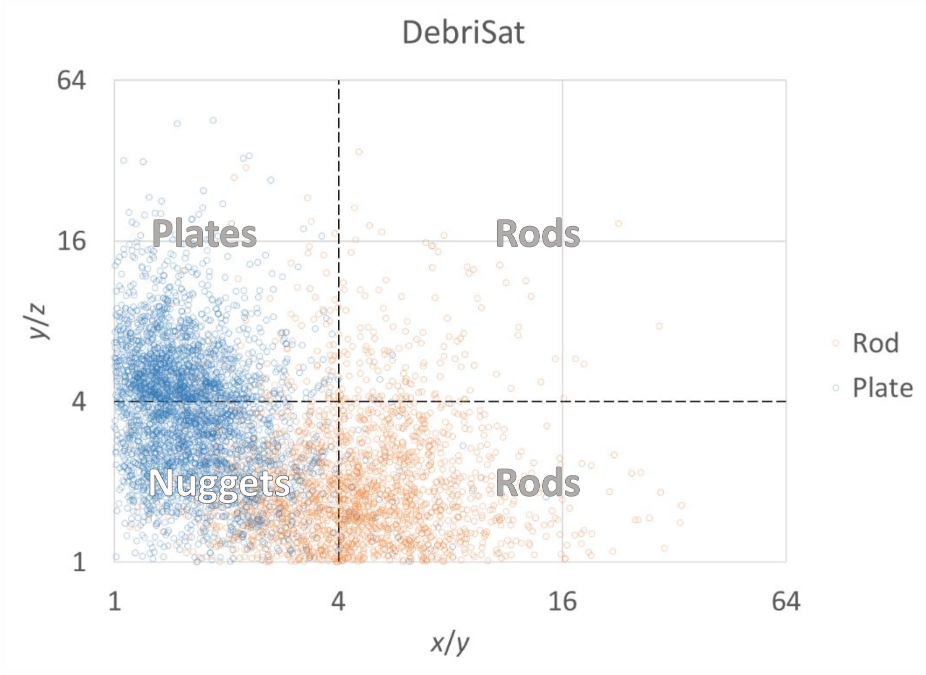
Ratio of Length-to-Diameter $L{:}D \equiv h \div D$

$$D = (d_1 d_2)^{1/2}$$

	"Rod-like"	"Plate-like"
$h^2 =$	$\frac{1}{2}\left(1 + \sqrt{1 - \left(\frac{y}{x}\right)^2}\right)x^2$	$\frac{1}{2}\left(1 - \sqrt{1 - \left(\frac{z}{x}\right)^2}\right)x^2$
$d_1 =$	$\frac{yx}{2h}$	$\frac{zx}{2h}$
$d_2 =$	z	y

Plane geometry can transform orthogonal projections ($x \geq y \geq z$) to (h, d_1, d_2) defining $L{:}D$

Cylindrical Shape Based on ($x \geq y \geq z$)



	Plates		Rods	
	($x \geq y \geq z$)	(h, d_1, d_2)	($x \geq y \geq z$)	(h, d_1, d_2)
SOCIT	43%	75%	69%	69%
DebriSat	76%	92%	67%	88%
DebriSat (w/o CFRP)	37%	75%	26%	67%
DebriSat (w/o CFRP, unbent only)	46%	84%	57%	83%
DebriSat (w/o CFRP, bent only)	16%	56%	16%	62%

For RODS & PLATES, transformation of ($x \geq y \geq z$) to (h, d_1, d_2) correlates better to inspector-assigned shapes using the DebriSat Shape Logic Rubric

Cylindrical Shape Based on Volume

Geometric Volume of a Cylinder $V \equiv \frac{1}{4} \pi D^2 h$

$$D = (d_1 d_2)^{1/2}$$

	Flat Plate	Nugget/ Spheroid	Straight Rod
L:*D*	$\frac{4\,V}{\pi}(\,d_1\,d_2)^{-\frac{3}{2}}$	$\sqrt{\frac{\pi\,y^3}{4\,V}}$	$\sqrt{\frac{\pi\,h^3}{4\,V}}$

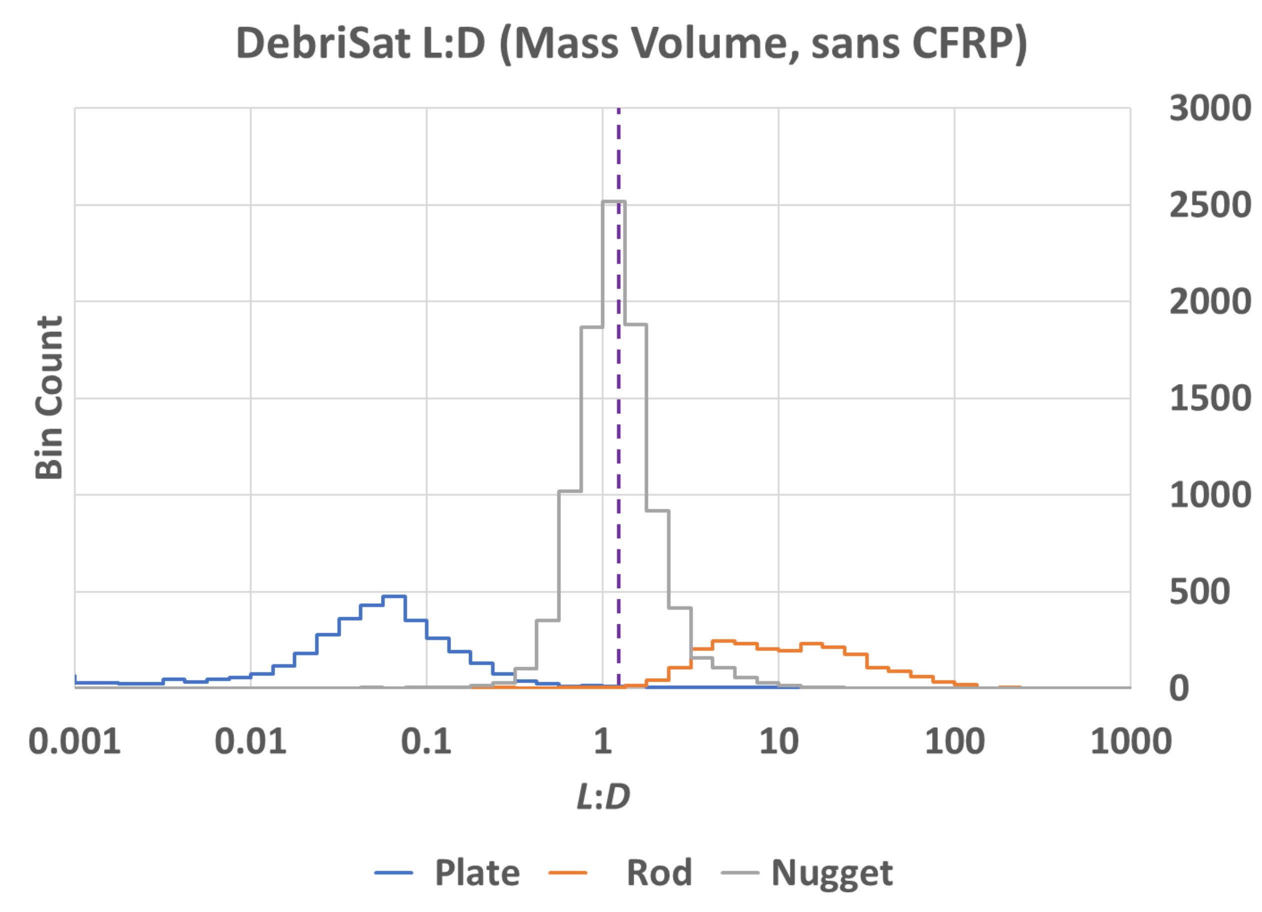
Volume can be substituted into the *L*:*D* ratio through a change of variable(s) to estimate *L*:*D* = *f*(*V*).

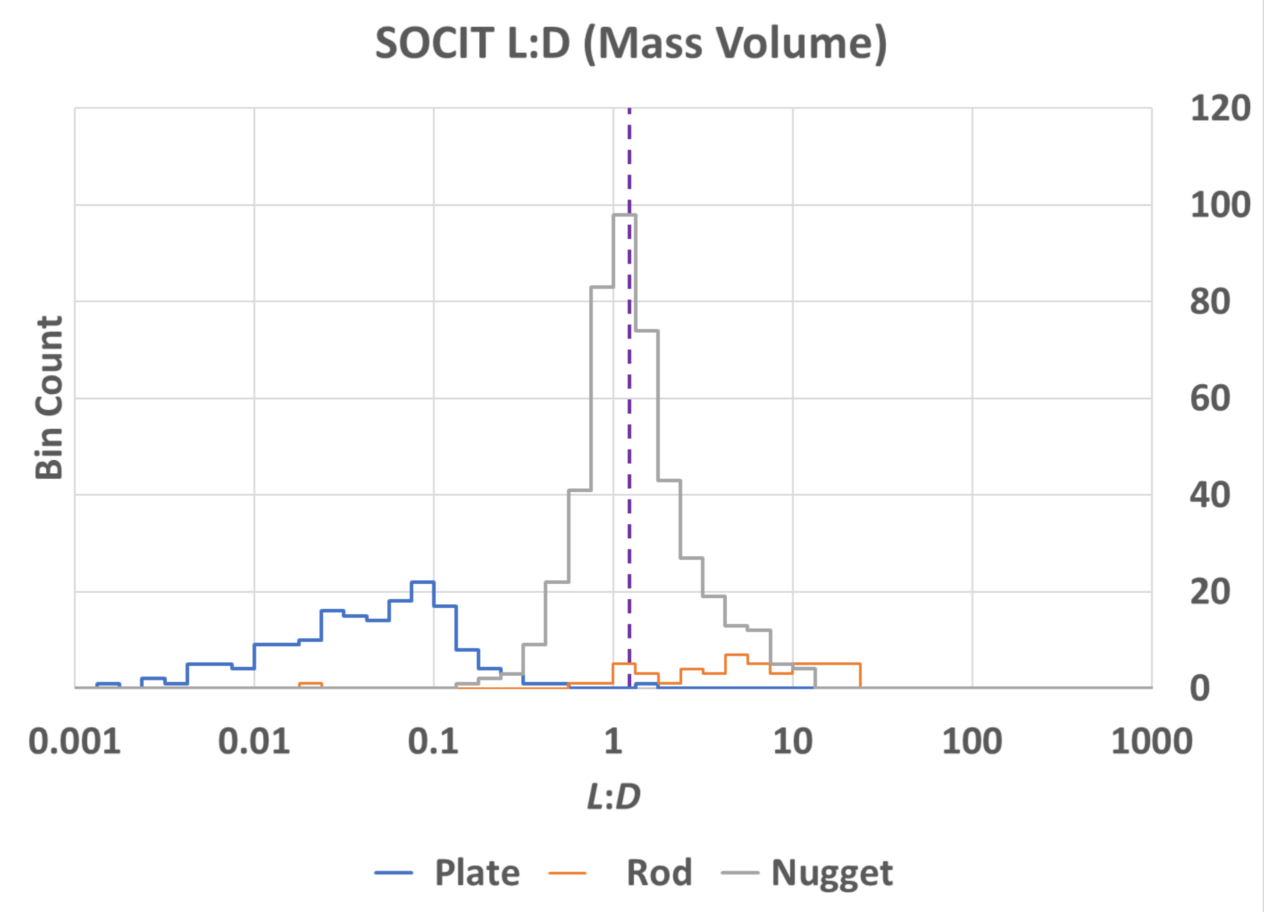
Cylindrical Shape Based on Volume

Geometric Volume of a Cylinder $V \equiv \frac{1}{4} \pi D^2 h$

Volume Type	Expression	Advantages	Disadvantages
Geometric	$\frac{1}{4} \pi d_1 d_2 h$	• Definable for all usable fragments from $x \geq y \geq z$ alone	• Assumes a cylindrically shaped fragment orthogonally measured
Bulk	"Measured"	• Based on observed fragment dimensions (actual shape) • Distributionally well-behaved	• **SOCIT records no bulk volumes** • Only DebriSat has measured volumes
Mass	m / ρ	• Definable for all usable fragments • Explicit function of mass • Conservative risk assessments	• Fragment densities approximate, based only on primary material • Materials not always accurate • Shape distributions spread out

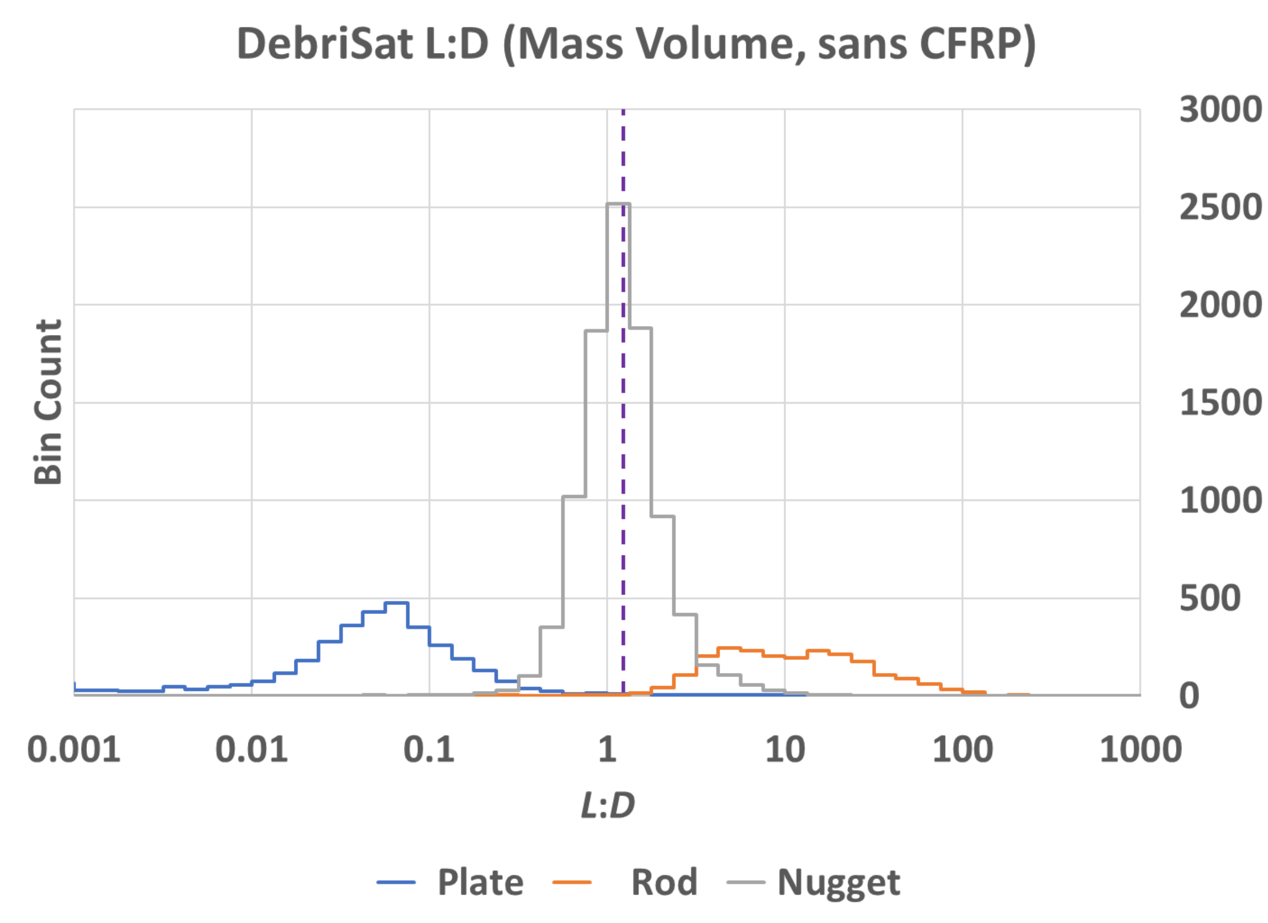
Distributions of Simplified Shape

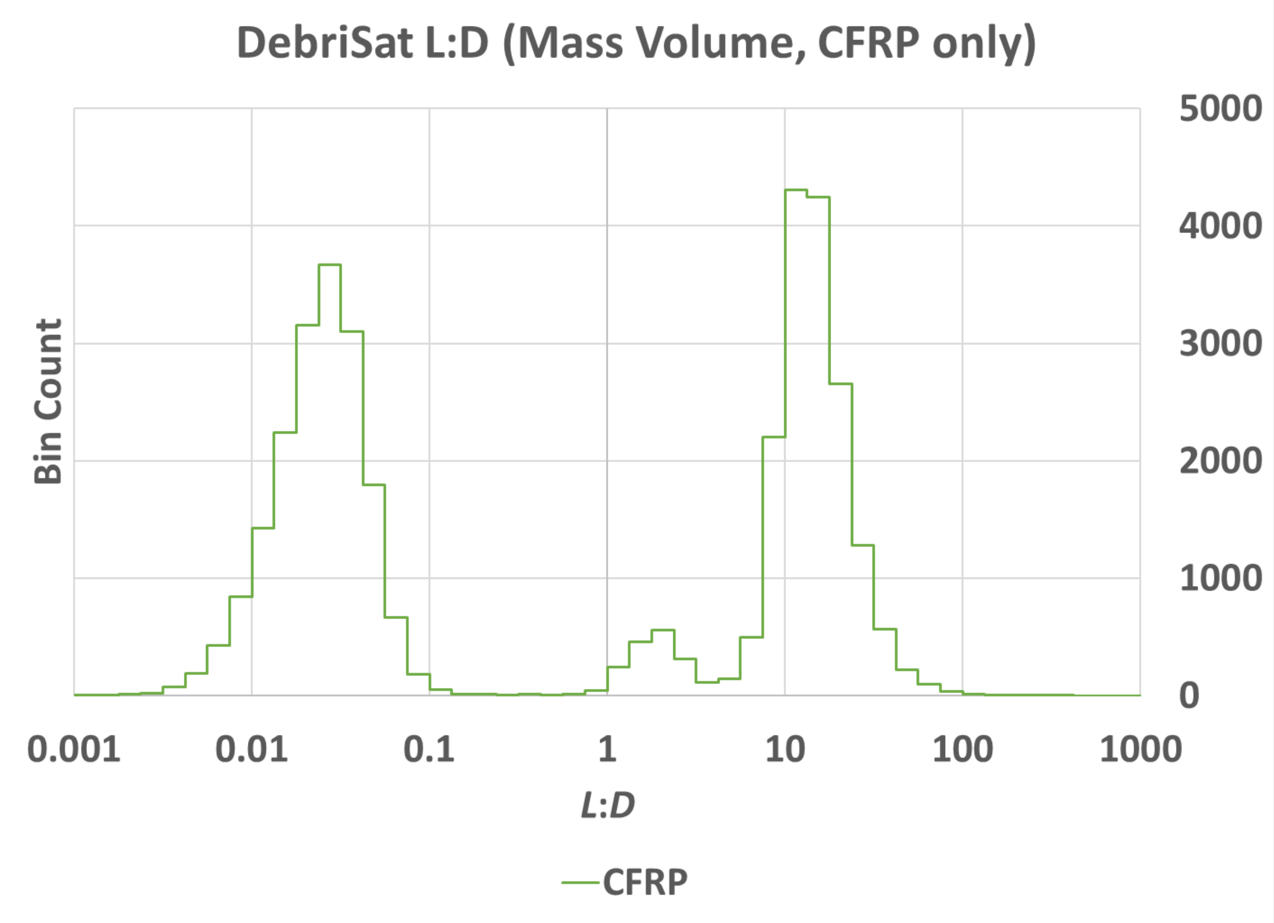




Distributions of estimated *L:D* ratio based on $V = m/\rho$ (with bent shapes omitted)
CFRP omitted from DebriSat & SOCIT counts based on groups
Dashed vertical indicates stubby rod with spherical volume

Distributions of Simplified Shape





Distributions of estimated *L*:*D* ratio based on $V = m/\rho$ (with bent shapes omitted)

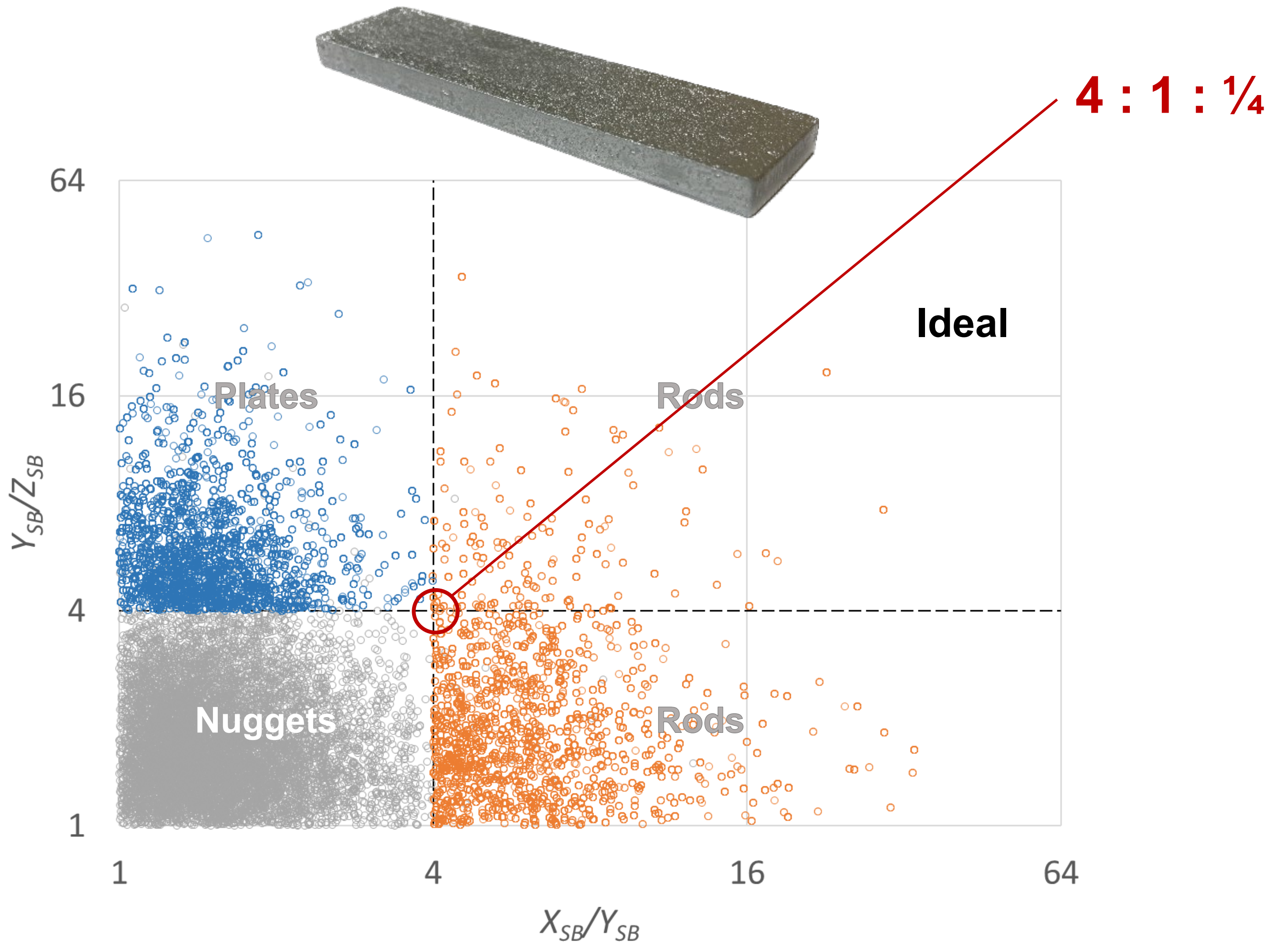
Simplified Density Categories

SOCIT Material	%	DebriSat Material	%*	Category	Density
		○ CFRP	61%	**CFRP**	1.5 g/cm^3
• Fiberglass • Phenolic/Plastic	8% 68%	○ Epoxy ○ Polyimide film ○ Para-aramid synthetic fiber ○ Multi-Layer Insulation, MLI ○ Printed Circuit Board, PCB ○ Plastic ○ Silicon	6% 0.8% 0.4% 4% 1% 6% 0.8%	**Low Density (LD)**	< 2 g/cm^3
• Al • Other	22% 1%	○ Al ○ Glass ○ Metal ○ Solar Cell	5% 1% 2% 0.4%	**Medium-Low Density (MD-lo)**	2–4 g/cm^3
		○ Titanium	1%	**Medium-High Density (MD-hi)**	4–6 g/cm^3
• Copper • Steel	0.3% 0.7%	○ Copper ○ Steel	9% 2%	**High Density (HD)**	> 6 g/cm^3
	100%		100%		

*DebriSat database contents as of 27 January 2023

RCC *L*:*D* Ratio Definitions: Why 3 Groups?

- ***L*:*D* estimates collect into three populations**
  - Inspector's designated shape predestines magnitude of *L*:*D* ratio
  - Fragment's relative dimensions add precision to *L*:*D* estimate.
- **Hypothetical fragment**
  - $X_{SB}/Y_{SB} = Y_{SB}/Z_{SB} = 4$
- **Different *L*:*D* based on assigned shape**
  - $L{:}D_{plate}$ = 1:8 (< 1)
  - $L{:}D_{rod}$ = 8:1 (> 1)
  - $L{:}D_{nugget} \approx$ 27:10 (~1)



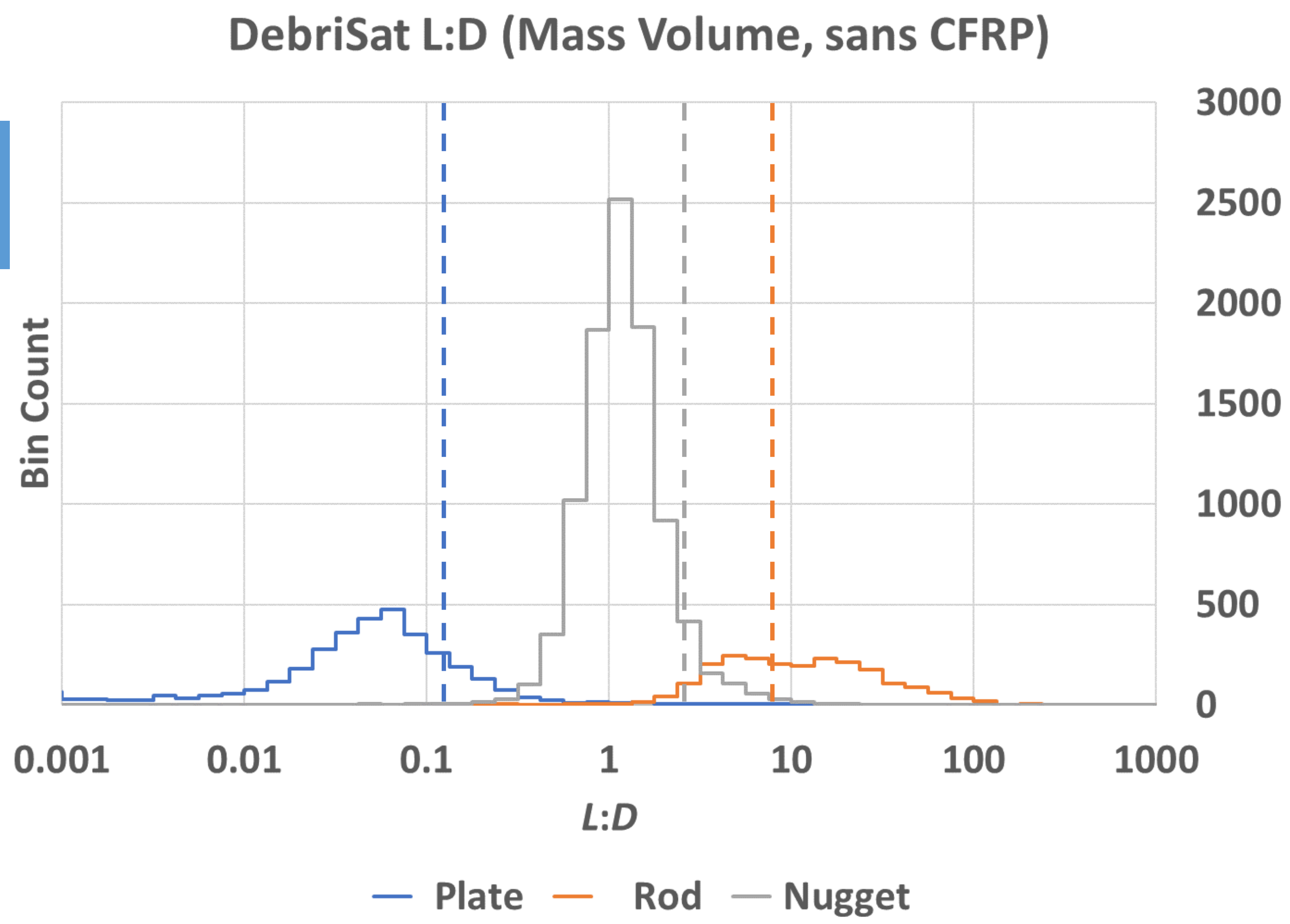
RCC *L*:*D* Ratio Definitions: Why 3 Groups?

$$L:D_{ave} = \frac{\sum_{i=1}^{nbins} n_i \cdot (L:D)_i}{\sum_{i=1}^{nbins} n_i}$$

Ave. $L{:}D_{plate}$ = 1:19

Ave. $L{:}D_{nugget}$ = 1:1

Ave. $L{:}D_{rod}$ = 15:1



L:*D* ratios of the borderline (4 : 1 : ¼) shape

$L{:}D_{plate}$ = 1:8 (< 1)

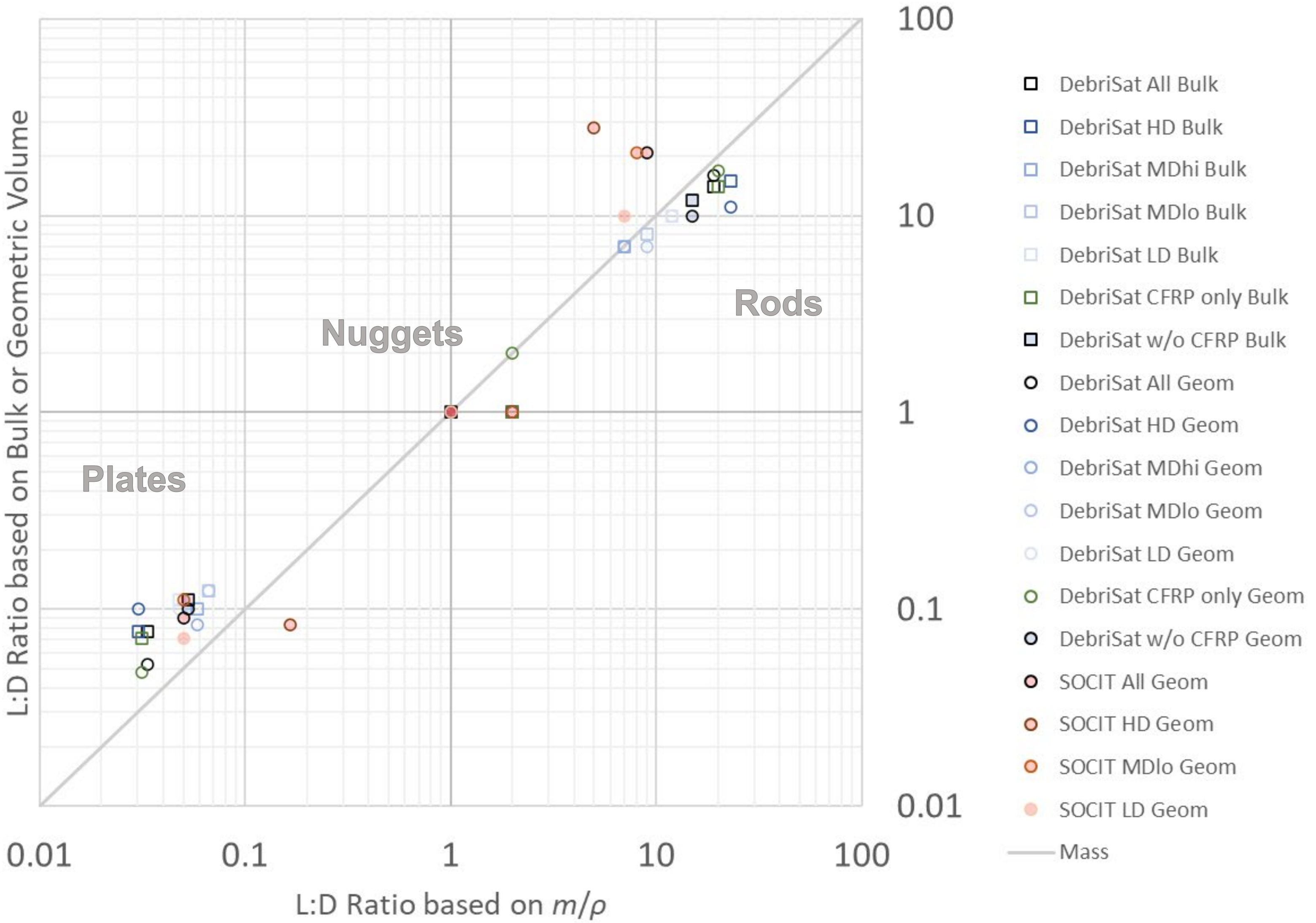
$L{:}D_{nugget} \approx$ 27:10 (~ 1)

$L{:}D_{rod}$ = 8:1 (> 1)

Average *L*:*D* from Different Estimators

		Mass-based, V = *m*/*ρ*			Bulk, V "observed"			Geometric, $V = \frac{1}{4} \pi h d_1 d_2$		
		Plates	Nuggets	Rods	Plates	Nuggets	Rods	Plates	Nuggets	Rods
SOCIT	All	1:20	1:1	9:1	--	--	--	1:11	1:1	21:1
DebriSat	All	1:30	2:1	19:1	1:13	1:1	14:1	1:19	1:1	16:1
DebriSat	w/o CFRP	1:19	1:1	15:1	1:9	1:1	12:1	1:10	1:1	10:1
DebriSat	CFRP only	1:32	2:1	20:1	1:14	1:1	14:1	1:21	2:1	17:1
SOCIT	LD	1:20	1:1	7:1	--	--	--	1:14	1:1	10:1
DebriSat	LD	1:21	1:1	12:1	1:9	1:1	10:1	1:10	1:1	10:1
SOCIT	MDlo	1:20	2:1	8:1	--	--	--	1:9	1:1	21:1
DebriSat	MDlo	1:15	1:1	9:1	1:8	1:1	8:1	1:8	1:1	7:1
DebriSat	MDhi	1:17	1:1	7:1	1:10	1:1	7:1	1:12	1:1	7:1
SOCIT	HD	1:6	1:1	11:1	--	--	--	1:12	1:1	28:1
DebriSat	HD	1:33	2:1	23:1	1:13	1:1	15:1	1:10	1:1	11:1

Average *L*:*D* from Different Estimators



- **Notable correlation/ consistency between DebriSat *L*:*D* estimates based on V_{bulk} & V_{geom}**
- **SOCIT Geometric values**
  - Plates well matched
    - Except MD_lo
  - Rods seem outlying
    - Few rods (2%) = uncertainty
- **No SOCIT *L*:*D* estimates based on bulk volume (unavailable)**

Conclusions & Future Work

- **RCCs are an advantageous shape model**
  - Practical for hypervelocity-impact testing
  - Characterize shapes w one parameter *L*:*D*
- **RCCs use different *L*:*D* estimators for rods, plates, and nuggets**
  - Inspectors' shape designation predestines the scope of population values
  - Suggests that entire shape category might be represented by a sample mean or simple distribution
- **Volume can be leveraged to provide more than one type of *L*:*D* estimate for intercomparisons**
  - Geometric (cylindrical) volume depends only on physical dimensions
    - May be an option for SOCIT data without measured (bulk) volume
  - Mass-based volume (m/ρ) least dependent upon dimensional data
    - Likely the best option going forward for impact fragments bent during capture

SOCIT and DebriSat *L*:*D* distributions comparable when CFRP is excluded because CFRP as a material category has exceptional fragmentation behavior