# AutoORSAT Parametric Studies: a Step Toward Incorporating Uncertainty into Reentry Simulation

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**NASA Orbital Debris Program Office**

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# Introduction

- **ORSAT: Object oriented approach to reentry casualty risk**
  - Spacecraft is modeled as a collection of nested shape primitives
  - Each object is released and begins aerodynamic heating when its container fully demises
- **AutoORSAT: Python wrapper for ORSAT to extend object nesting and parametric study functionality**
  - Allows arbitrary number of nesting levels
  - Parametric study of an arbitrary number of variations in an arbitrary number of input variables
  - Output to CSV files and to a SQLite3 database file for simple cross-referencing of variables

# Questions

- **How much is demisability affected by (realistic) initial conditions?**
- **How much does the change in demisability realistically affect the total Debris Casualty Area (DCA) and Expectation of Casualty ($E_c$)?**
- **Which initial conditions affect the DCA and $E_c$ the most?**
- **How best to interpret a Monte Carlo analysis of the range of realistic entry conditions?**

## Parameter Space Study

# REPRESENTATIVE COMPONENTS

# Parameter Space

- **Each spacecraft component can have up to 65 independent parameters**
  - Geometry
  - Initial trajectory
  - Materials
  - Computation model flags
- **To study the effect of $n$ variations in all parameters of $m$ components of a spacecraft requires $m * 65^n$ separate ORSAT runs**
- **Some of these variables have a greater impact on the demise of a given component than others**

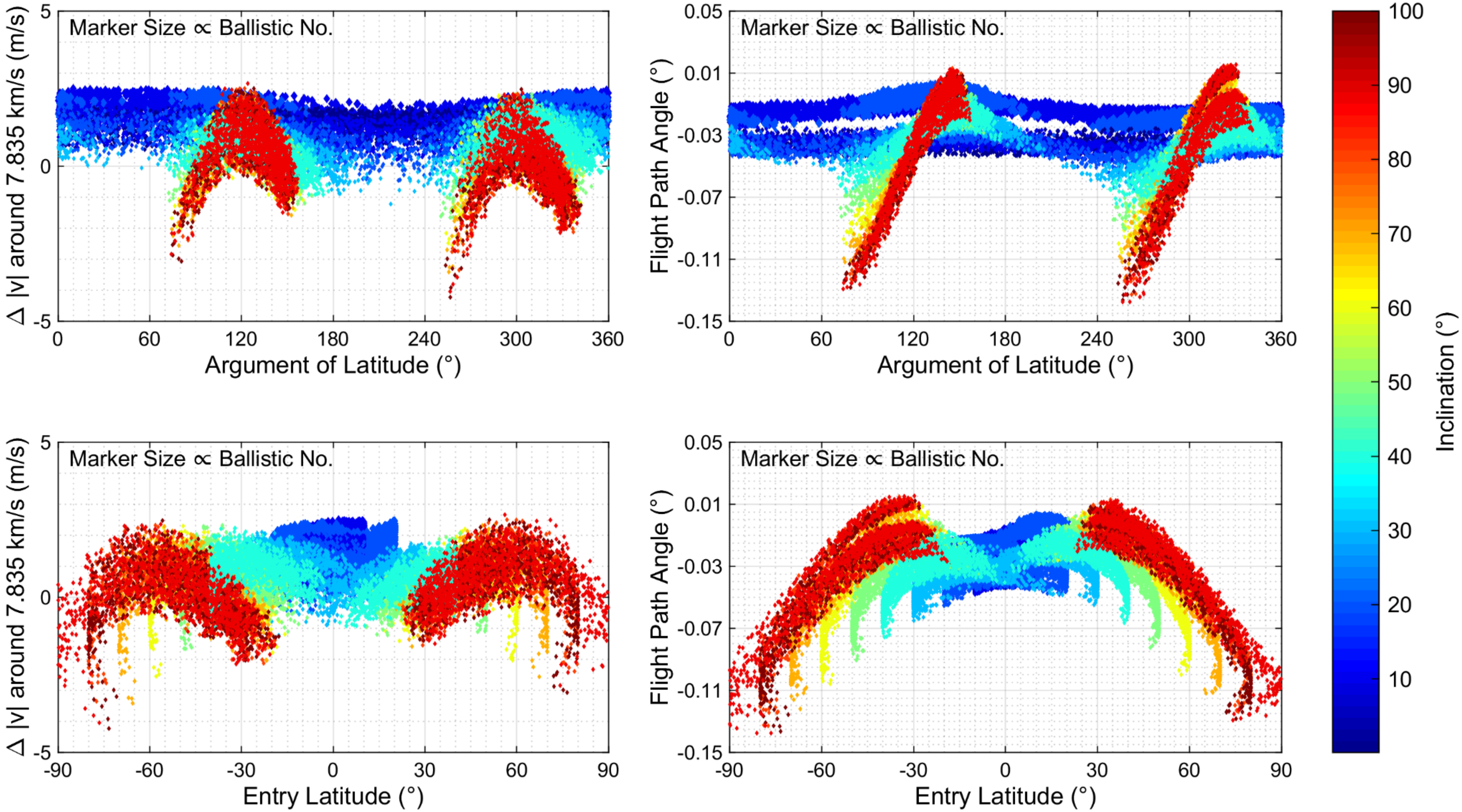
# Parameter Space Study

- **Design limited parameter space study to relative influence of parameters**
  - Restrict inputs to realistic values
  - Components represent typical components of a spacecraft
  - Measure outcome as Demise/Survive Only/Survive with Casualty
- **Parameters Studied**
  - Initial trajectory
  - Shape
  - Dimensions
  - Mass

# Realistic Initial Trajectory

- **Assumptions:**
  - Spacecraft starts at a 300 km circular orbit
  - A random reentry could occur at any RAAN, at any time of year, and will be uniformly distributed along the mean anomaly
- **Use the NASA General Mission Analysis Tool (GMAT) to simulate trajectories from 300 km altitude to the standard ORSAT 122 km entry altitude**
  - Uniform distribution of initial RAAN
  - Uniform distribution of entry day of year
  - Uniform distribution of entry argument of latitude
- **Use the final trajectory at 122 km as the ORSAT input trajectory**
- **Generate entry trajectories for**
  - 10 orbit inclinations between 10° and 100°
  - 2 spacecraft ballistic numbers: 50 kg/m$^2$ and 150 kg/m$^2$

# Initial Trajectories



# Components

- **Screws**
  - M6 and M8 size
  - 15 mm to 40 mm long
  - Aluminum, Steel, and Titanium
- **Magnetorquers**
  - Copper windings
  - Iron cores
- **Structural Panels**
  - 1 m and 0.5 m square
  - Aluminum and Steel
- **Spherical Tanks**
  - 0.2, 0.5, and 1m
  - 5 mm – 25 mm thick
  - Aluminum, Steel, Titanium, Carbon Overwrapped Titanium
- **PCBs**
  - Fiberglass
  - 3mm thick
  - 25, 50, and 100 mm square

# Unchanged Outcomes

| Always Demised | Always Survived |
|---|---|
| • 25 mm and 50 mm PCB<br>• All magnetorquer copper windings<br>• M8 aluminum screws<br>• 15 mm and 25 mm long M8 steel screws<br>• 25 mm long M8 titanium screws | • Steel structural panels<br>• 1 m titanium spherical tank<br>• 1 m carbon overwrapped titanium tank |

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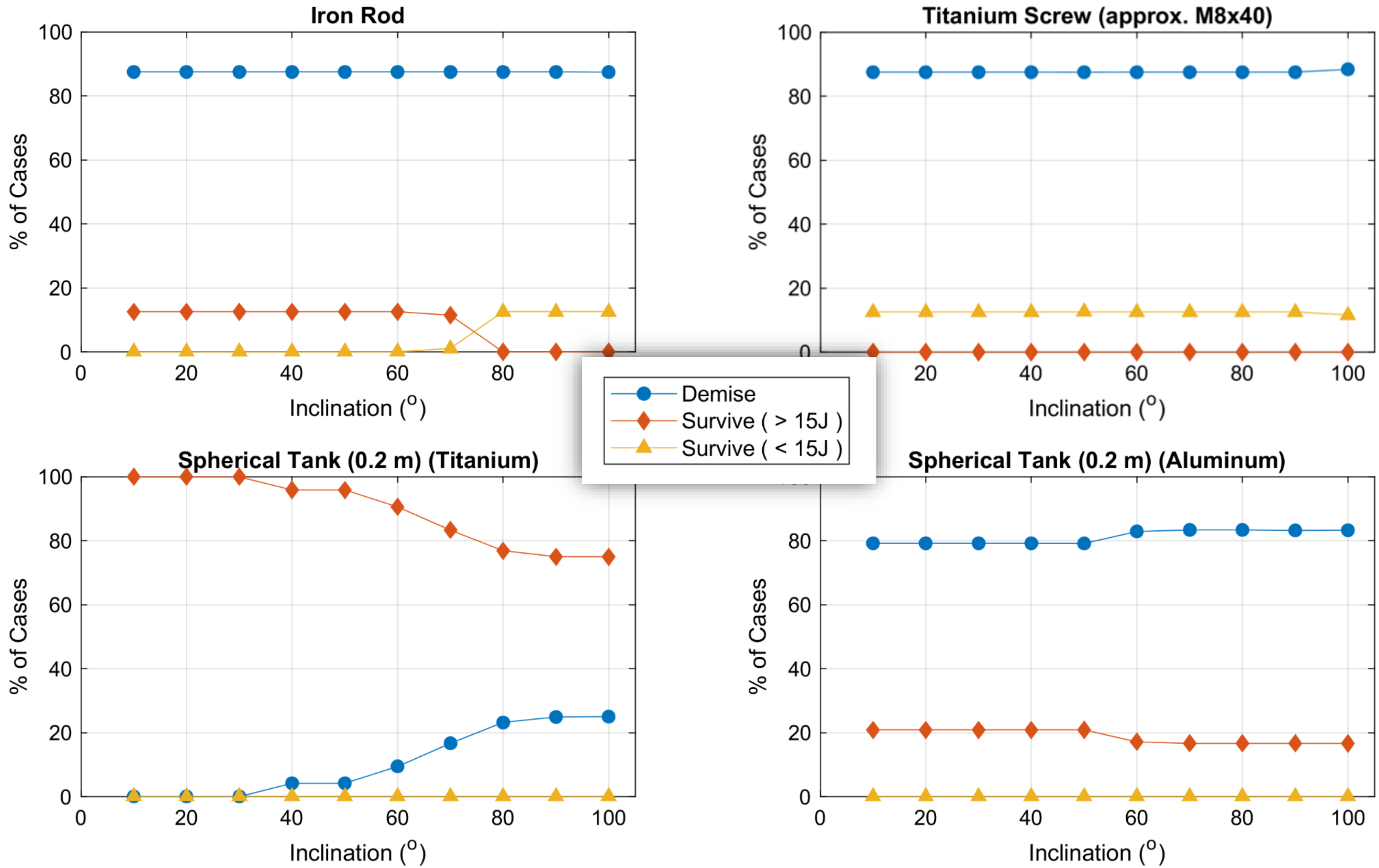
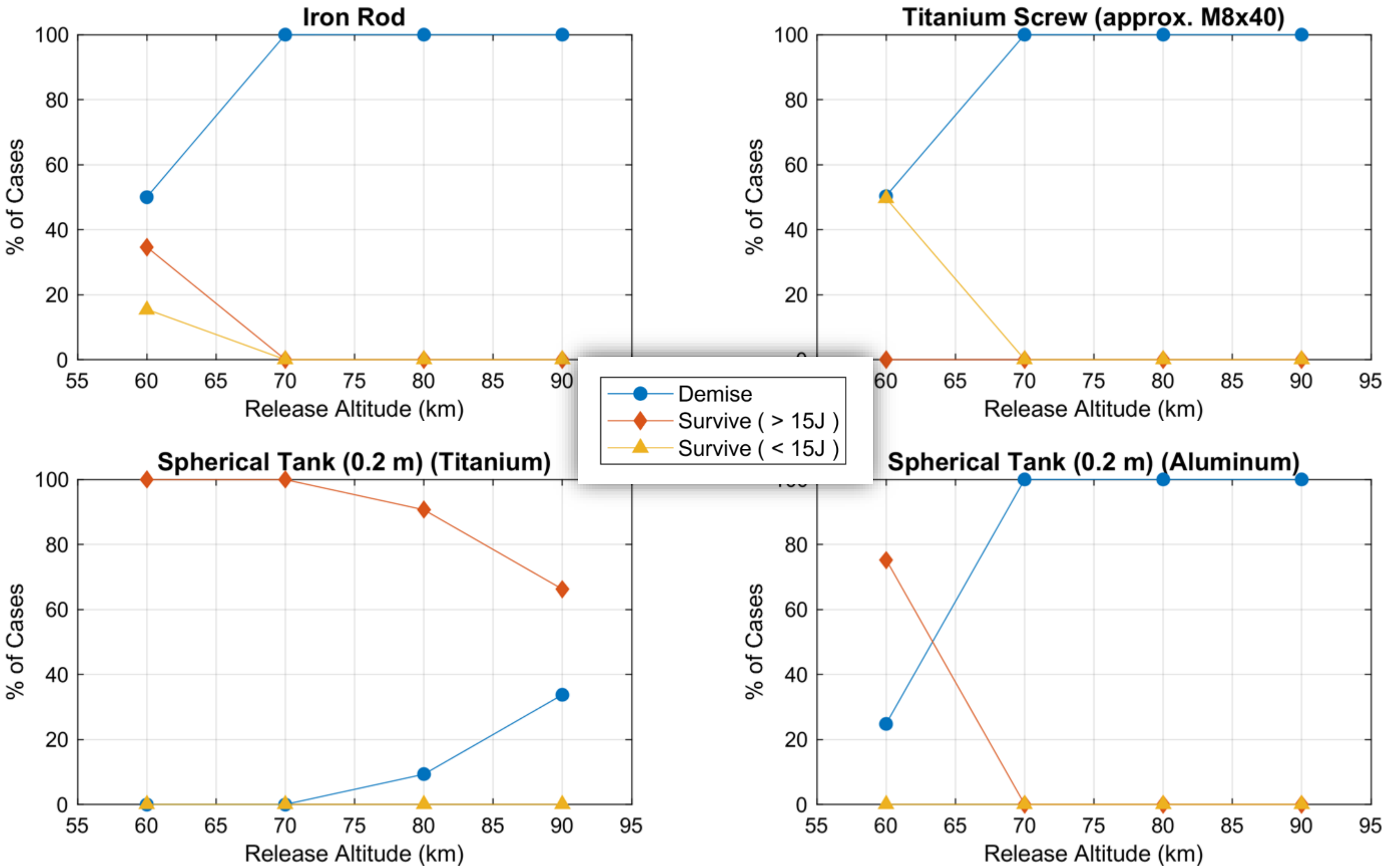
# Marginal Outcomes



# Marginal Outcomes



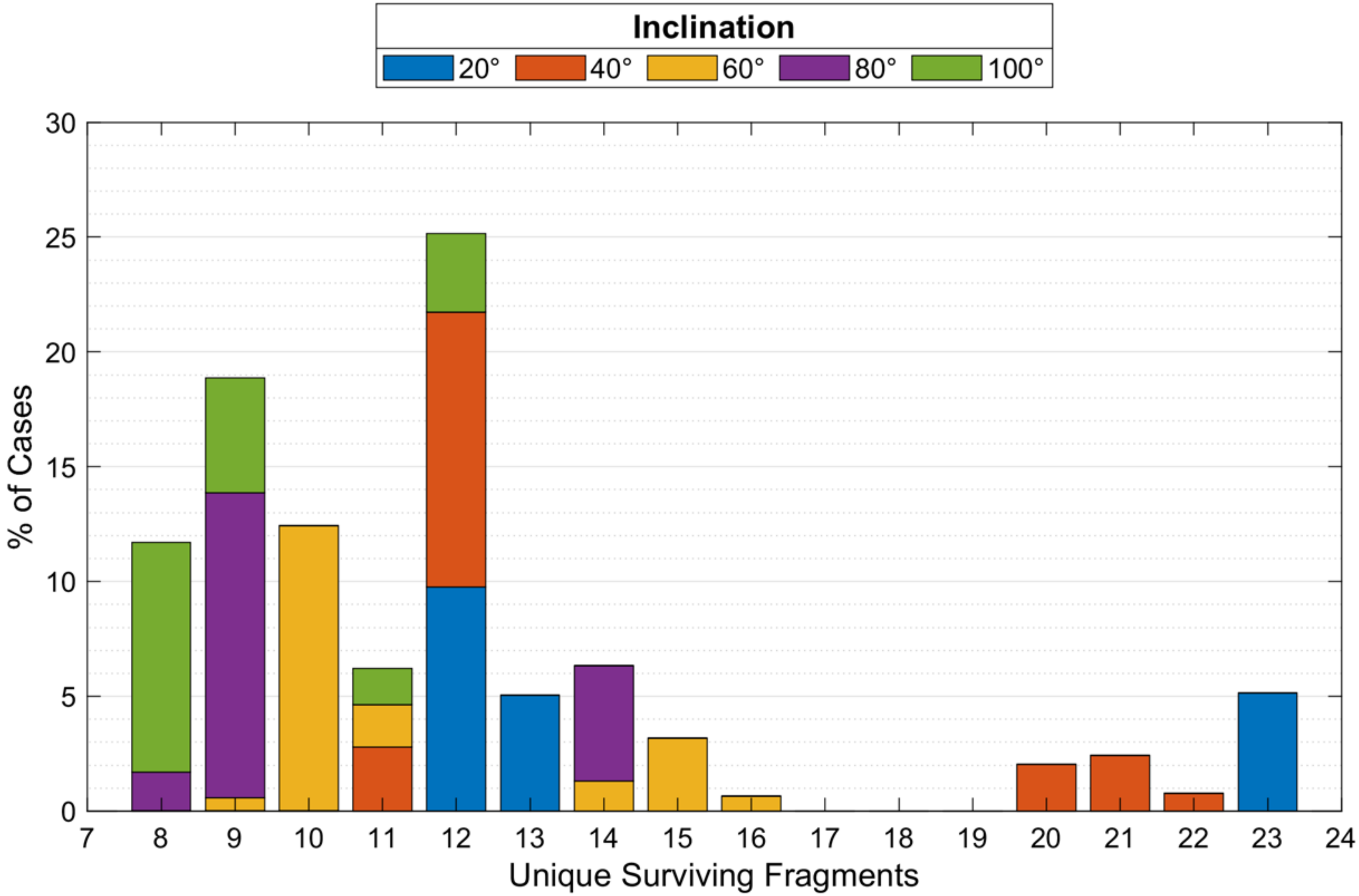
Parameter Space Study

# REPRESENTATIVE SPACECRAFT

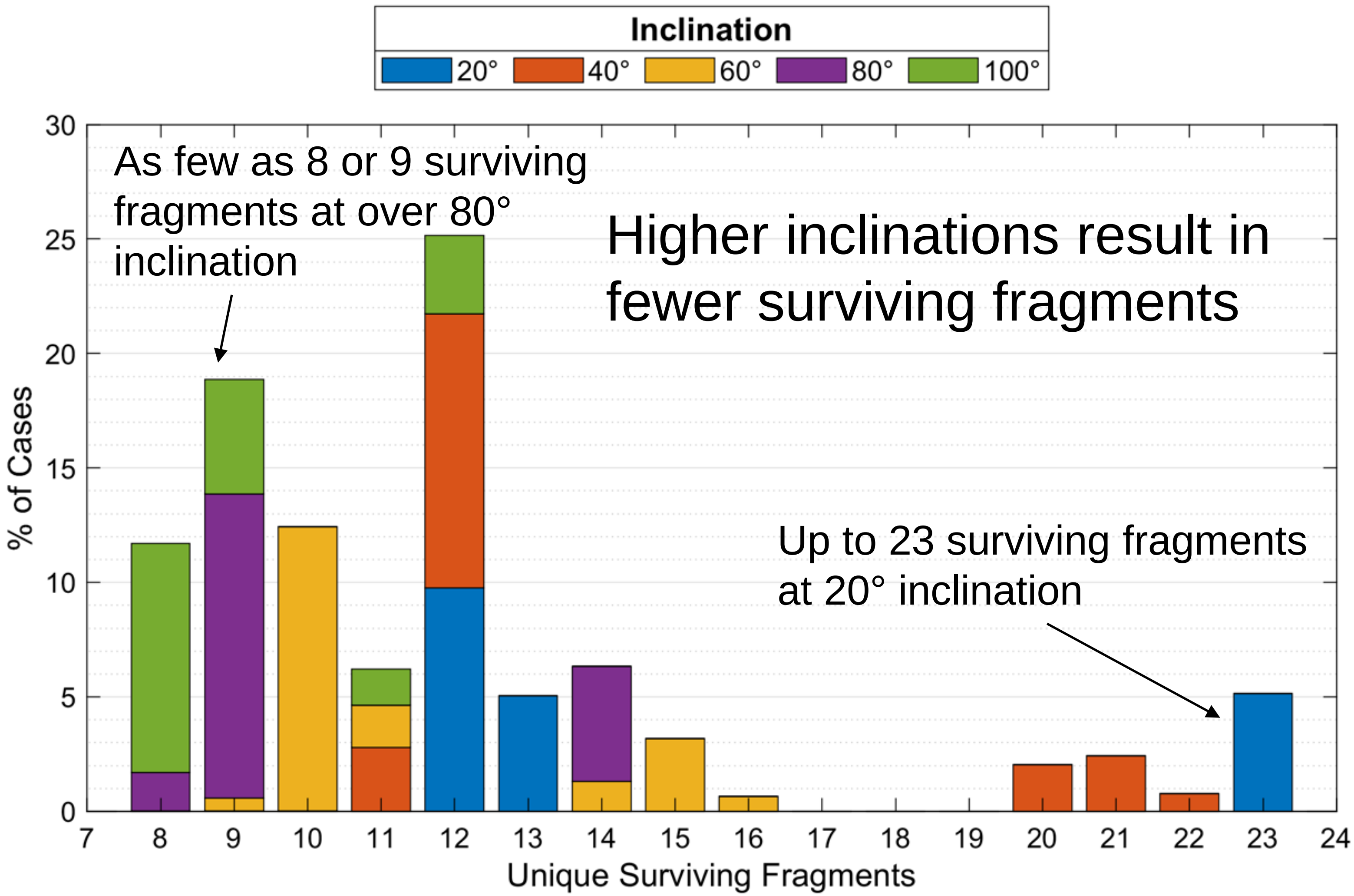
# Representative Spacecraft

- **Hypothetical 2100 kg Spacecraft**
  - Carbon fiber solar array substrate
  - Aluminum structural panels
  - Magnetorquer, reaction wheels
  - Propulsion system & tank
  - Communication antennas
  - Telescope
  - 18650 Li-ion battery pack
  - Various sizes of printed circuit board
- **Variation in demise altitude of parent spacecraft between 74 km and 82 km**

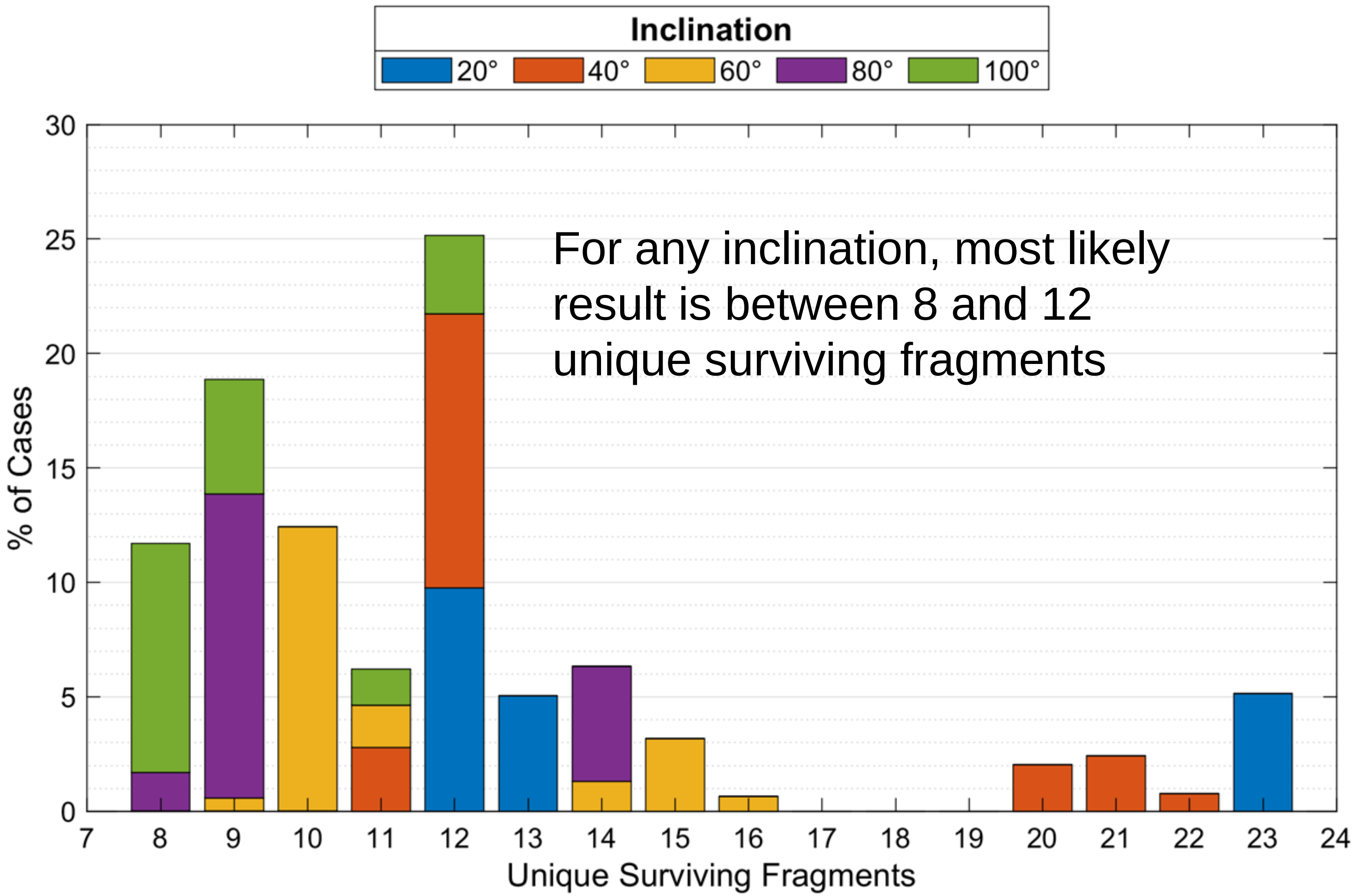
# Effect on DCA of Representative Spacecraft



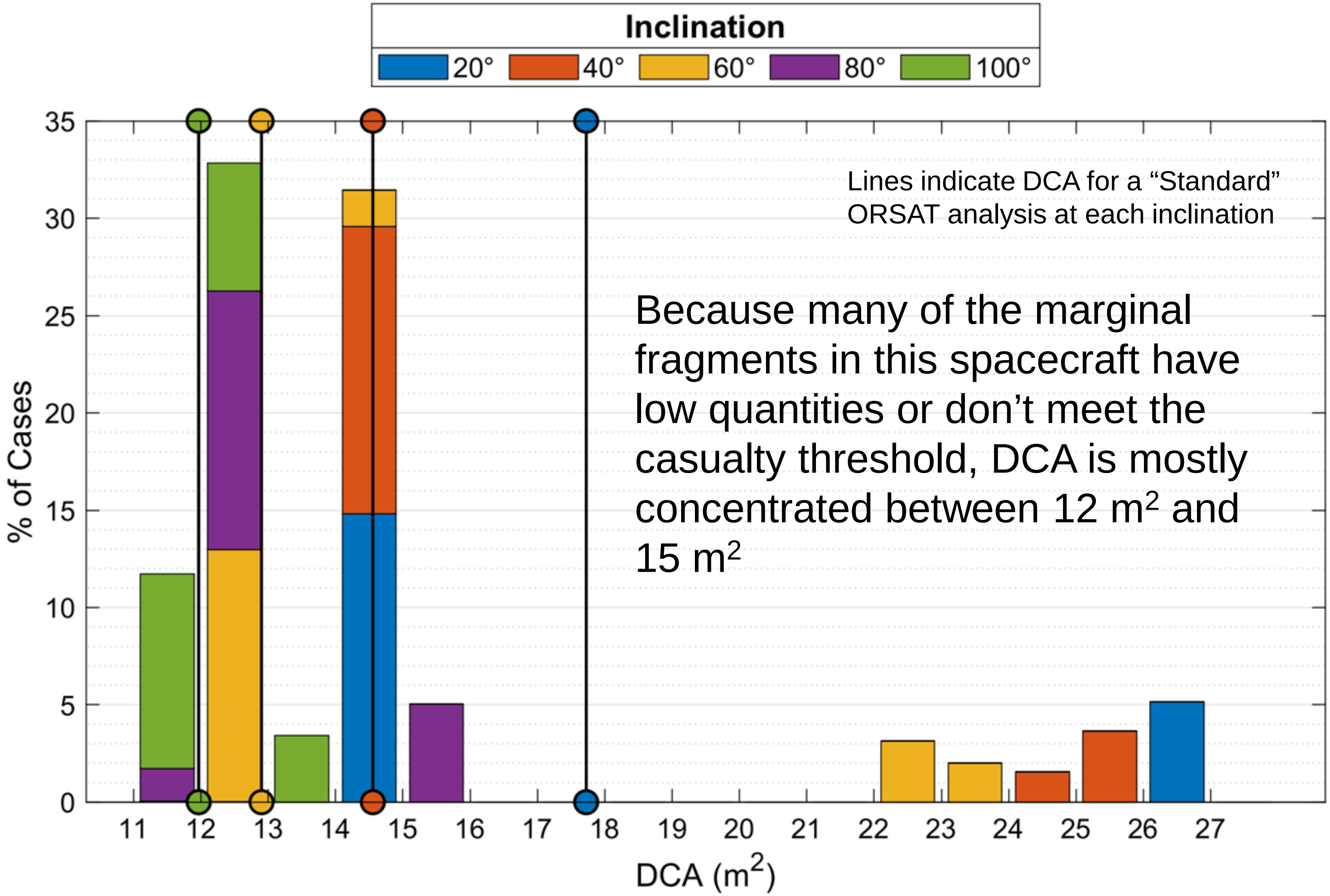
# Effect on DCA of Representative Spacecraft



# Effect on DCA of Representative Spacecraft

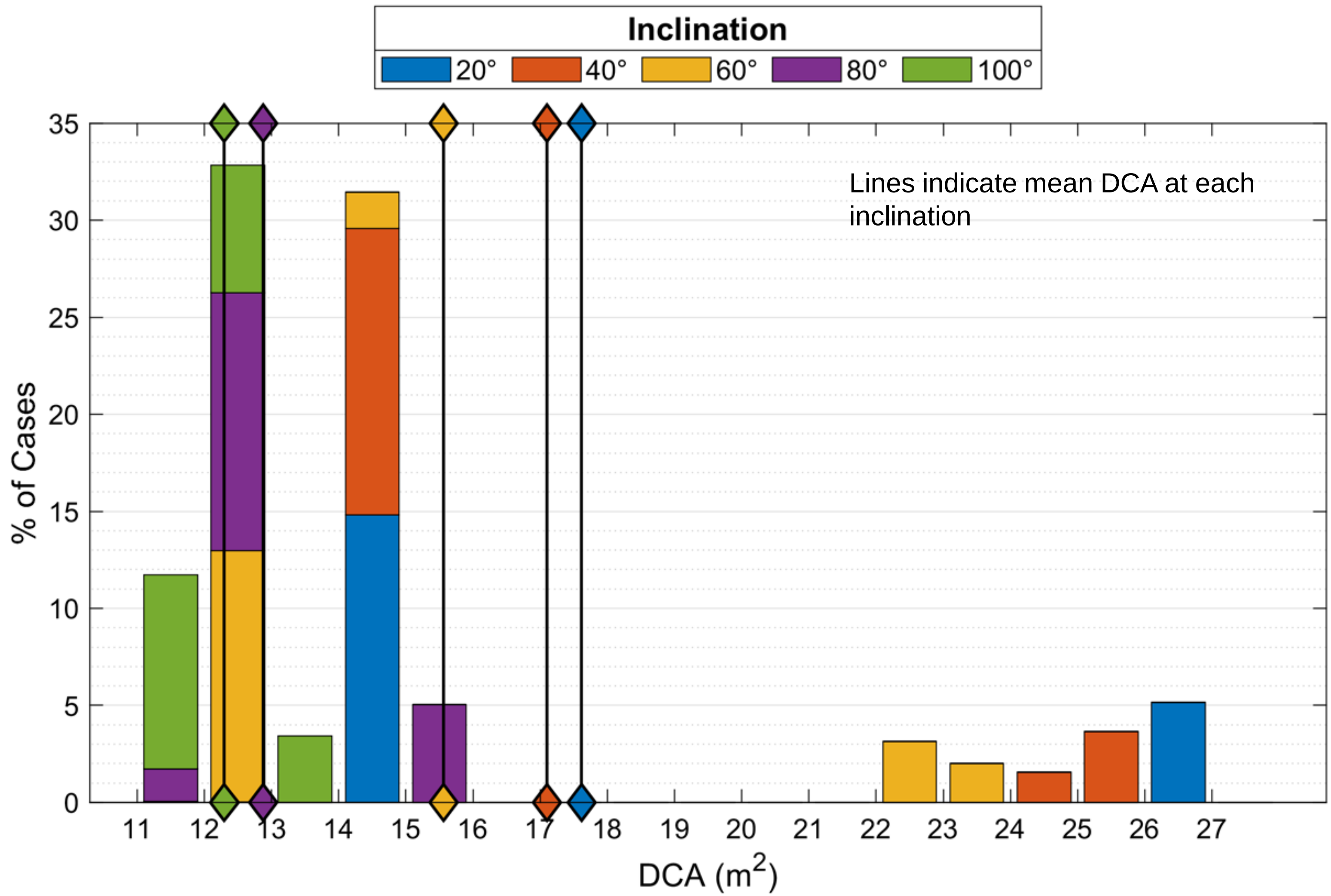


# Effect on DCA of Representative Spacecraft




Because many of the marginal fragments in this spacecraft have low quantities or don't meet the casualty threshold, DCA is mostly concentrated between 12 $m^2$ and 15 $m^2$

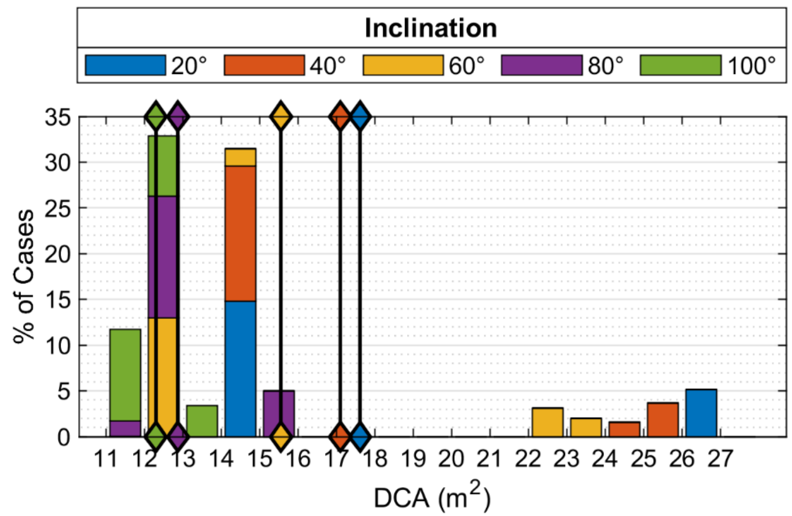
# Effect on DCA of Representative Spacecraft



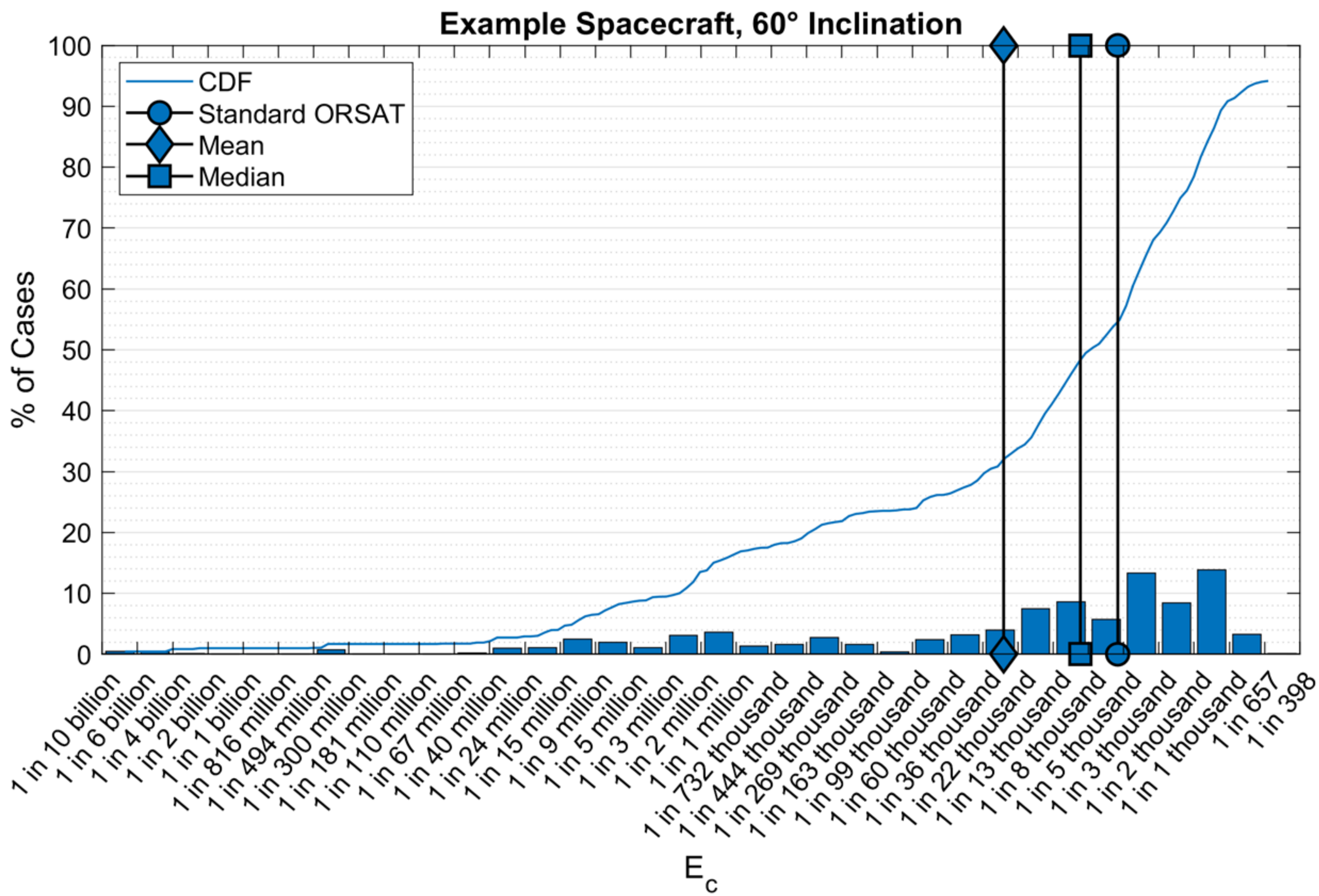
# Effect on DCA of Representative Spacecraft

- **“Standard” ORSAT analysis:**
  - Altitude: 122 km
  - FPA: -0.1°
  - Breakup: 78 km
- **Standard ORSAT less conservative than mean**
- **Usually aligns with highest-count bin**

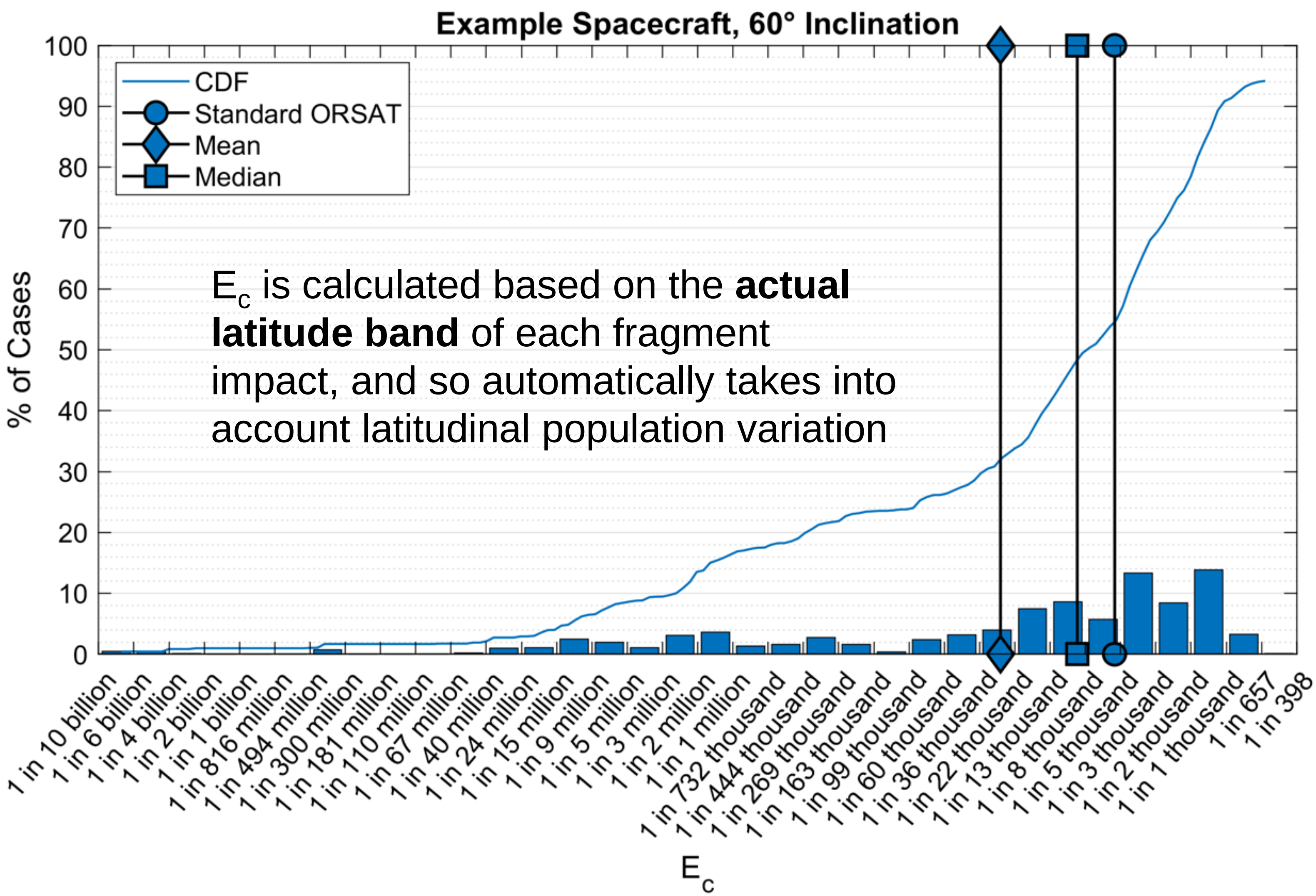
| Inclination | Standard ORSAT DCA | Mean DCA |
|---|---|---|
| 20° | 17.7 $m^2$ | 17.6 $m^2$ |
| 40° | 14.6 $m^2$ | 17.2 $m^2$ |
| 60° | 12.9 $m^2$ | 15.6 $m^2$ |
| 80° | 12.0 $m^2$ | 12.9 $m^2$ |
| 100° | 12.0 $m^2$ | 12.3 $m^2$ |



# Effect on Expectation of Casualty ($E_c$)

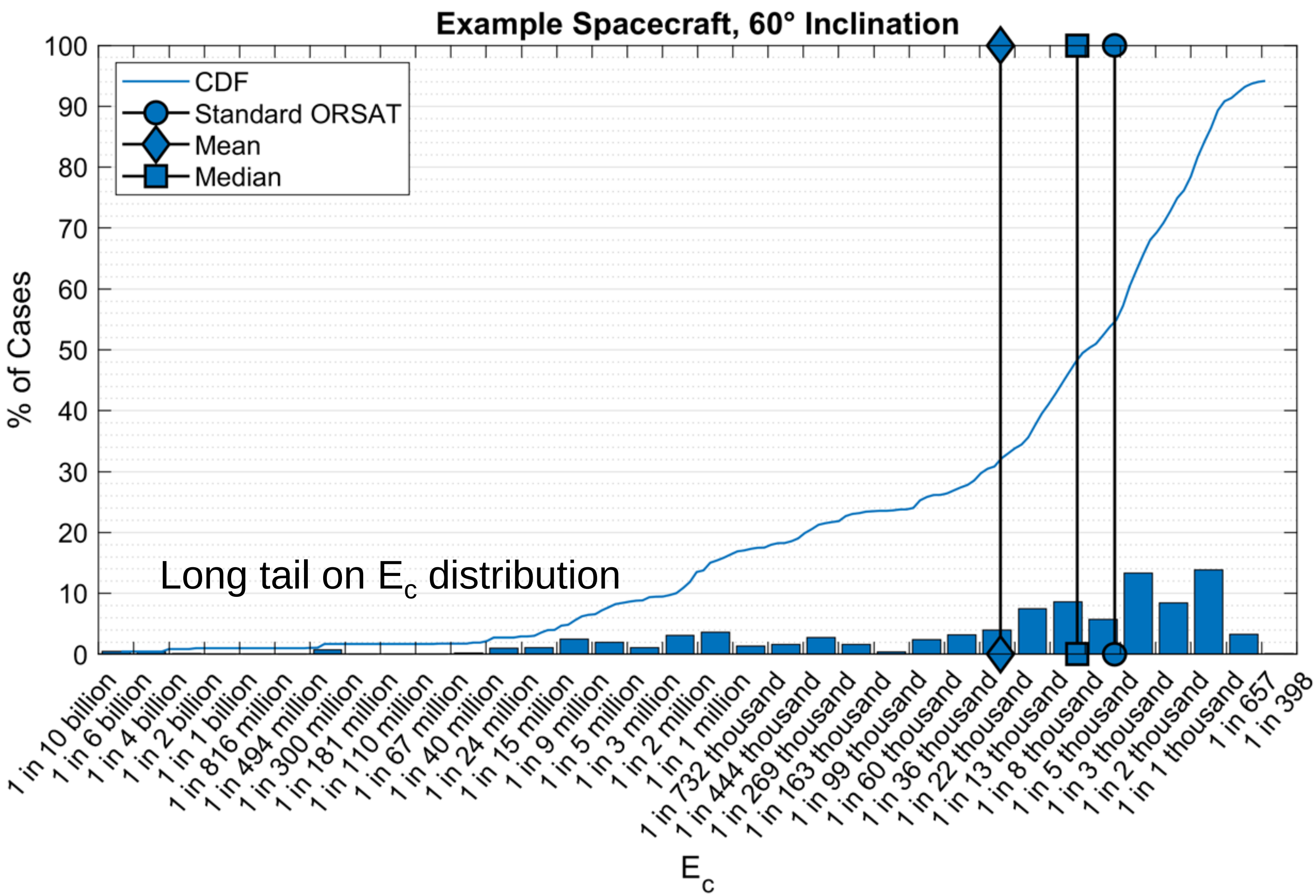


# Effect on Expectation of Casualty ($E_c$)

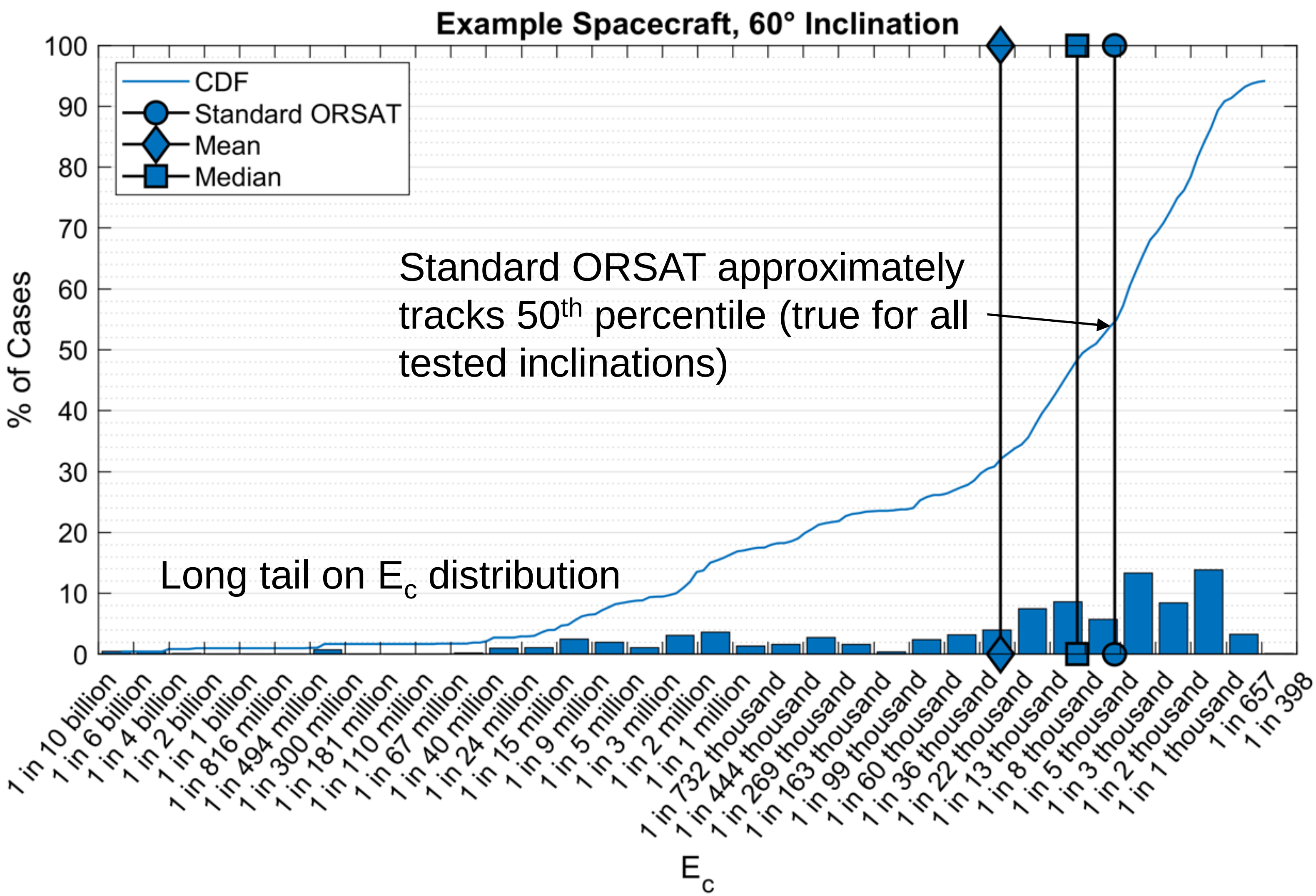



$E_c$ is calculated based on the **actual latitude band** of each fragment impact, and so automatically takes into account latitudinal population variation

# Effect on Expectation of Casualty ($E_c$)



# Effect on Expectation of Casualty ($E_c$)



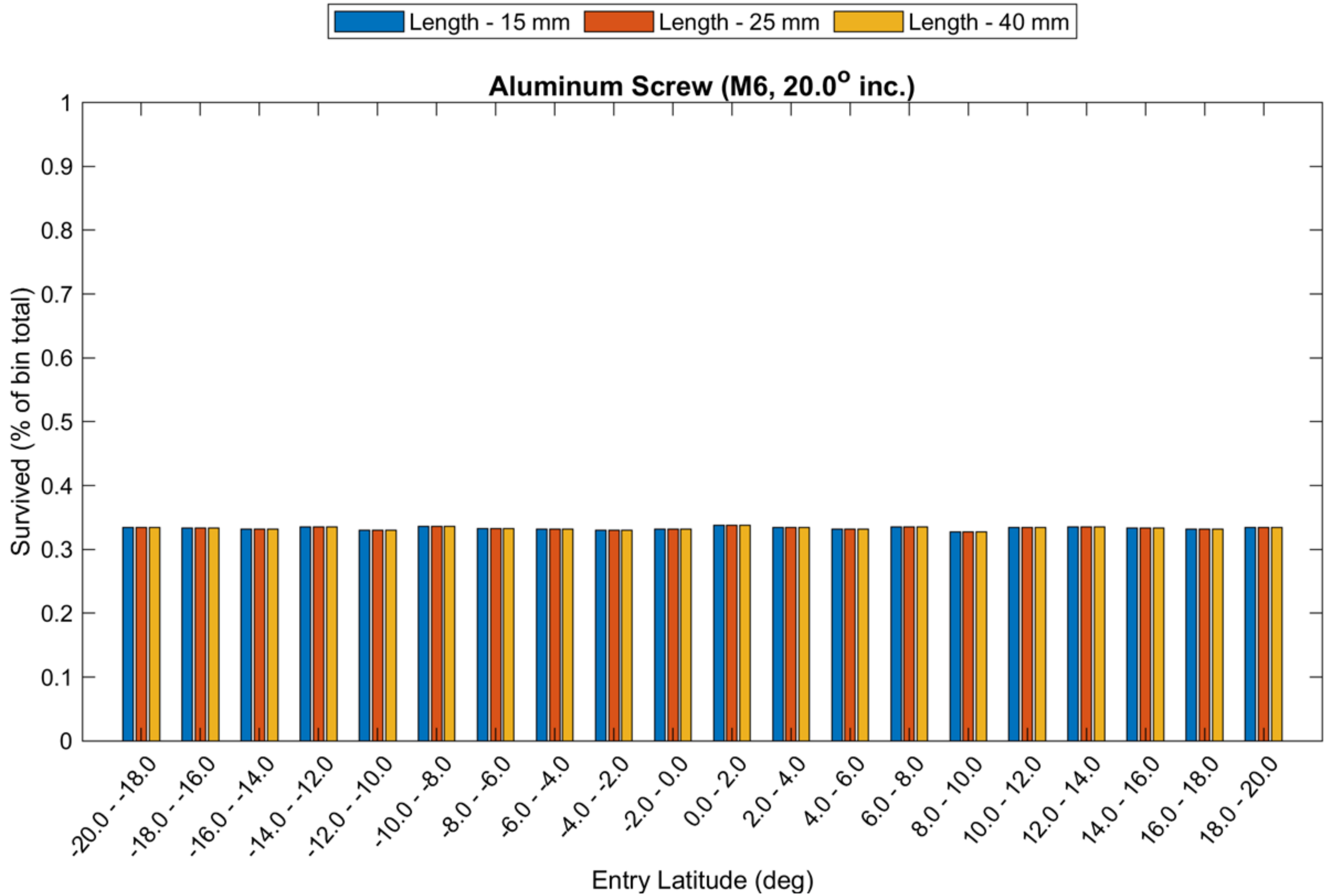
# Conclusions

- **Demisability of many types of components not affected at all by even large changes in initial conditions**
- **Marginally demisable components can have a very large effect on the DCA of a spacecraft**
- **A relatively small parametric study can determine whether any of the components are marginal**
- **The vast majority of variability in DCA comes from**
  - Release altitude of the component (unfortunately also the least well-known input)
  - Inclination of the orbit
- **The vast majority of variability in $E_c$ comes from variability in impact latitude**

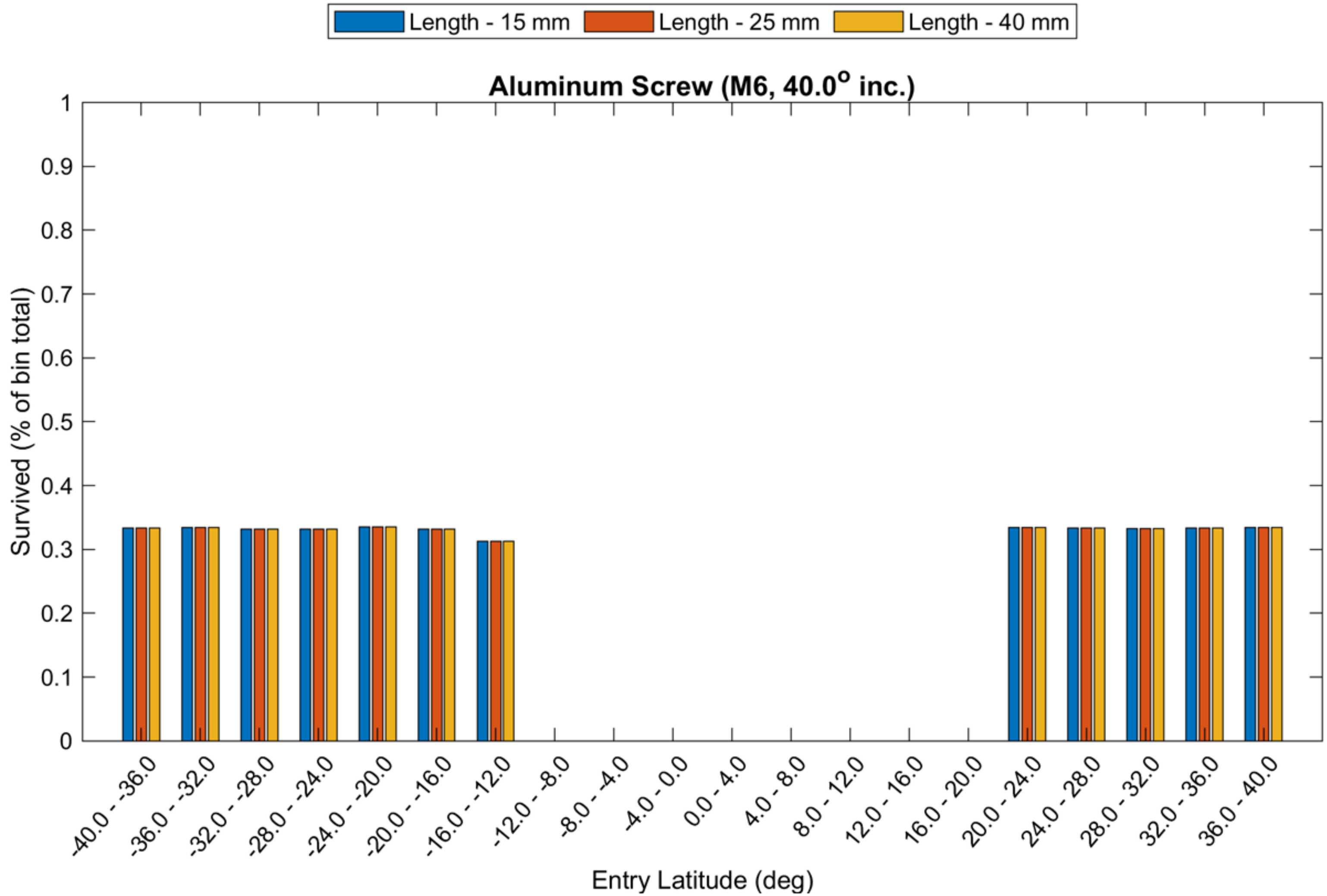
# Future Work

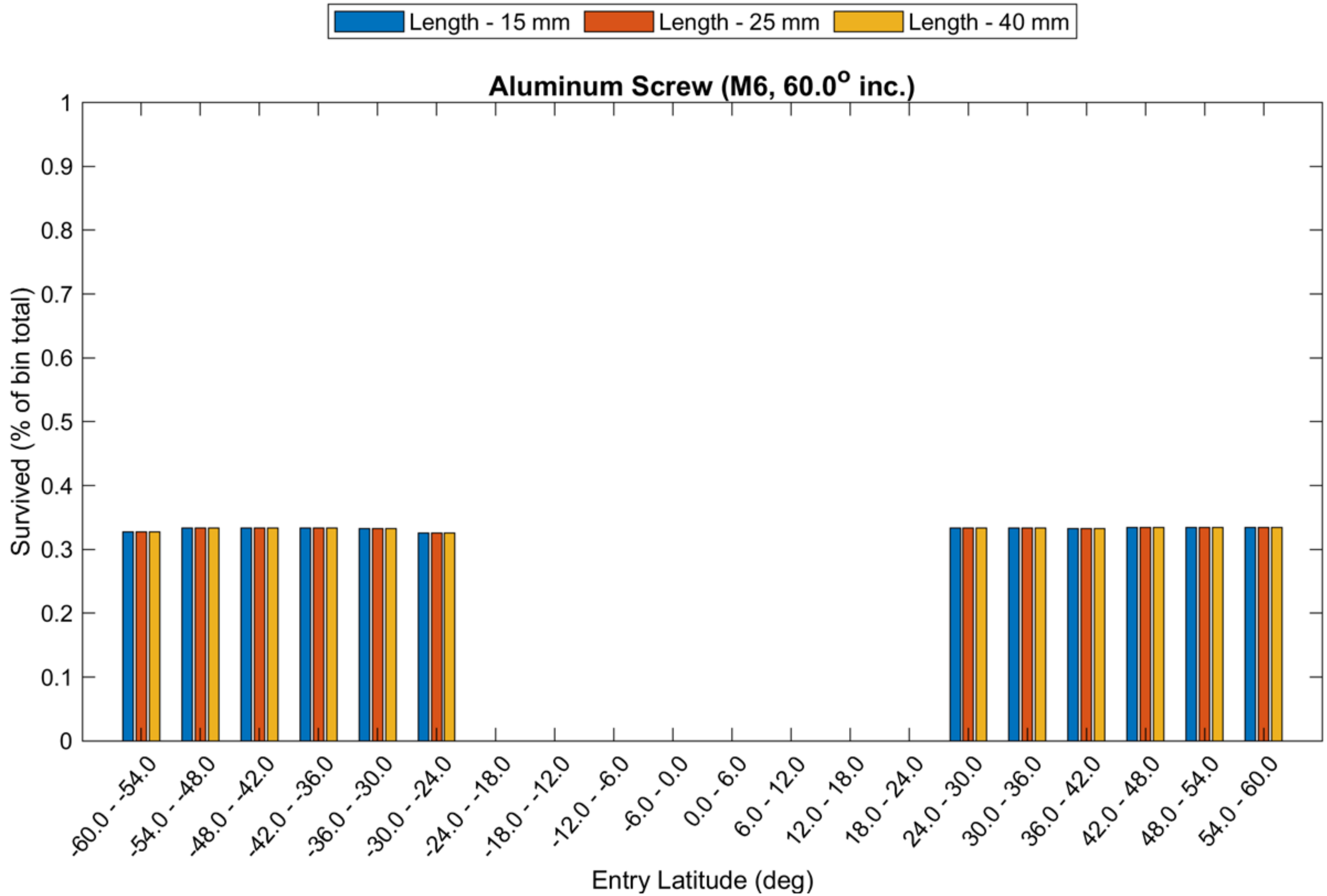
- **Develop statistical model for**
  - Distribution of release altitudes
  - Distribution of initial entry trajectory
- **Implement true Monte-Carlo analysis in AutoORSAT**
  - Likely require fewer ORSAT runs to achieve representative results
  - Mean value of final DCA will be representative of likeliest DCA

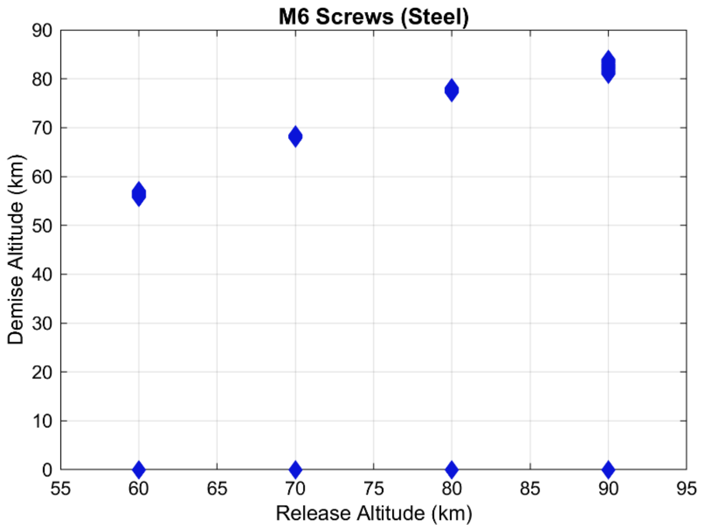
# BACKUP SLIDES

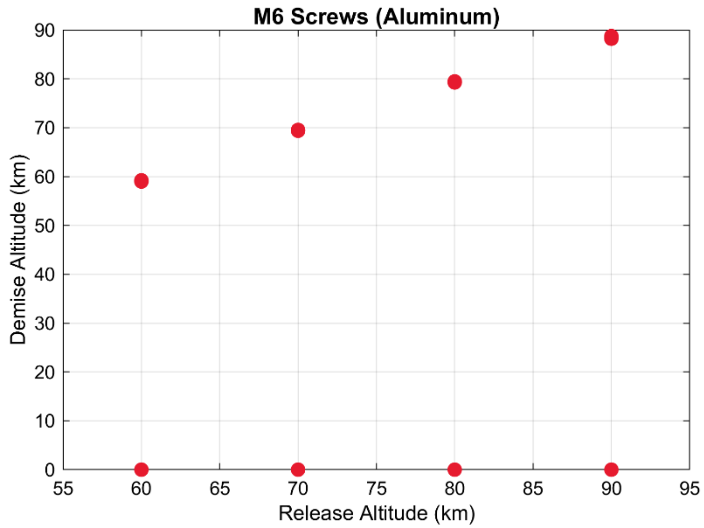


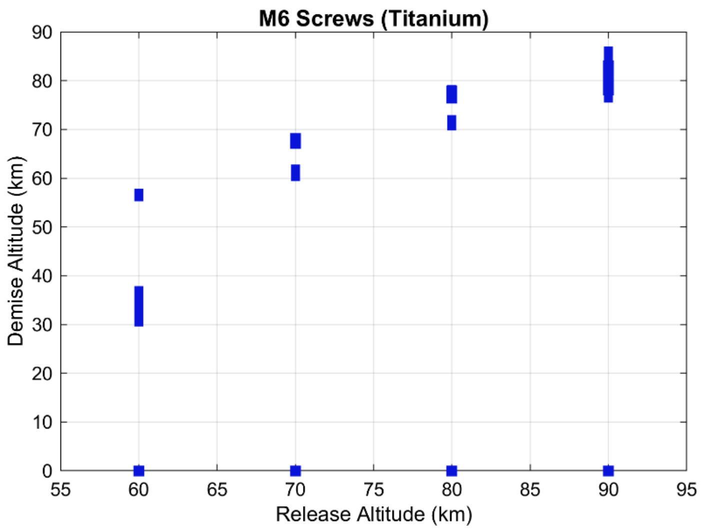
Length - 15 mm
Length - 25 mm
Length - 40 mm
Aluminum Screw (M6, 20.0° inc.)
Survived (% of bin total)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-20.0 - -18.0
-18.0 - -16.0
-16.0 - -14.0
-14.0 - -12.0
-12.0 - -10.0
-10.0 - -8.0
-8.0 - -6.0
-6.0 - -4.0
-4.0 - -2.0
-2.0 - 0.0
0.0 - 2.0
2.0 - 4.0
4.0 - 6.0
6.0 - 8.0
8.0 - 10.0
10.0 - 12.0
12.0 - 14.0
14.0 - 16.0
16.0 - 18.0
18.0 - 20.0
Entry Latitude (deg)

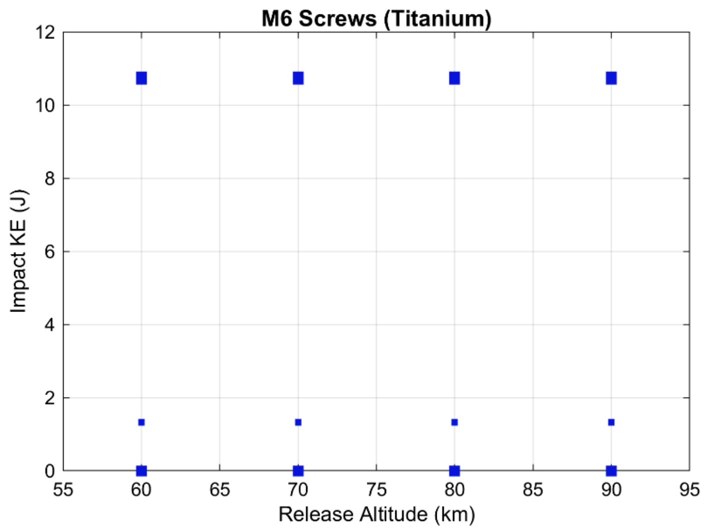

Length - 15 mm
Length - 25 mm
Length - 40 mm
Aluminum Screw (M6, 40.0° inc.)
Survived (% of bin total)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-40.0 - -36.0
-36.0 - -32.0
-32.0 - -28.0
-28.0 - -24.0
-24.0 - -20.0
-20.0 - -16.0
-16.0 - -12.0
-12.0 - -8.0
-8.0 - -4.0
-4.0 - 0.0
0.0 - 4.0
4.0 - 8.0
8.0 - 12.0
12.0 - 16.0
16.0 - 20.0
20.0 - 24.0
24.0 - 28.0
28.0 - 32.0
32.0 - 36.0
36.0 - 40.0
Entry Latitude (deg)

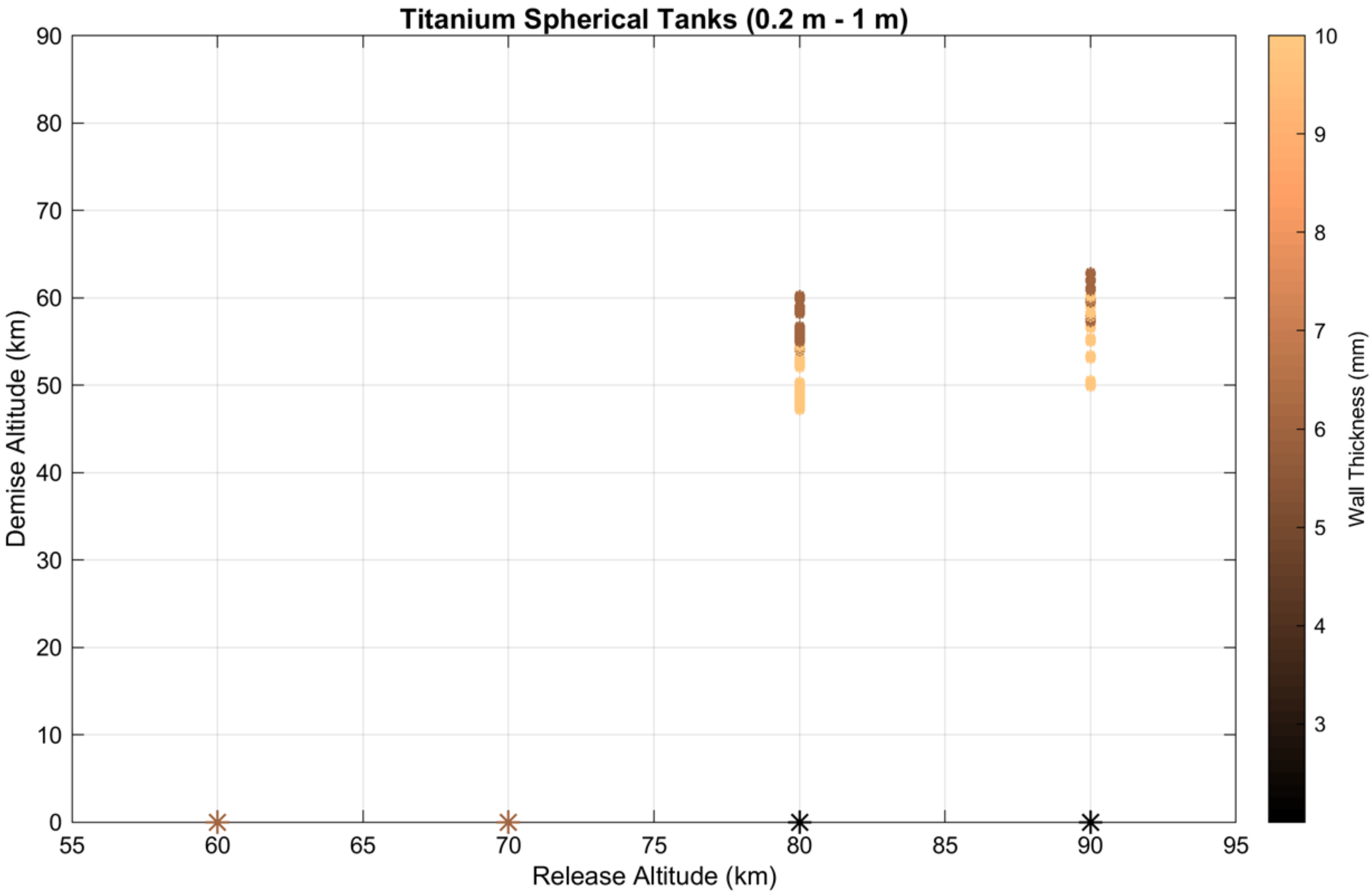

Length - 15 mm
Length - 25 mm
Length - 40 mm
Aluminum Screw (M6, 60.0° inc.)
Survived (% of bin total)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-60.0 - -54.0
-54.0 - -48.0
-48.0 - -42.0
-42.0 - -36.0
-36.0 - -30.0
-30.0 - -24.0
-24.0 - -18.0
-18.0 - -12.0
-12.0 - -6.0
-6.0 - 0.0
0.0 - 6.0
6.0 - 12.0
12.0 - 18.0
18.0 - 24.0
24.0 - 30.0
30.0 - 36.0
36.0 - 42.0
42.0 - 48.0
48.0 - 54.0
54.0 - 60.0
Entry Latitude (deg)

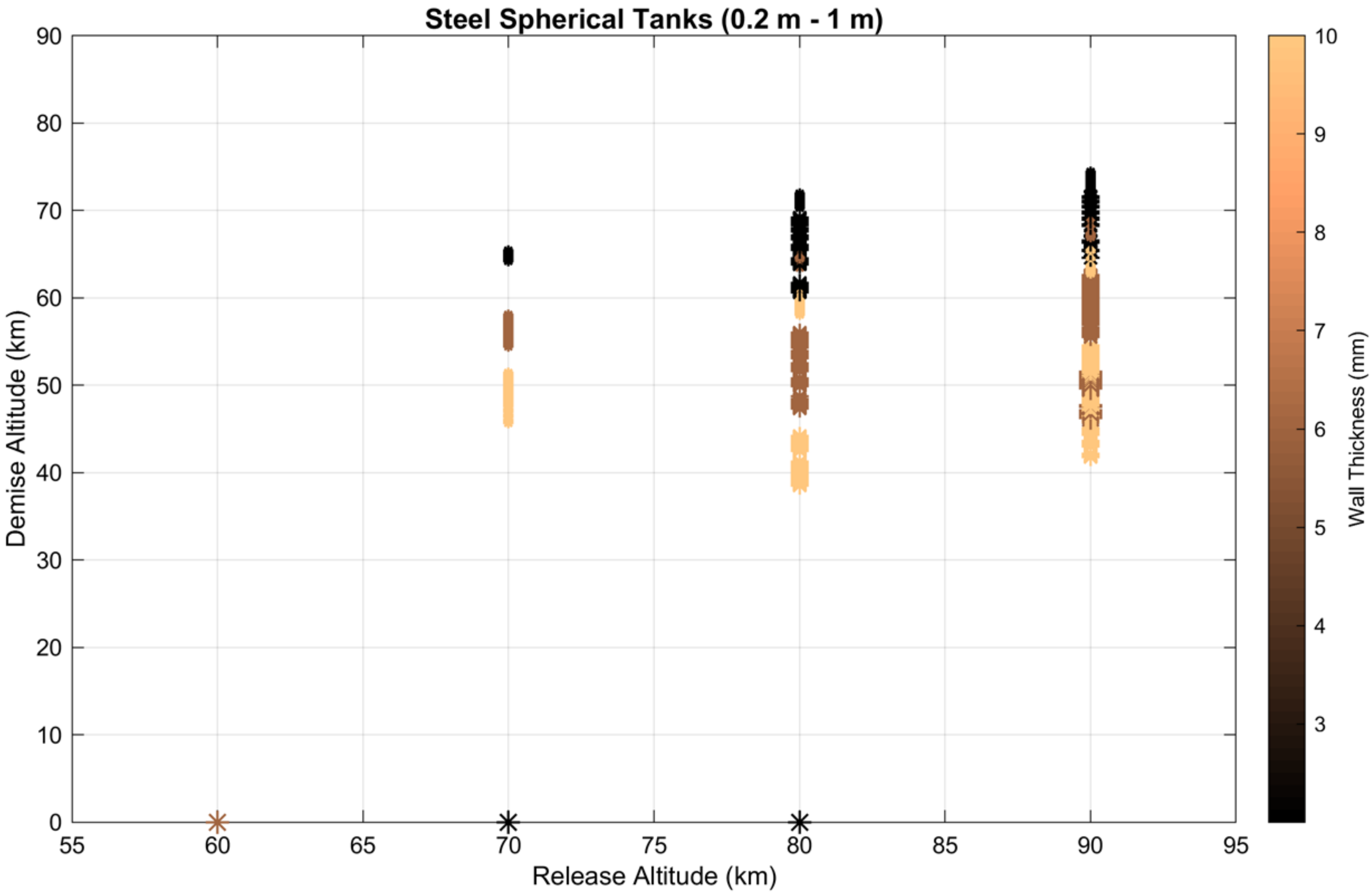

M6 Screws (Steel)
Demise Altitude (km)
Release Altitude (km)
0 10 20 30 40 50 60 70 80 90
55 60 65 70 75 80 85 90 95

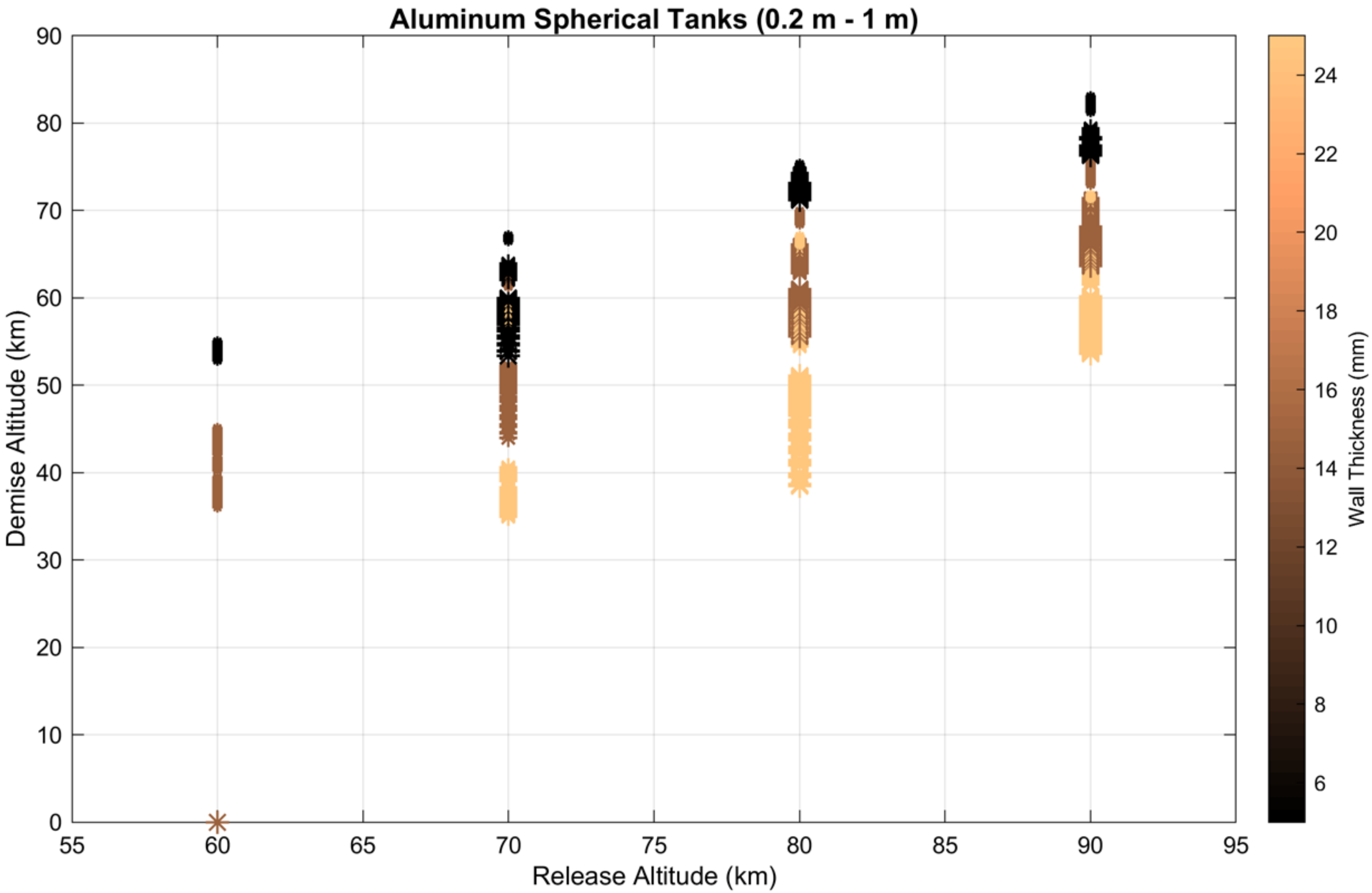

M6 Screws (Aluminum)
Demise Altitude (km)
Release Altitude (km)
0 10 20 30 40 50 60 70 80 90
55 60 65 70 75 80 85 90 95

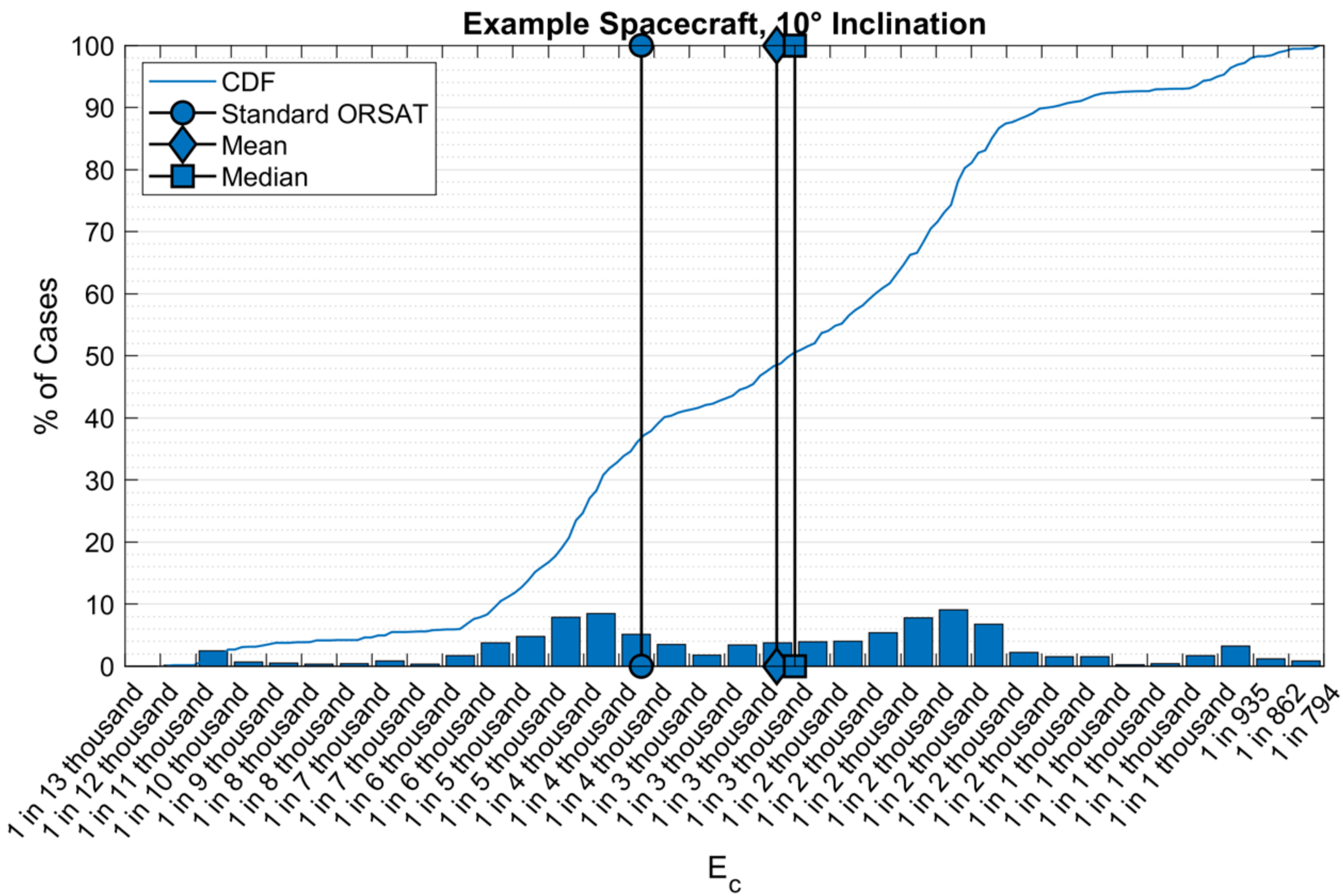

M6 Screws (Titanium)
Demise Altitude (km)
Release Altitude (km)
0 10 20 30 40 50 60 70 80 90
55 60 65 70 75 80 85 90 95


M6 Screws (Titanium)
Impact KE (J)
Release Altitude (km)
0 2 4 6 8 10 12
55 60 65 70 75 80 85 90 95

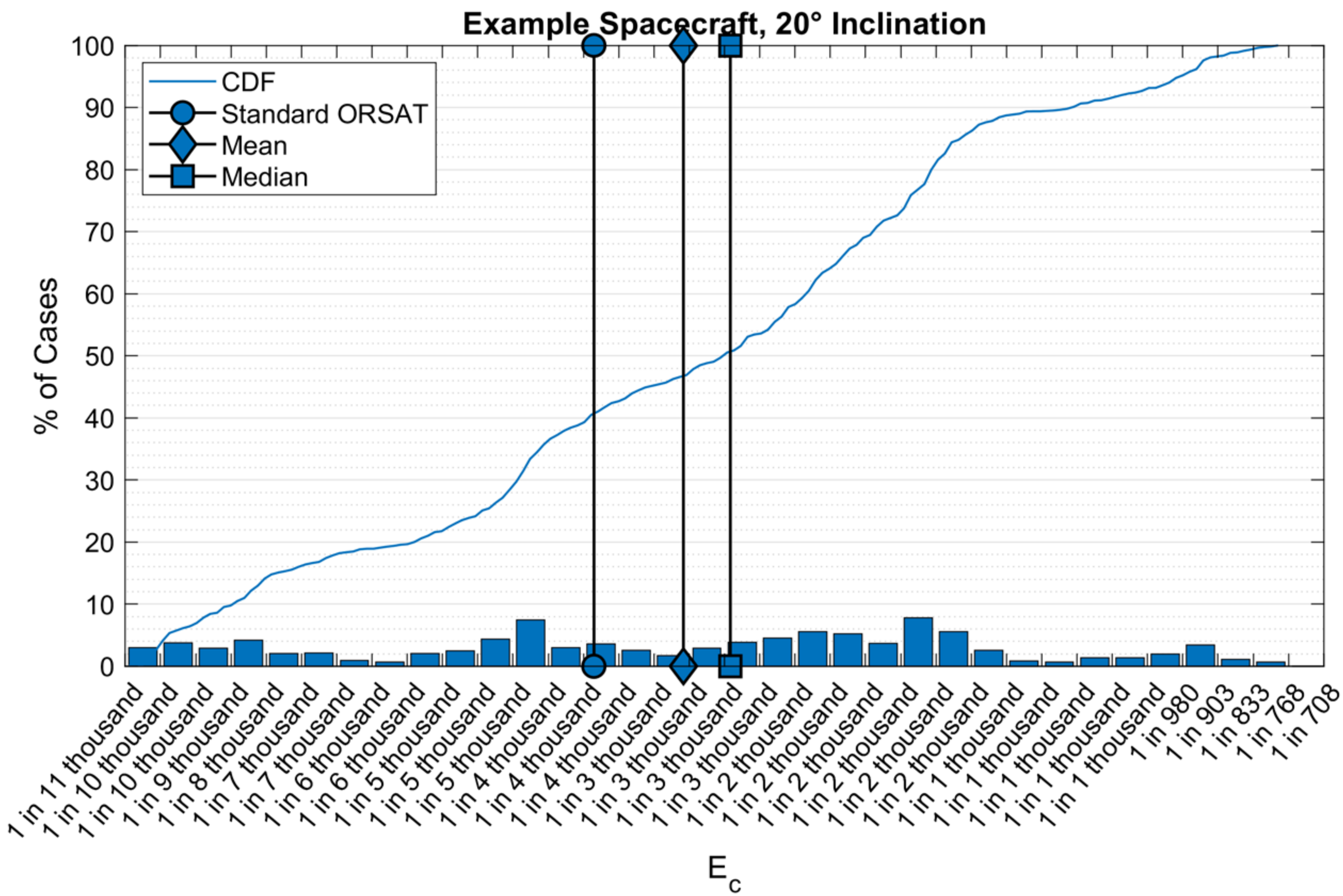

Titanium Spherical Tanks (0.2 m - 1 m)
Demise Altitude (km)
Release Altitude (km)
Wall Thickness (mm)
0
10
20
30
40
50
60
70
80
90
55
60
65
70
75
80
85
90
95
3
4
5
6
7
8
9
10

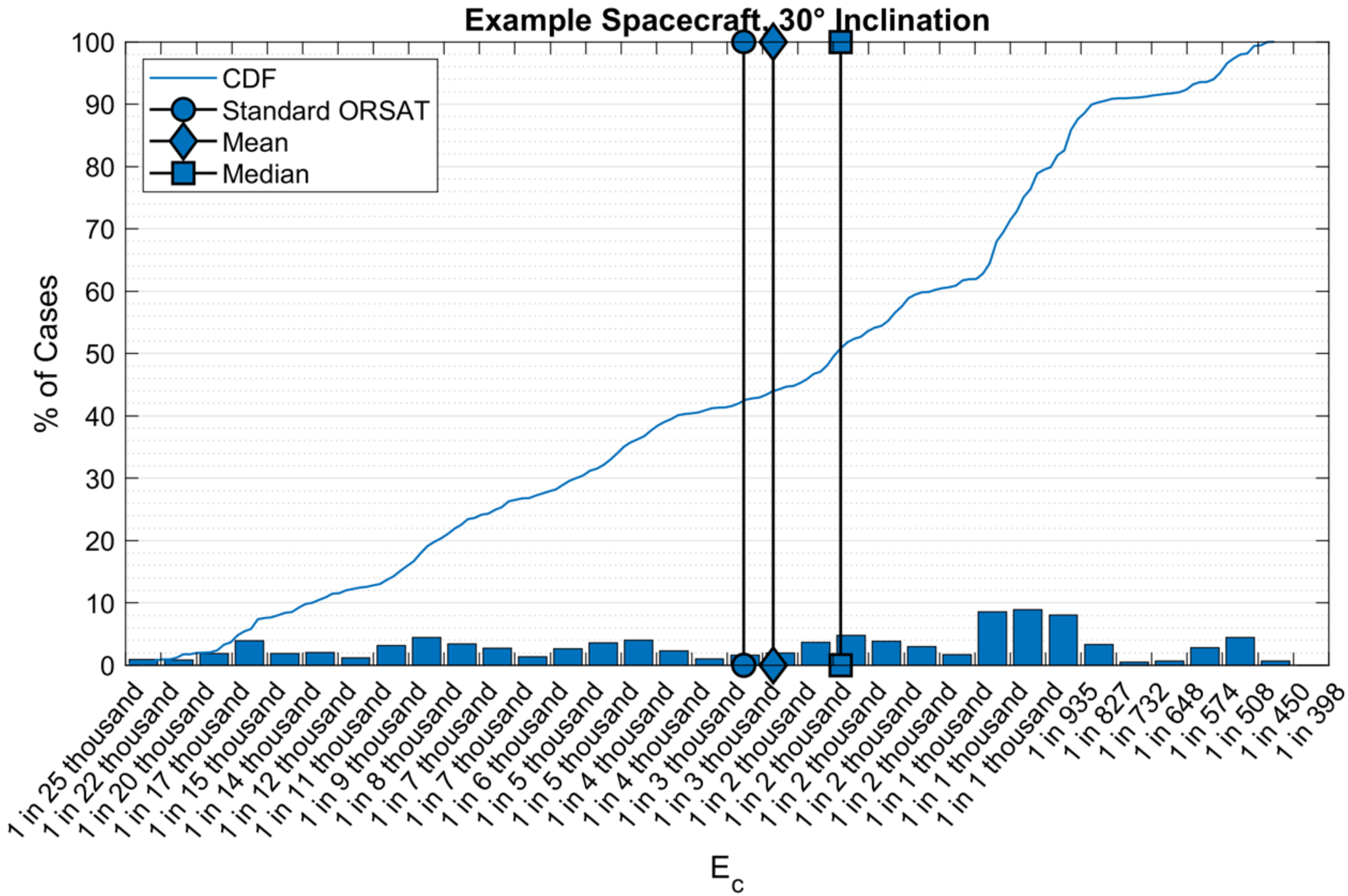

Steel Spherical Tanks (0.2 m - 1 m)
Demise Altitude (km)
Release Altitude (km)
Wall Thickness (mm)
0
10
20
30
40
50
60
70
80
90
55
60
65
70
75
80
85
90
95
3
4
5
6
7
8
9
10

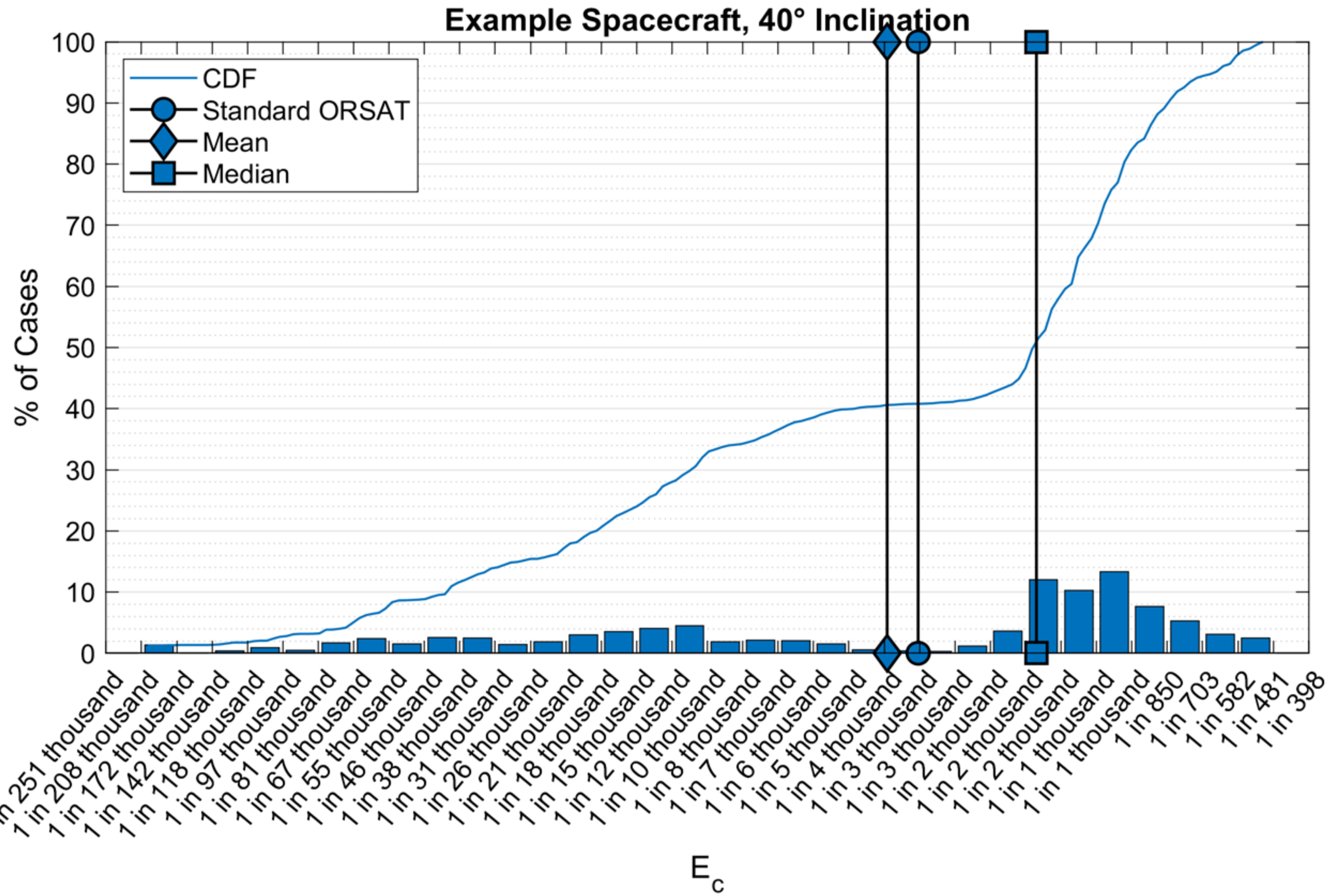

Aluminum Spherical Tanks (0.2 m - 1 m)
Demise Altitude (km)
Release Altitude (km)
Wall Thickness (mm)
0
10
20
30
40
50
60
70
80
90
55
60
65
70
75
80
85
90
95
6
8
10
12
14
16
18
20
22
24

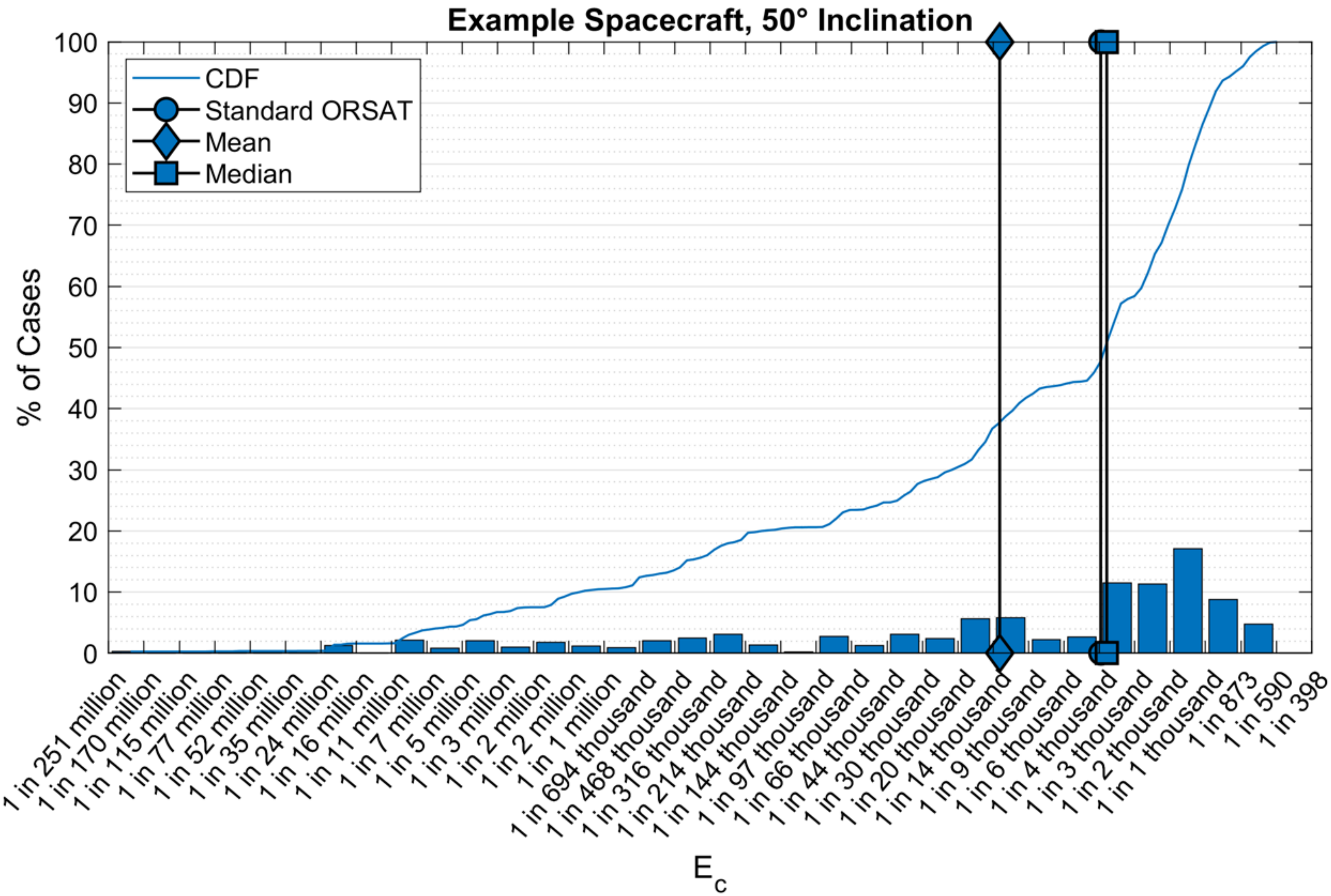


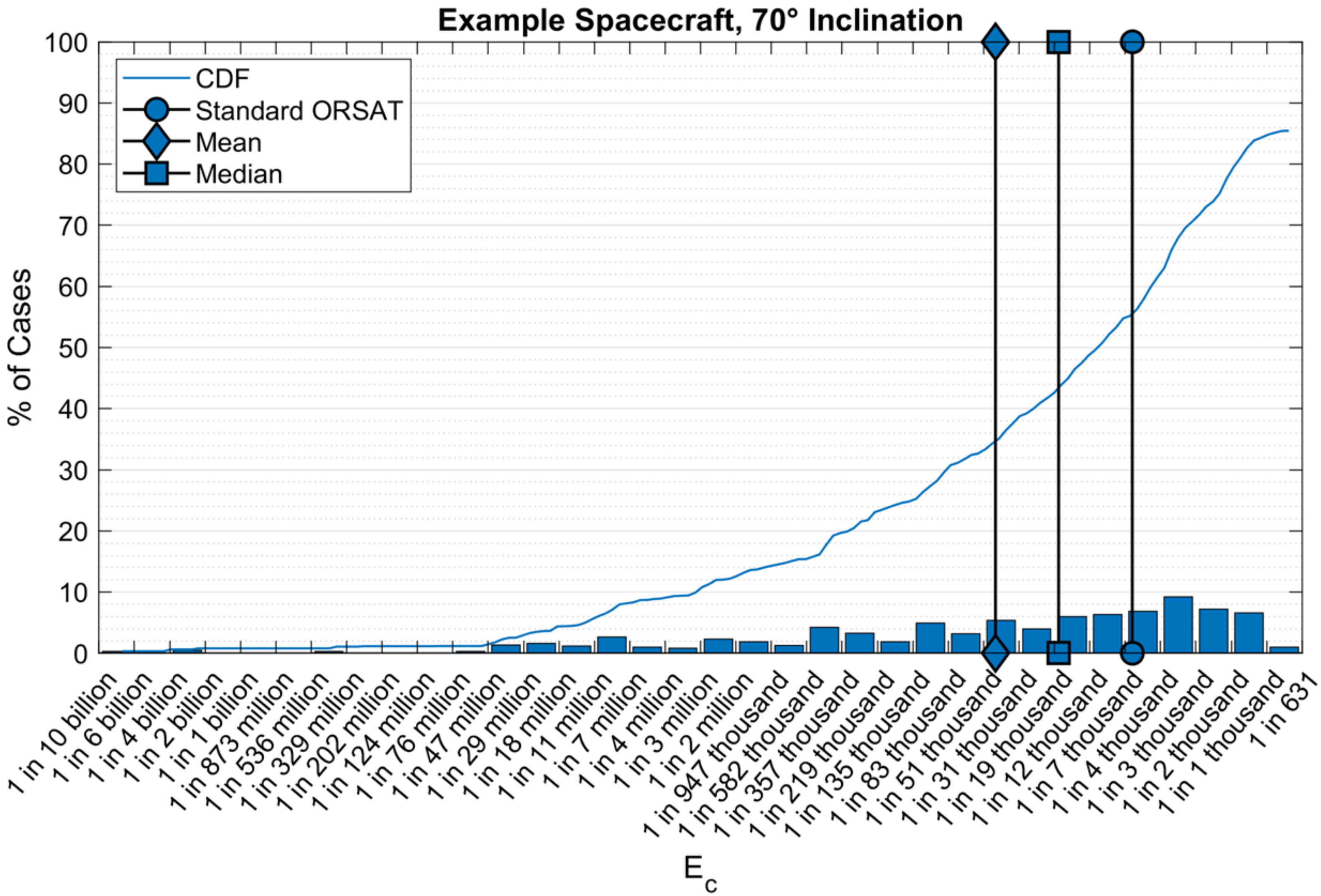
Example Spacecraft, 10° Inclination
CDF
Standard ORSAT
Mean
Median
% of Cases
100
90
80
70
60
50
40
30
20
10
0
1 in 13 thousand
1 in 12 thousand
1 in 11 thousand
1 in 10 thousand
1 in 9 thousand
1 in 8 thousand
1 in 8 thousand
1 in 7 thousand
1 in 7 thousand
1 in 6 thousand
1 in 6 thousand
1 in 5 thousand
1 in 5 thousand
1 in 4 thousand
1 in 4 thousand
1 in 4 thousand
1 in 3 thousand
1 in 3 thousand
1 in 3 thousand
1 in 3 thousand
1 in 2 thousand
1 in 2 thousand
1 in 2 thousand
1 in 2 thousand
1 in 2 thousand
1 in 2 thousand
1 in 1 thousand
1 in 1 thousand
1 in 1 thousand
1 in 1 thousand
1 in 1 thousand
1 in 935
1 in 862
1 in 794
E_c

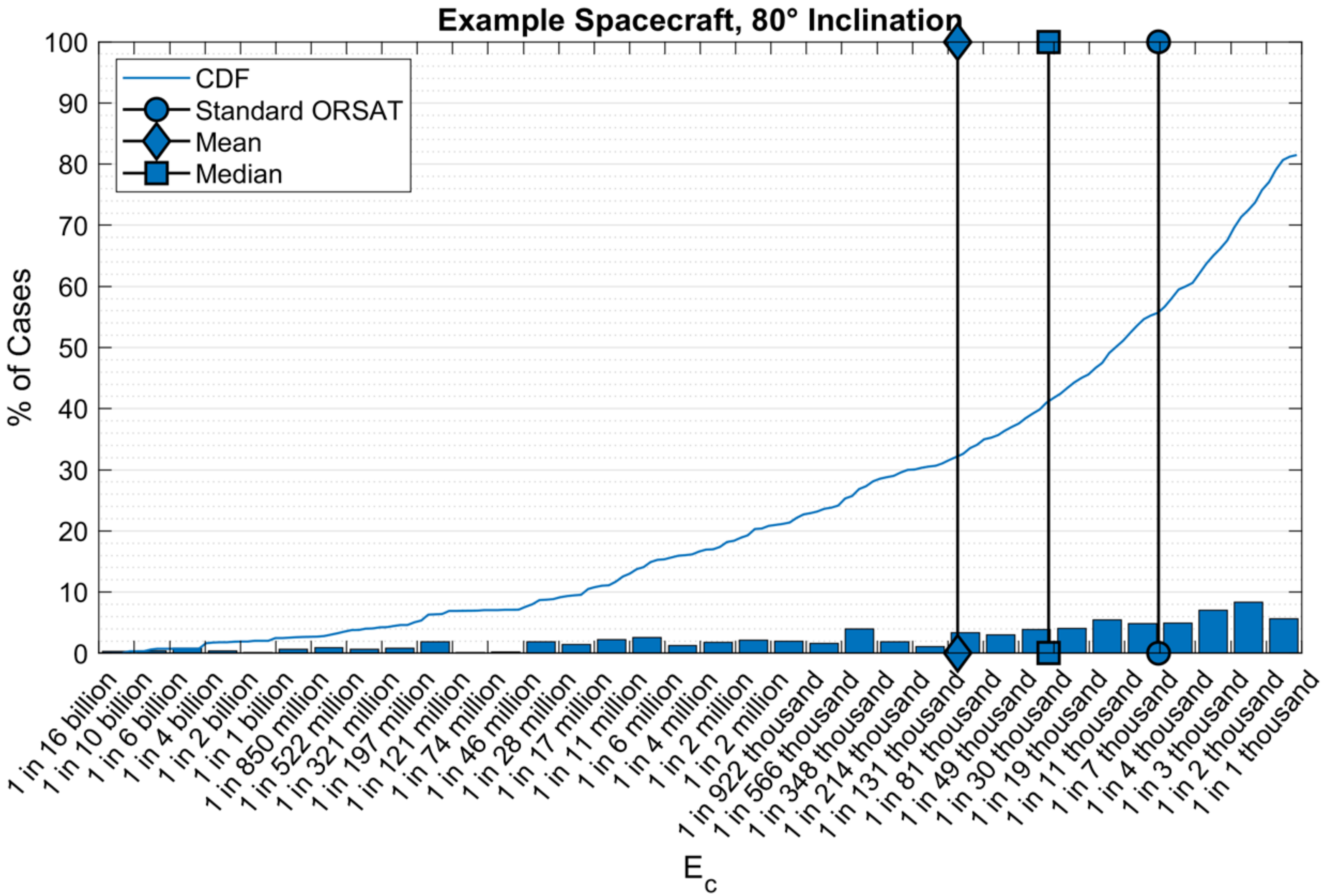

Example Spacecraft, 20° Inclination
CDF
Standard ORSAT
Mean
Median
% of Cases
0
10
20
30
40
50
60
70
80
90
100
1 in 11 thousand
1 in 10 thousand
1 in 10 thousand
1 in 9 thousand
1 in 8 thousand
1 in 7 thousand
1 in 7 thousand
1 in 6 thousand
1 in 6 thousand
1 in 5 thousand
1 in 5 thousand
1 in 5 thousand
1 in 4 thousand
1 in 4 thousand
1 in 4 thousand
1 in 3 thousand
1 in 3 thousand
1 in 3 thousand
1 in 3 thousand
1 in 2 thousand
1 in 2 thousand
1 in 2 thousand
1 in 2 thousand
1 in 2 thousand
1 in 2 thousand
1 in 1 thousand
1 in 1 thousand
1 in 1 thousand
1 in 1 thousand
1 in 1 thousand
1 in 980
1 in 903
1 in 833
1 in 768
1 in 708
$E_c$


Example Spacecraft, 30° Inclination
CDF
Standard ORSAT
Mean
Median
% of Cases
100
90
80
70
60
50
40
30
20
10
0
1 in 25 thousand
1 in 22 thousand
1 in 20 thousand
1 in 17 thousand
1 in 15 thousand
1 in 14 thousand
1 in 12 thousand
1 in 11 thousand
1 in 9 thousand
1 in 8 thousand
1 in 7 thousand
1 in 7 thousand
1 in 6 thousand
1 in 5 thousand
1 in 5 thousand
1 in 4 thousand
1 in 4 thousand
1 in 3 thousand
1 in 3 thousand
1 in 2 thousand
1 in 2 thousand
1 in 2 thousand
1 in 2 thousand
1 in 2 thousand
1 in 1 thousand
1 in 1 thousand
1 in 1 thousand
1 in 935
1 in 827
1 in 732
1 in 648
1 in 574
1 in 508
1 in 450
1 in 398
$E_c$


Example Spacecraft, 40° Inclination
CDF
Standard ORSAT
Mean
Median
% of Cases
100
90
80
70
60
50
40
30
20
10
0
1 in 251 thousand
1 in 208 thousand
1 in 172 thousand
1 in 142 thousand
1 in 118 thousand
1 in 97 thousand
1 in 81 thousand
1 in 67 thousand
1 in 55 thousand
1 in 46 thousand
1 in 38 thousand
1 in 31 thousand
1 in 26 thousand
1 in 21 thousand
1 in 18 thousand
1 in 15 thousand
1 in 12 thousand
1 in 10 thousand
1 in 8 thousand
1 in 7 thousand
1 in 6 thousand
1 in 5 thousand
1 in 4 thousand
1 in 3 thousand
1 in 3 thousand
1 in 2 thousand
1 in 2 thousand
1 in 2 thousand
1 in 1 thousand
1 in 1 thousand
1 in 850
1 in 703
1 in 582
1 in 481
1 in 398
$E_c$


Example Spacecraft, 50° Inclination
CDF
Standard ORSAT
Mean
Median
% of Cases
100
90
80
70
60
50
40
30
20
10
0
1 in 251 million
1 in 170 million
1 in 115 million
1 in 77 million
1 in 52 million
1 in 35 million
1 in 24 million
1 in 16 million
1 in 11 million
1 in 7 million
1 in 5 million
1 in 3 million
1 in 2 million
1 in 2 million
1 in 1 million
1 in 694 thousand
1 in 468 thousand
1 in 316 thousand
1 in 214 thousand
1 in 144 thousand
1 in 97 thousand
1 in 66 thousand
1 in 44 thousand
1 in 30 thousand
1 in 20 thousand
1 in 14 thousand
1 in 9 thousand
1 in 6 thousand
1 in 4 thousand
1 in 3 thousand
1 in 2 thousand
1 in 1 thousand
1 in 873
1 in 590
1 in 398
E<sub>c</sub>


Example Spacecraft, 70° Inclination
CDF
Standard ORSAT
Mean
Median
% of Cases
100
90
80
70
60
50
40
30
20
10
0
1 in 10 billion
1 in 6 billion
1 in 4 billion
1 in 2 billion
1 in 1 billion
1 in 873 million
1 in 536 million
1 in 329 million
1 in 202 million
1 in 124 million
1 in 76 million
1 in 47 million
1 in 29 million
1 in 18 million
1 in 11 million
1 in 7 million
1 in 4 million
1 in 3 million
1 in 2 million
1 in 947 thousand
1 in 582 thousand
1 in 357 thousand
1 in 219 thousand
1 in 135 thousand
1 in 83 thousand
1 in 51 thousand
1 in 31 thousand
1 in 19 thousand
1 in 12 thousand
1 in 7 thousand
1 in 4 thousand
1 in 3 thousand
1 in 2 thousand
1 in 1 thousand
1 in 631
E$_c$


Example Spacecraft, 80° Inclination
CDF
Standard ORSAT
Mean
Median
% of Cases
100
90
80
70
60
50
40
30
20
10
0
1 in 16 billion
1 in 10 billion
1 in 6 billion
1 in 4 billion
1 in 2 billion
1 in 1 billion
1 in 850 million
1 in 522 million
1 in 321 million
1 in 197 million
1 in 121 million
1 in 74 million
1 in 46 million
1 in 28 million
1 in 17 million
1 in 11 million
1 in 6 million
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1 in 2 million
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1 in 81 thousand
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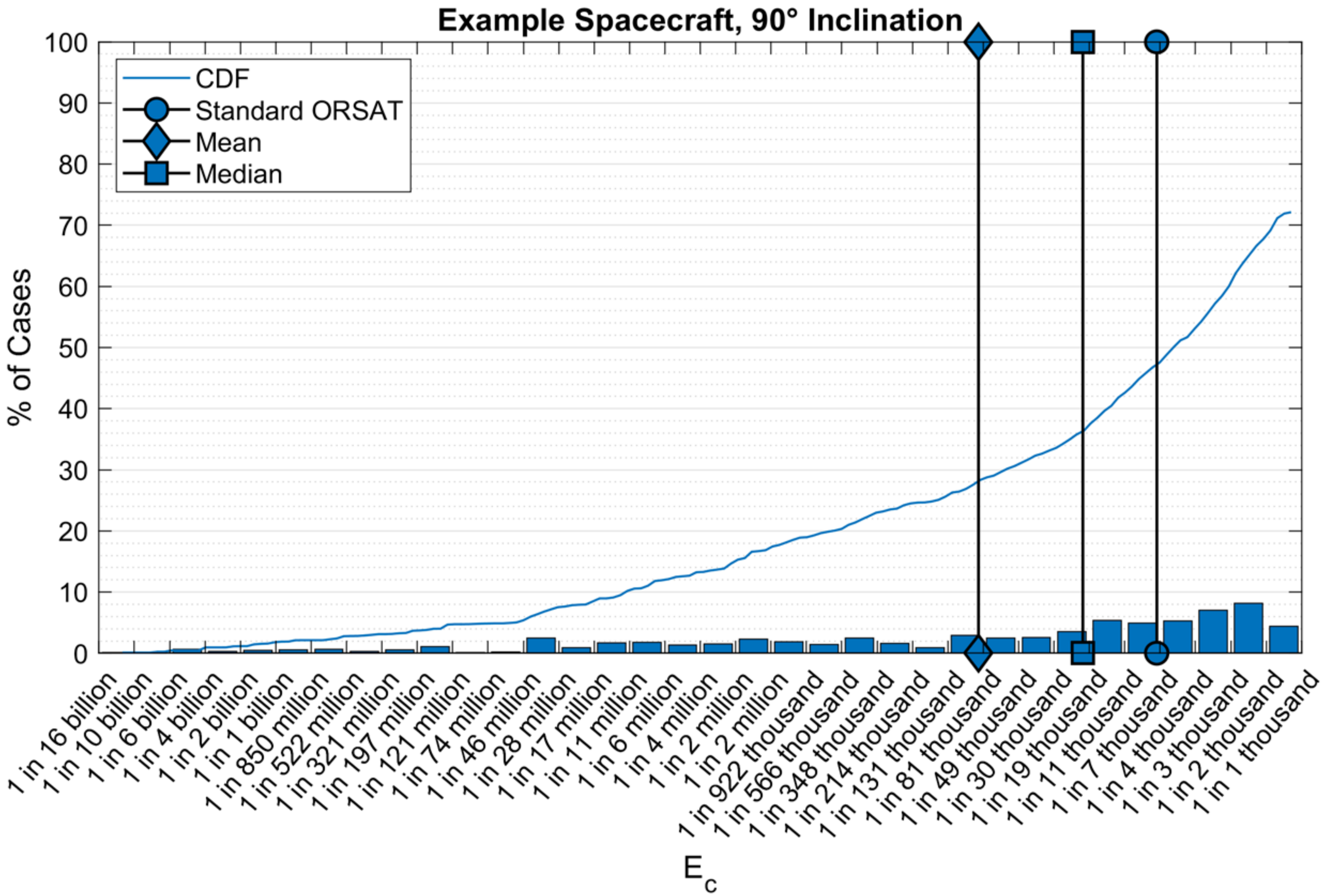
$E_c$


Example Spacecraft, 90° Inclination
CDF
Standard ORSAT
Mean
Median
% of Cases
100
90
80
70
60
50
40
30
20
10
0
1 in 16 billion
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