WG2 Action Item 19.1

"Benefits and Risks of using Electrodynamic Tethers to De-orbit Spacecraft"

Space Tethers Survivability Concerns

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Institute of Information Science and Technologies

Italian National Research Council

Introduction

The IADC WG2 Action Item 19.1 on benefits and risks of using space tethers has been focused on reviews and investigations dealing with the use of Electrodynamic Tethers systems (EDT) to de-orbit spacecraft and spent upper stages in low earth orbit (LEO).

At the 21st IADC meeting in Bangalore, India, the state-of-the-art knowledge on this topic was presented and a proposal to address the EDT system survivability concern was advanced inside IADC WG2.

A study plan was prepared by C. Pardini (Lead, ISTI/CNR – ASI) and sent to all WG2 members on 20 November 2003.

Three Space Agencies (ASI, JAXA and NASA) participated in the proposed study.

The study plan and the main results obtained so far will be presented.

Space Environment Models and Assumptions

The study plan proposed that all participants in the study used the space debris environment and impact probability models of their own choice

Space Debris Environment Models

ASI

Meteoroids — **SSP 30425** of the NASA **DAS 1.5.3** model

Orbital Debris — **ORDEM96** of the NASA **DAS 1.5.3** model for OD smaller than 1 mm

ISTI/CNR **CODRM-99R** model for OD larger than 1 mm

JAXA

Meteoroids & Orbital Debris

ESA **MASTER 2001** model

Orbital Debris

NASA **ORDEM2000** MODEL

NASA

Meteoroids

Grun, 1985, Meteoroid Flux

Orbital Debris

NASA **ORDEM2000** MODEL

Space Environment Models and Assumptions

Models to Compute the Sever Probability

ASI

in "*Methodology used at ISTI/CNR to Assess the Sever Probability of Space Tethers*" by C. Pardini and L. Anselmo, 22nd IADC Meeting presentation.

JAXA

Models and methods published in – "*Debris Collision Analysis for Tethers*", by A. Nishimine, paper ISTS 2002-s-29, 23rd International Symposium on Space Technology and Science, Matsue, Japan, May 26- June 2, 2002 – modified by Atushi Ooishi (Kyushu University, Japan) to model double-line tethers.

NASA

Formulation published by P. Anz-Meador in "*A Probability of Sever Model for Tethers in Low Earth Orbit*", 20th IADC Meeting presentation (Test #1).

Tether Design & Configuration

A STABLE CYLINDRICAL SPACE TETHER, DEPLOYED ALONG THE GRAVITY GRADIENT AND IN A CIRCULAR ORBIT WAS ADOPTED

Tether Diameter

On the basis of the past space tether experiments and proposals for future applications, the following tether diameters were considered

Tether Diameter							
0.50 mm	0.75 mm	1 mm	2.5 mm	5 mm	1 cm	2.5 cm	5 cm

Tether diameters significantly larger than 1 mm are intended as geometric envelopes of much more complex configurations, like the Hoytether device.

Tether Length

Past studies have demonstrated that tether lengths on the order of 5-10 km are adequate to de-orbit spacecraft in LEO with an electrodynamic tether system. Therefore, the following tether lengths were assumed

Tether Length		
5 km	7.5 km	10 km

Tether Design

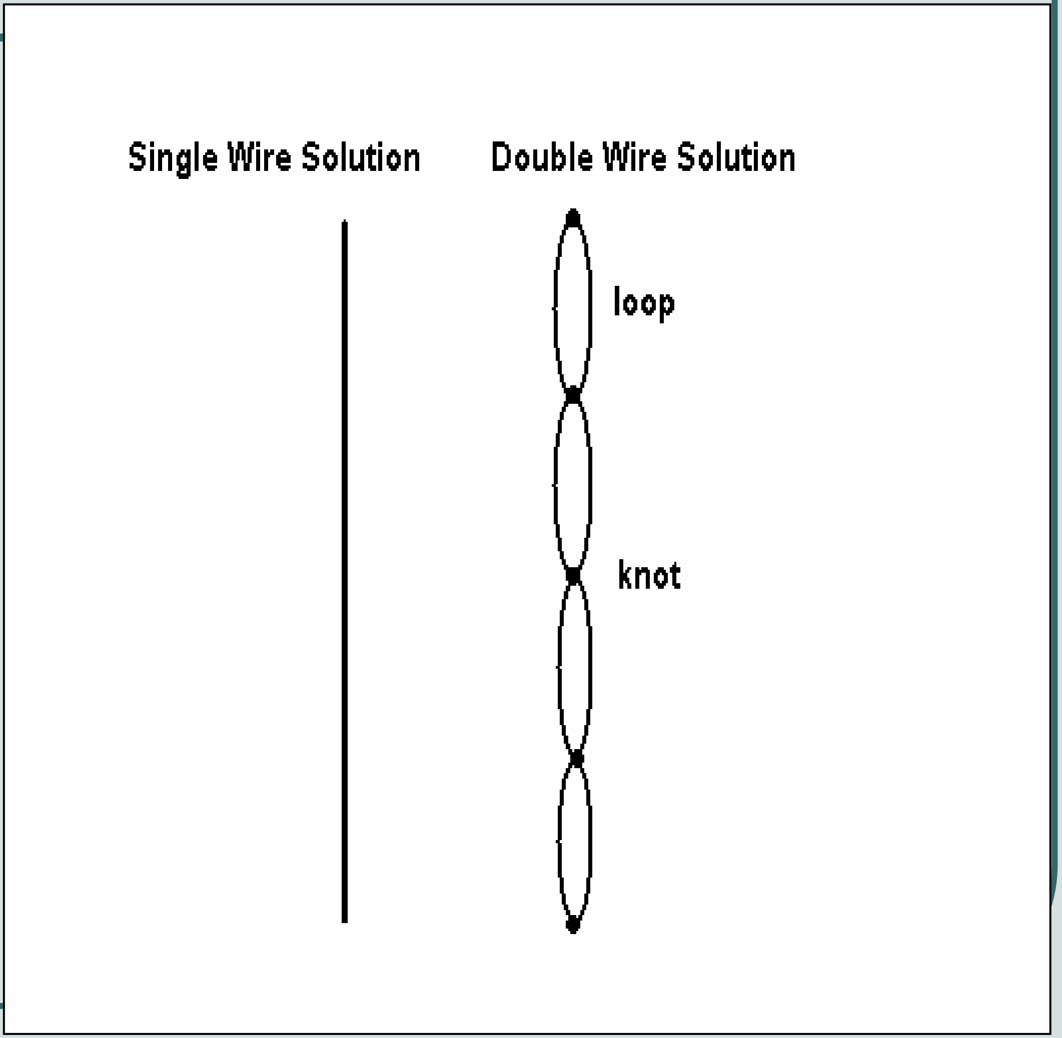
Two types of tethers were considered: **single-line tether**, **double-line tether with knots**

The tether diameter varied in between 0.5 mm and 5 cm for a **single-line tether**.

For a **double-line tether**, the tether diameter of each single wire was 0.5 mm or 1 mm.

The two cables were separated each other by a distance significantly larger than each line diameter and were designed to form *n* loops, tied together in *n* + 1 equidistant knots along the tether.

Distances between knots of 100 m, 10 m and 5 m were assumed.



Fatal Debris Diameter

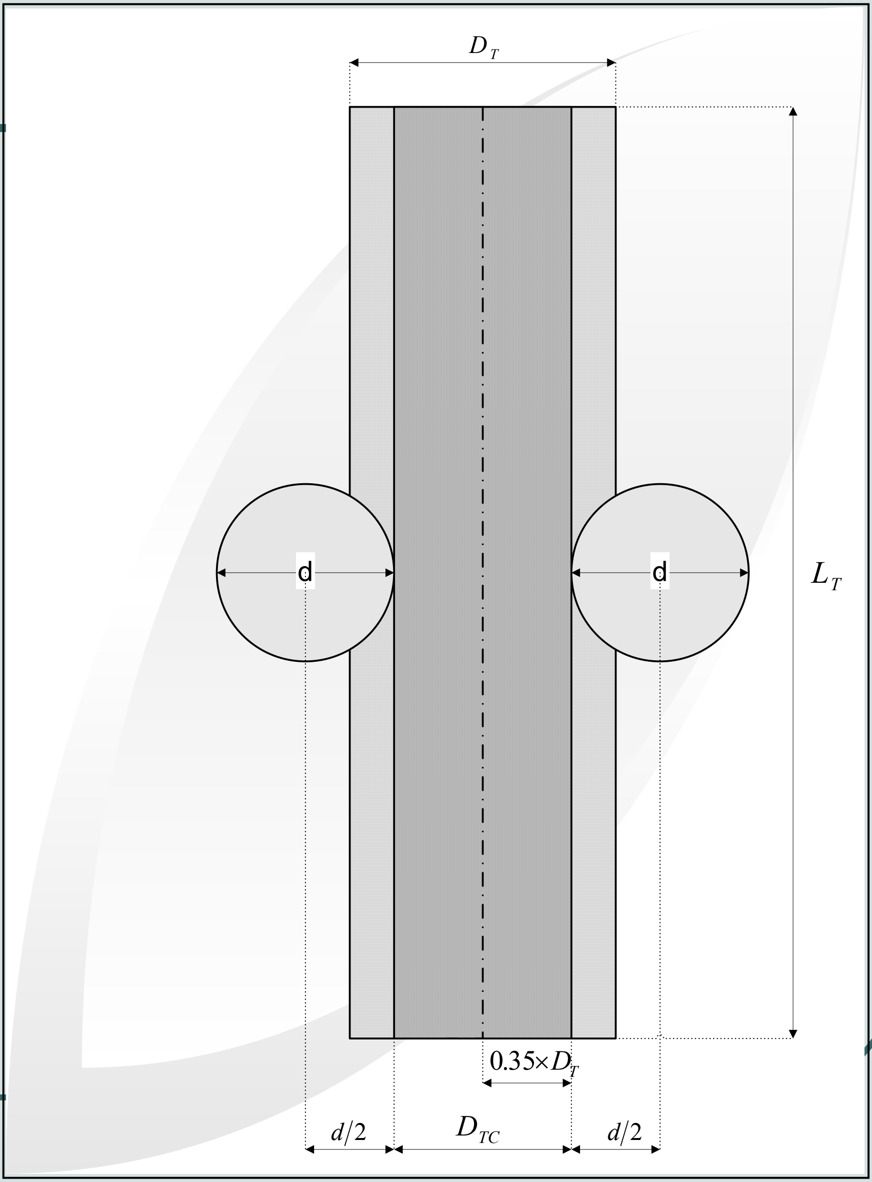
Only meteoroids or orbital debris satisfying the following relationship

$$d \geq 0.25 D_T$$

d debris diameter

D_T tether diameter

might have severed the tether provided the debris edge passed within 0.35 D_T of the tether centre of axial symmetry.



Proposed Tests

Two tests were proposed in the IADC WG2 AI 19.1 Study Plan

1. To compute the **Fatal Impact Rate** of meteoroids and orbital debris on space tethers in circular orbits, at different altitudes and inclinations, as a function of the tether diameter;

2. To assess the **Survival Probability** of a specific electrodynamic tether system during its baseline mission for end-of-life de-orbiting of satellites and upper stages from different altitudes and inclinations.

Test 1
Fatal Impact Rate Analysis

The **Fatal Impact Rate**, in [yr^{-1} km^{-1}], i.e. the rate at which a tether may be severed by meteoroids and orbital debris, was computed for each selected altitude and inclination, as a function of the tether diameter.

Orbit Altitudes [km]	Orbit Inclinations [deg]	Tether Diameter
1400	25, 50, 75	0.50 mm, 0.75 mm, 1 mm, 2.5 mm, 5 mm, 1 cm, 2.5 cm, 5 cm
1000	25, 50, 75	0.50 mm, 0.75 mm, 1 mm, 2.5 mm, 5 mm, 1 cm, 2.5 cm, 5 cm
800	25, 50, 75	0.50 mm, 0.75 mm, 1 mm, 2.5 mm, 5 mm, 1 cm, 2.5 cm, 5 cm

The severing rate and orbital lifetime of typical electrodynamic devices, i.e. tethers with a length of 5 km, 7.5 km or 10 km, was then estimated.

Test 2
Survivability Analysis
The "Terminator Tether"

A specific electrodynamic tether system, namely the **"Terminator Tether (TT)"** of *Tether Unlimited , Inc.* was adopted.

The TT system modelled by Hoyt R. and Forward R. ("Performance of the Terminator TetherTM for Autonomous Deorbit of LEO Spacecraft", *Paper AIAA 99-2839*, 1999) consisted of a 15 kg aluminium tether, with a 15 kg end-mass. **The tether was chosen to be 7.5 km long**. The host spacecraft mass was 1500 kg, so the tether massed 1% of the spacecraft mass. It was also assumed that the TT has completed its mission when the spacecraft altitude drops below 250 km.

This lightweight tether system can effectively de-orbit satellites in inclinations up to about 75°, if the initial altitude is less than 1000 km. For polar orbits, de-orbit times with such a low-mass tether are rather high. In this case, lower de-orbit times could be achieved using more massive tethers.

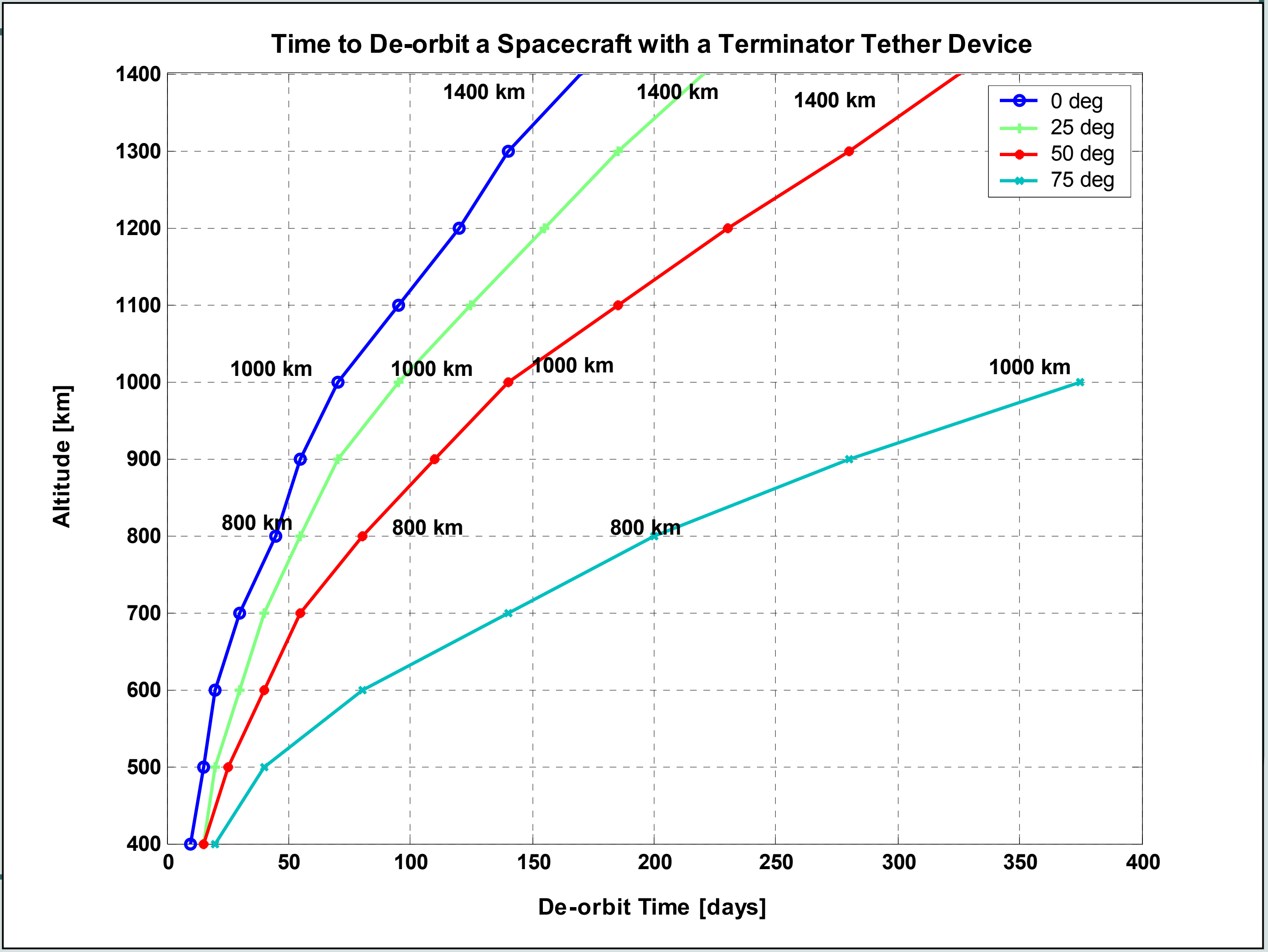
Test 2
Survivability Analysis
TT De-orbit Times

Time to de-orbit a satellite with a 7.5 km TT massing 1% of the satellite mass from a given initial altitude to 250 km

Initial Altitude [km]	**Orbit Inclination**			
	0°	25°	50°	75°
	DE-ORBIT TIME [days]			
1400	170	220	325	TT not efficient at these altitudes and inclinations
1300	140	185	280	
1200	120	155	230	
1100	95	125	185	
1000	70	95	140	375
900	55	70	110	280
800	45	55	80	200
700	30	40	55	140
600	20	30	40	80
500	15	20	25	40
400	10	15	15	20

Test 2
Survivability Analysis
TT De-orbit Times

Time to de-orbit a satellite with a 7.5 km TT from a given initial altitude to 250 km



Test 2
Survivability Analysis
TT Decay Time per Altitude Shell

Altitude Shell [km]	Inclination			
	0°	25°	50°	75°
	Decay Time per Altitude Shell [days]			
1400 – 1300	30	35	45	TT not efficient at these altitudes and inclinations
1300 – 1200	20	30	50	
1200 – 1100	25	30	45	
1100 – 1000	25	30	45	
1000 – 900	15	25	30	95
900 – 800	10	15	30	80
800 – 700	15	15	25	60
700 – 600	10	10	15	60
600 – 500	5	10	15	40
500 – 400	5	5	10	20
400 – 250	10	15	15	20

Test 2
Survivability Analysis
Proposed Cases

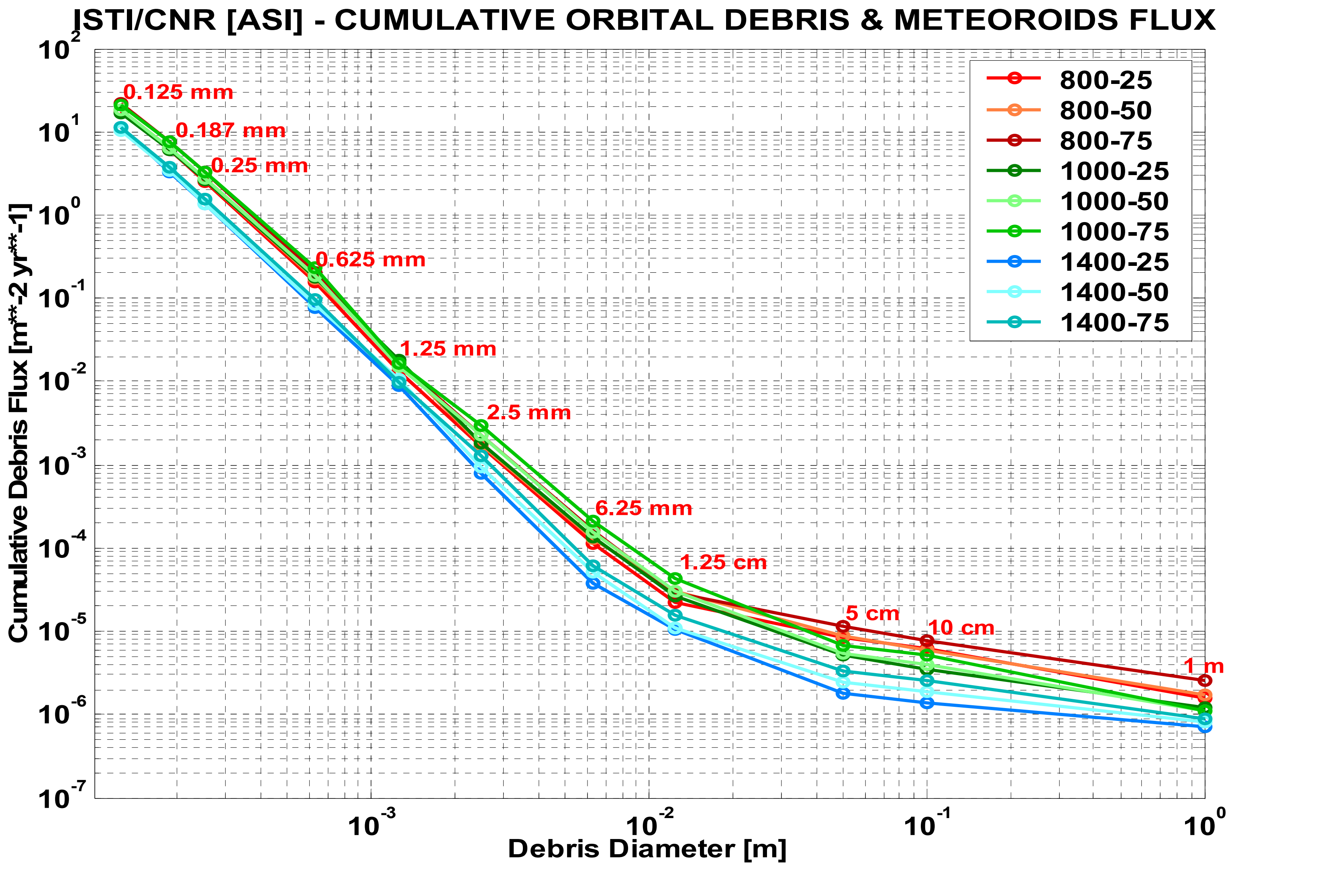
Three initial altitudes and four orbital inclinations were considered:

1. **de-orbiting from an altitude of 1400 km with inclination of 0°, 25°, 50°**
2. **de-orbiting from an altitude of 1000 km with inclination of 0°, 25°, 50°, 75°**
3. **de-orbiting from an altitude of 800 km with inclination of 0°, 25°, 50°, 75°**

For each case 1-3, two different diameters were assumed for the 7.5 km long tether and the following configurations were investigated:

- single-line tether with a diameter of 0.5 mm;
- single-line tether with a diameter of 1 mm;
- double-line tether with a diameter of 0.5 mm for each single wire and with equidistant knots spaced at intervals of 100 m;
- double-line tether with a diameter of 0.5 mm for each single wire and with equidistant knots spaced at intervals of 10 m;
- double-line tether with a diameter of 0.5 mm for each single wire and with equidistant knots spaced at intervals of 5 m;
- *double-line tether with a diameter of 1 mm for each single wire and with equidistant knots spaced at intervals of 5 m.*

Test 1
Fatal Impact Rate Analysis
ASI Space Debris Flux



Test 1
Fatal Impact Rate Analysis
JAXA Space Debris Flux

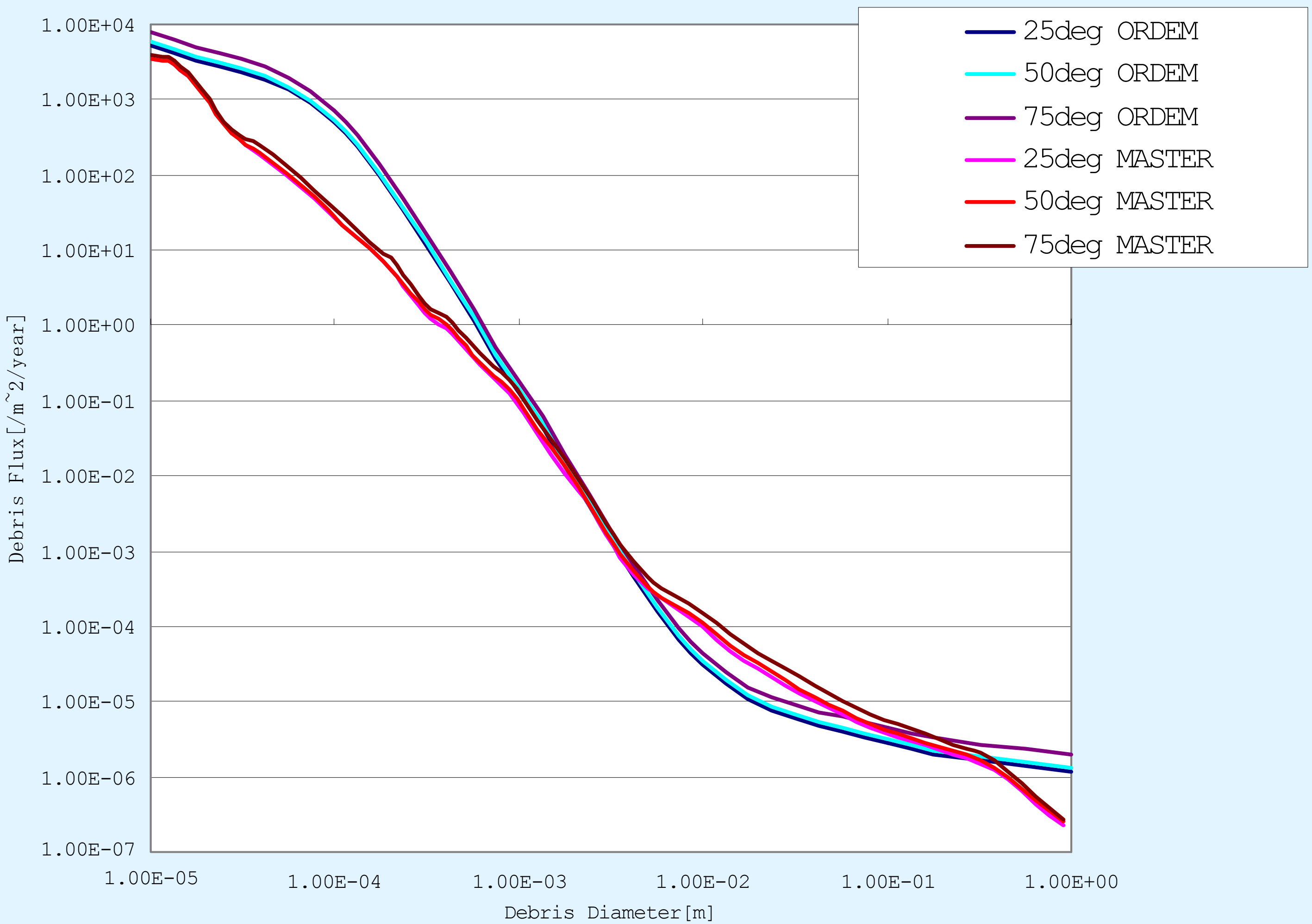


Fig1 Comparison of debris flux(Altitude = 800km)

Test 1
Fatal Impact Rate Analysis
JAXA Space Debris Flux

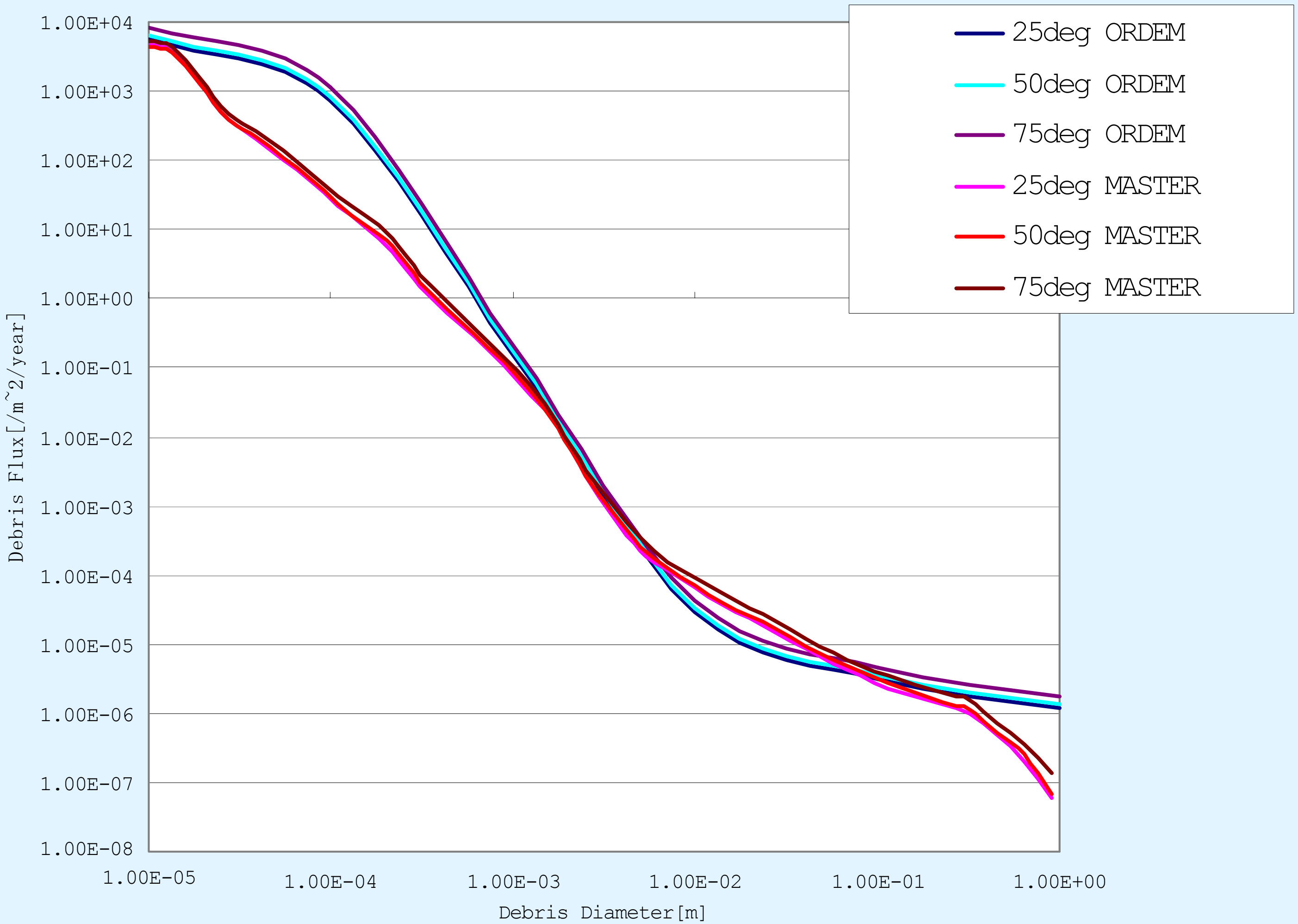


Fig2 Comparison of debris flux(Altitude = 1000km)

Test 1
Fatal Impact Rate Analysis
JAXA Space Debris Flux

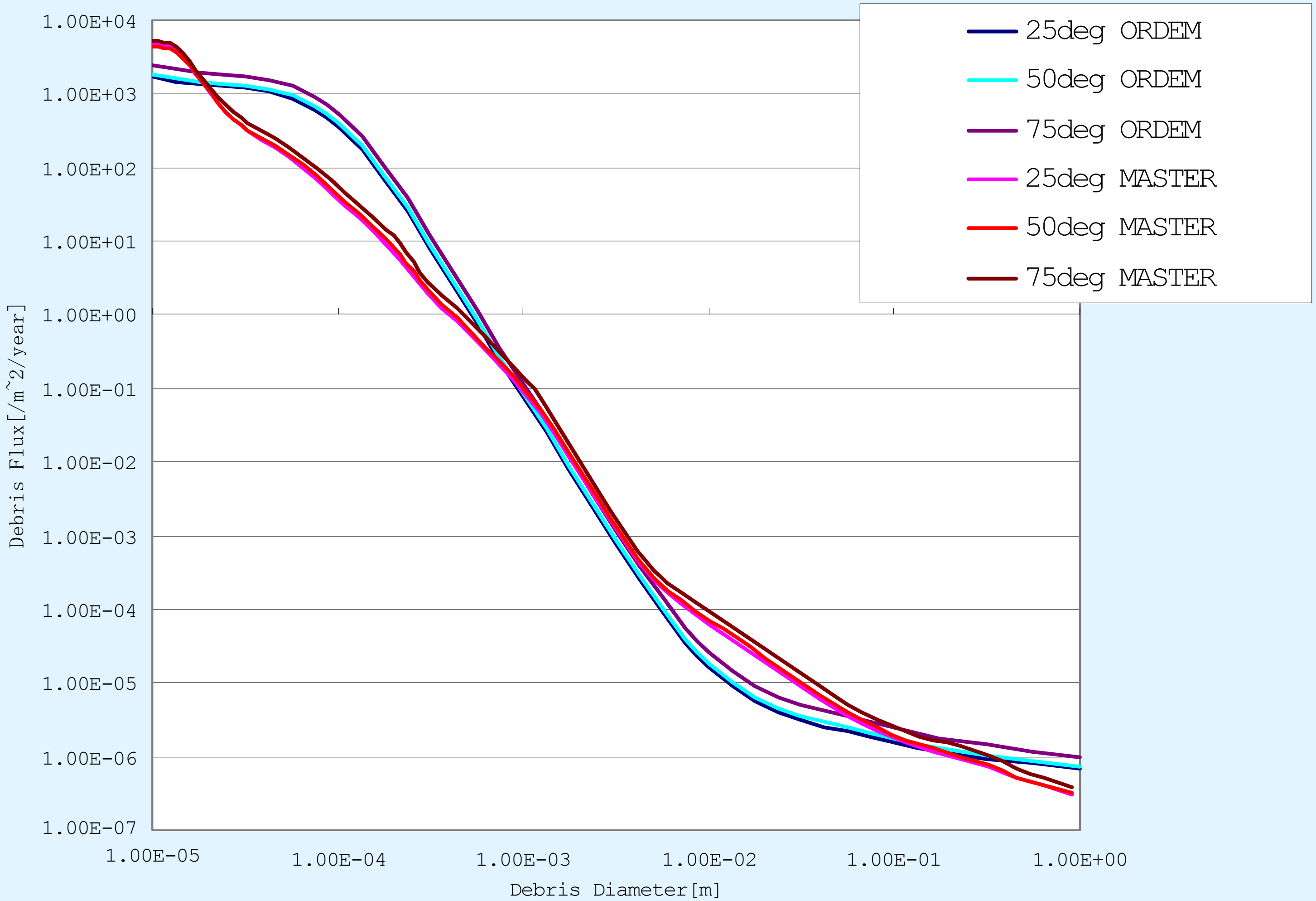
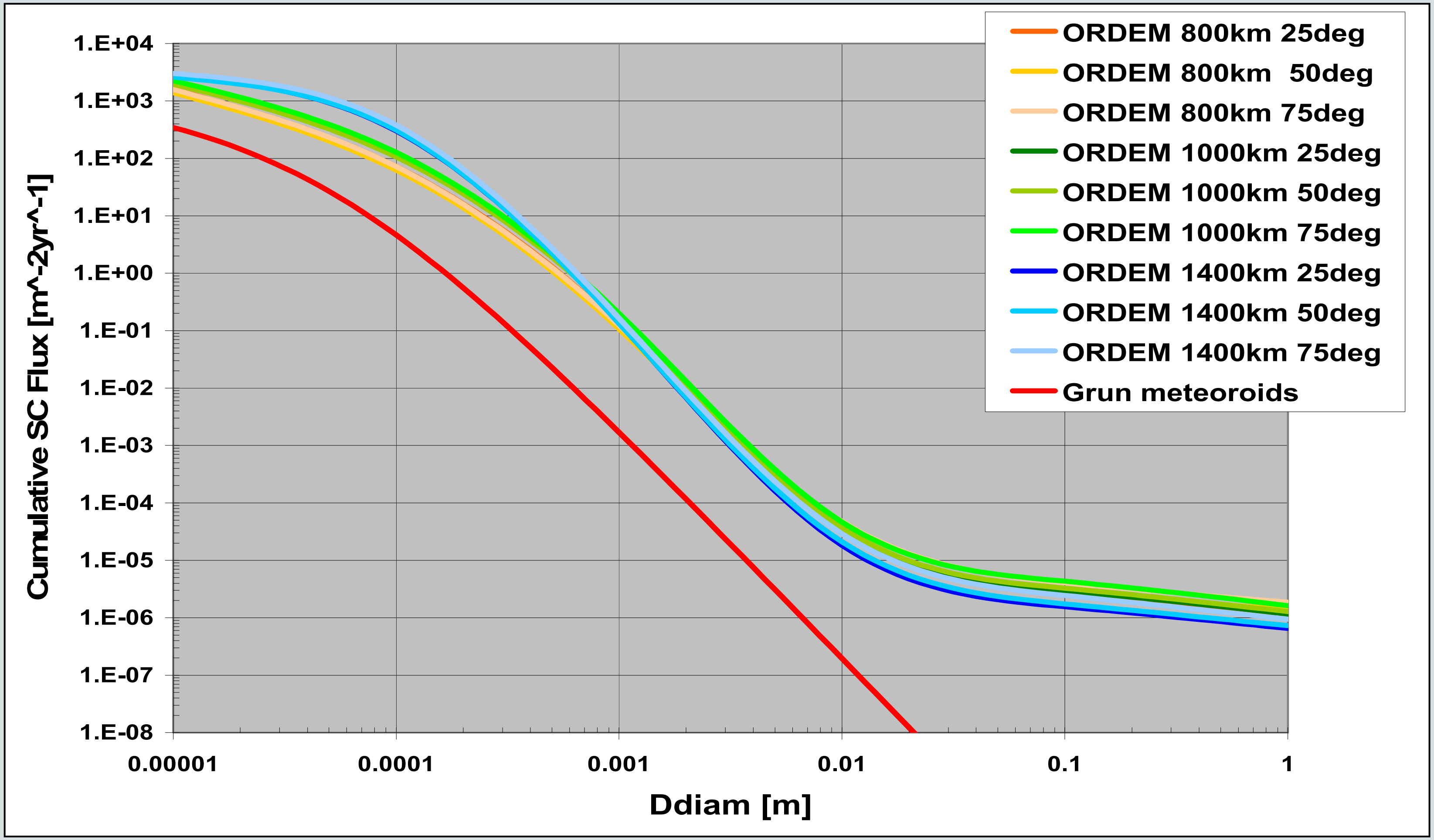
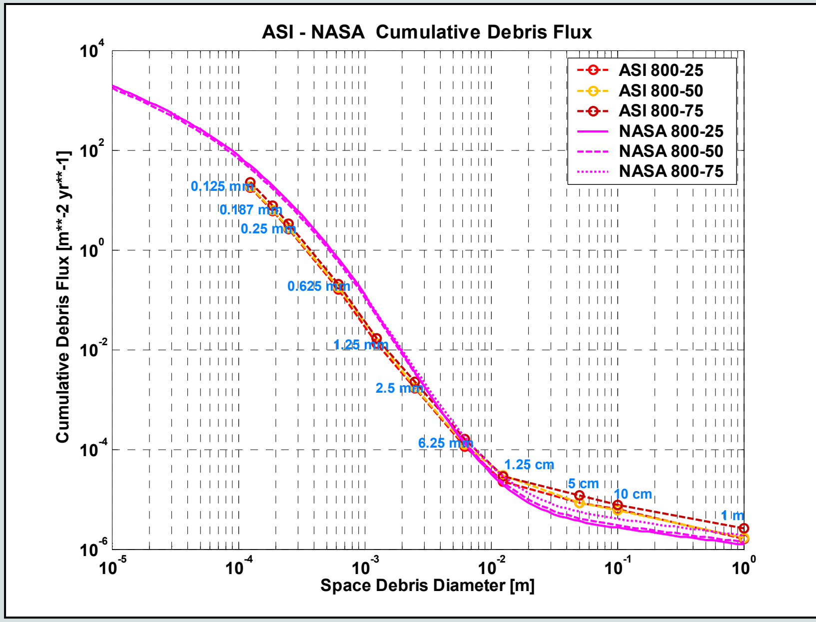


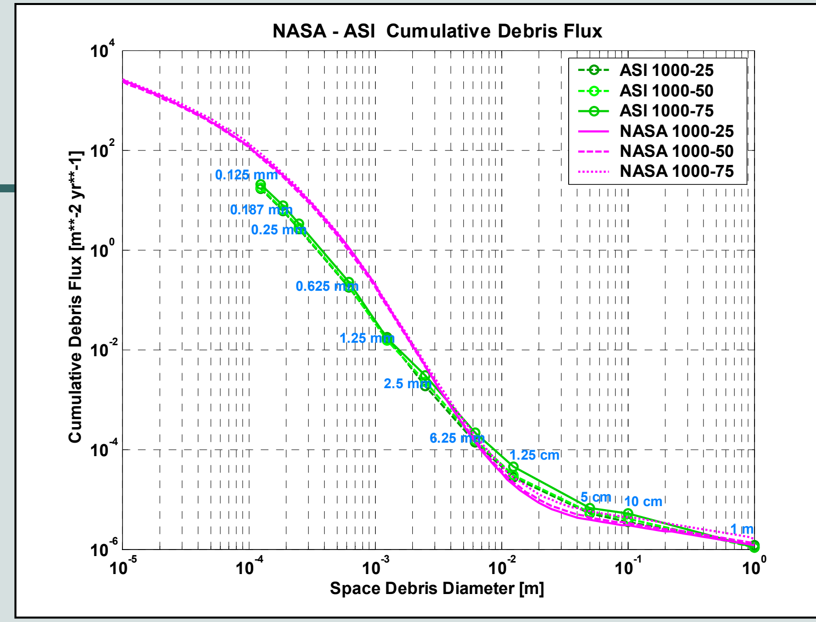
Fig3 Comparison of debris flux(Altitude = 1400km)

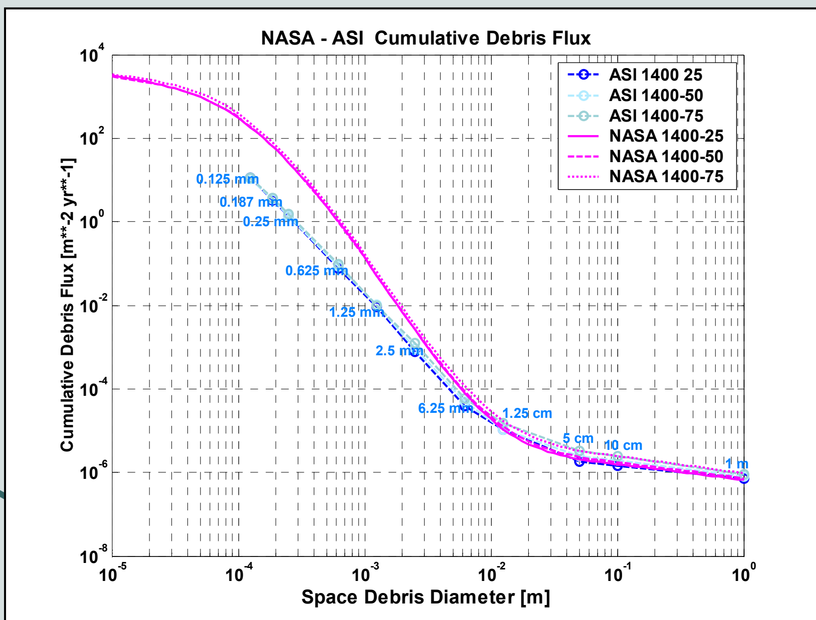
Test 1
Fatal Impact Rate Analysis
NASA Space Debris Flux

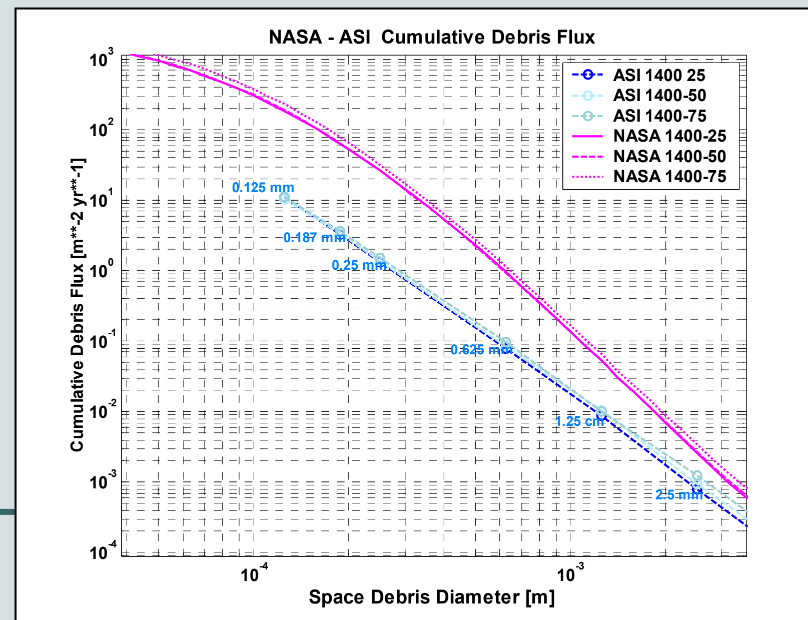


ASI - NASA Space Debris Flux Comparison





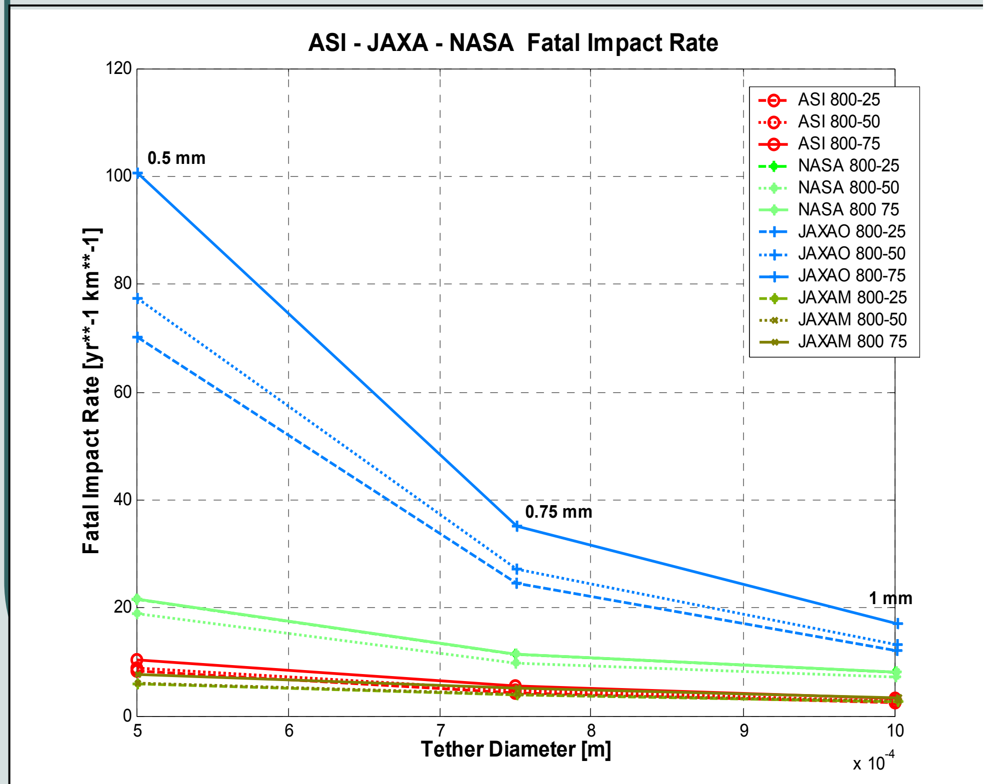


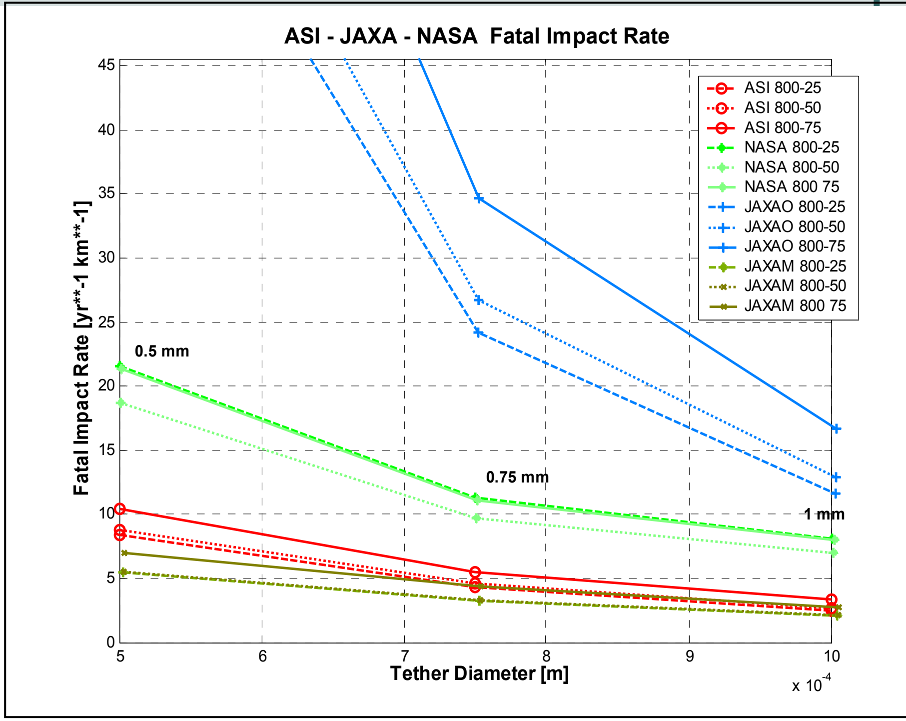


Test 1
Fatal Impact Rate Analysis Results
Tether Diameter: 0.5 mm, 0.75 mm, 1mm

ASI and NASA computed the Fatal Impact Rate for all tether diameters in between 0.5 mm and 5 cm
JAXA computed the Fatal Impact Rate for tether diameters in between 0.5 and 1 mm

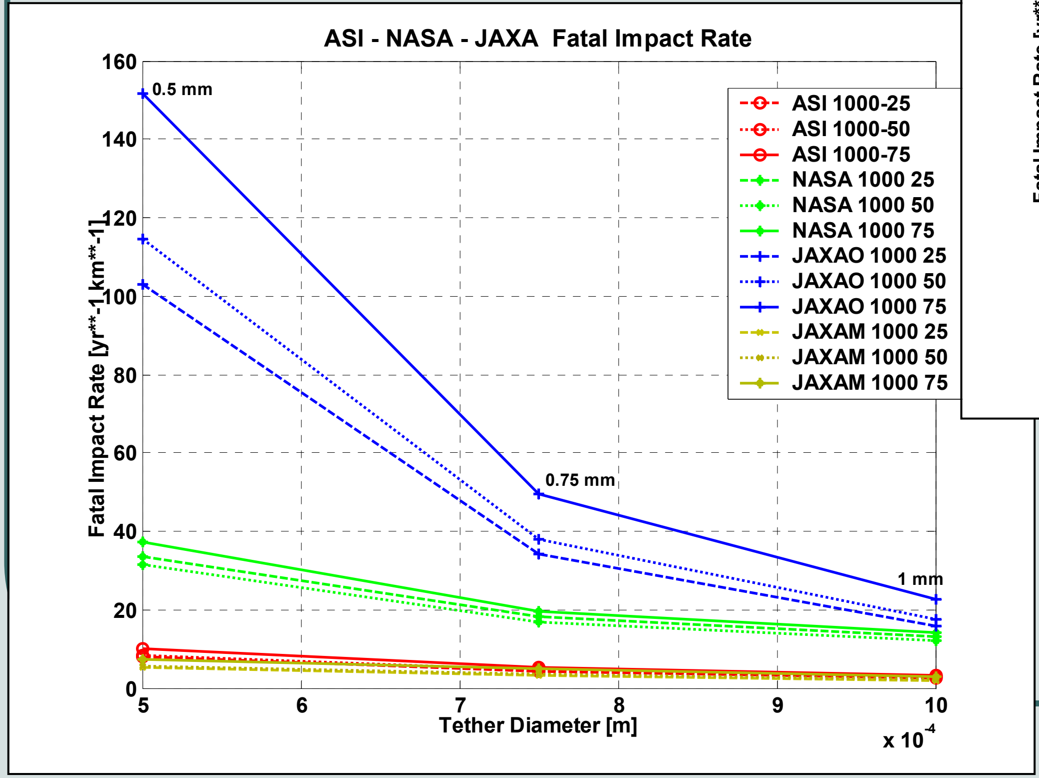
Orbit Altitude
800 km

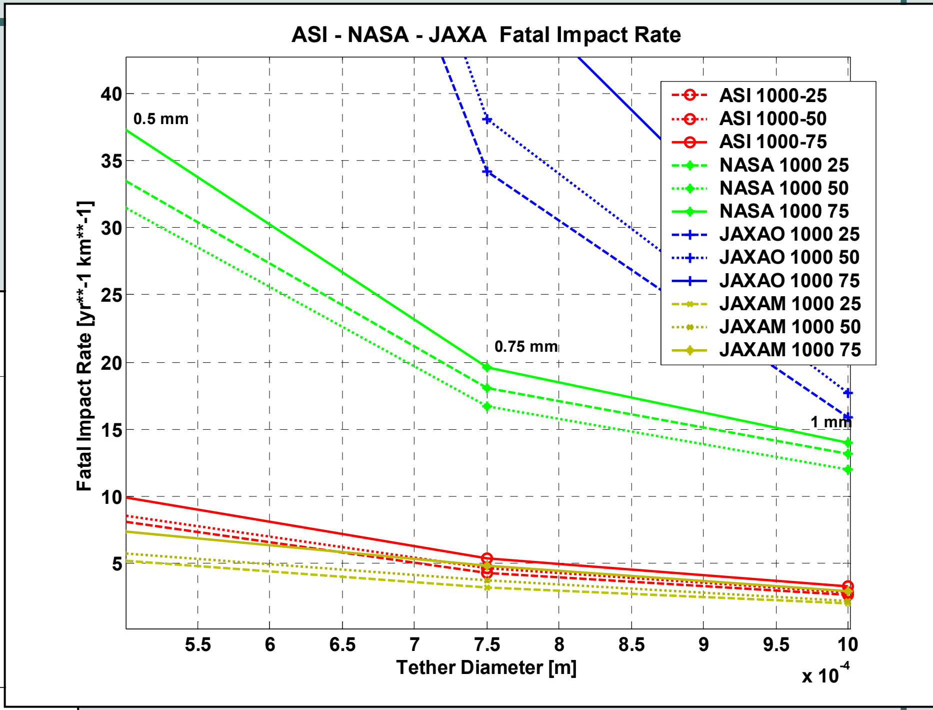




Test 1
Fatal Impact Rate Analysis Results
Tether Diameter: 0.5 mm, 0.75 mm, 1mm

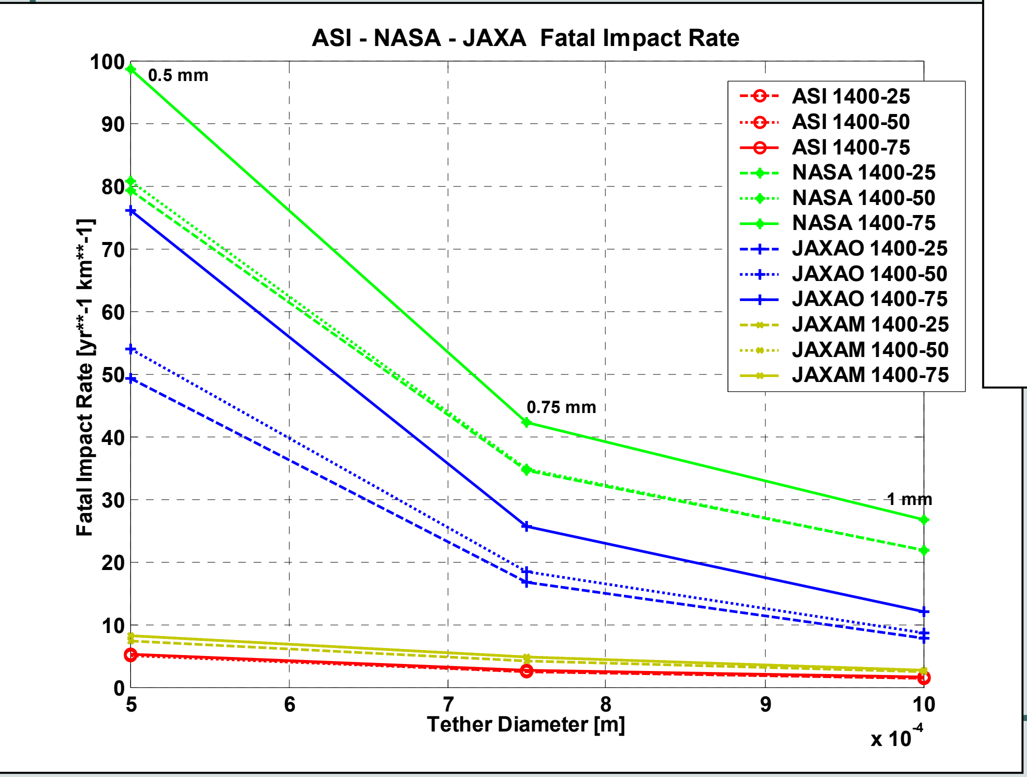
Orbit Altitude
1000 km

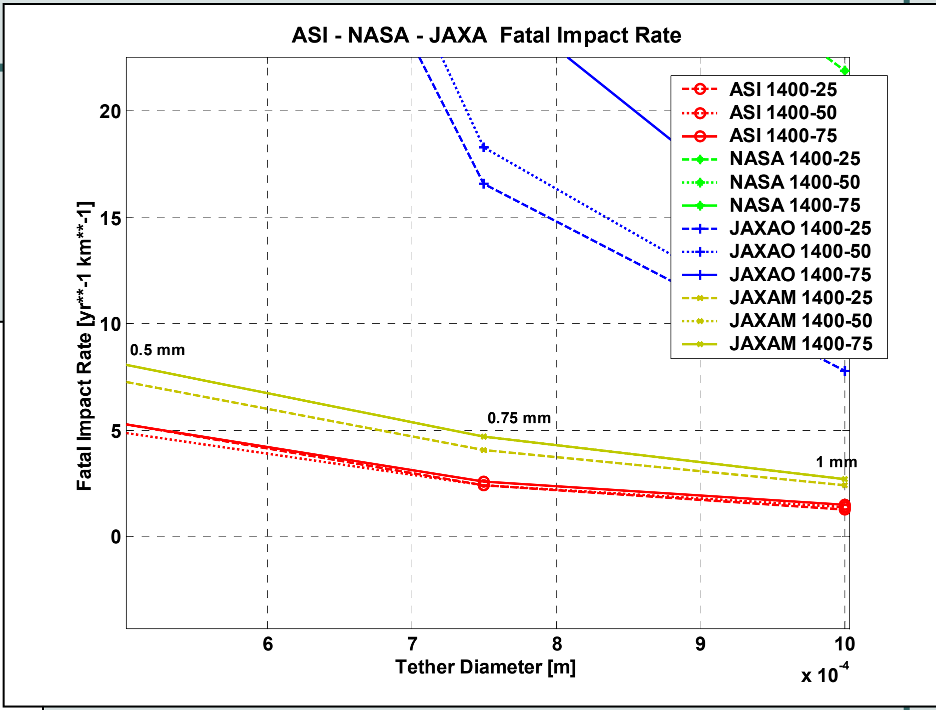




Test 1
Fatal Impact Rate Analysis Results
Tether Diameter: 0.5 mm, 0.75 mm, 1mm

Orbit Altitude
1400 km





Test 1
Fatal Impact Rate Analysis Results
Tether Diameter: 0.5 mm, 0.75 mm, 1mm

Altitude [km] & Inc [deg]	ASI – JAXA Fatal Impact Rate of a Single-line Tether [yr^{-1} km^{-1}]								
	Tether Diameter								
	0.5 mm			0.75 mm			1 mm		
	DAS 1.5.3 ASI	ORDEM 2000 JAXA	MASTER 2001 JAXA	DAS 1.5.3 ASI	ORDEM 2000 JAXA	MASTER 2001 JAXA	DAS 1.5.3 ASI	ORDEM 2000 JAXA	MASTER 2001 JAXA
800-25	8.4	69.8	5.3	4.3	24.1	3.1	2.5	11.5	1.9
800-50	8.8	76.9	5.3	4.6	26.6	3.1	2.7	12.7	1.9
800-75	10.4	100.1	6.7	5.5	34.5	4.1	3.3	16.5	2.5
1000-25	8.1	103.0	5.2	4.3	34.2	3.2	2.6	15.9	2.0
1000-50	8.5	114.6	5.7	4.6	38.1	3.7	2.8	17.7	2.2
1000-75	9.9	151.8	7.4	5.4	49.5	4.8	3.3	22.8	2.9
1400-25	5.3	49.3	7.3	2.4	16.6	4.1	1.3	7.8	2.4
1400-50	4.9	54.0	8.1	2.4	18.3	4.7	1.4	8.6	2.7
1400-75	5.3	76.1	8.1	2.6	25.7	4.7	1.5	12.1	2.7

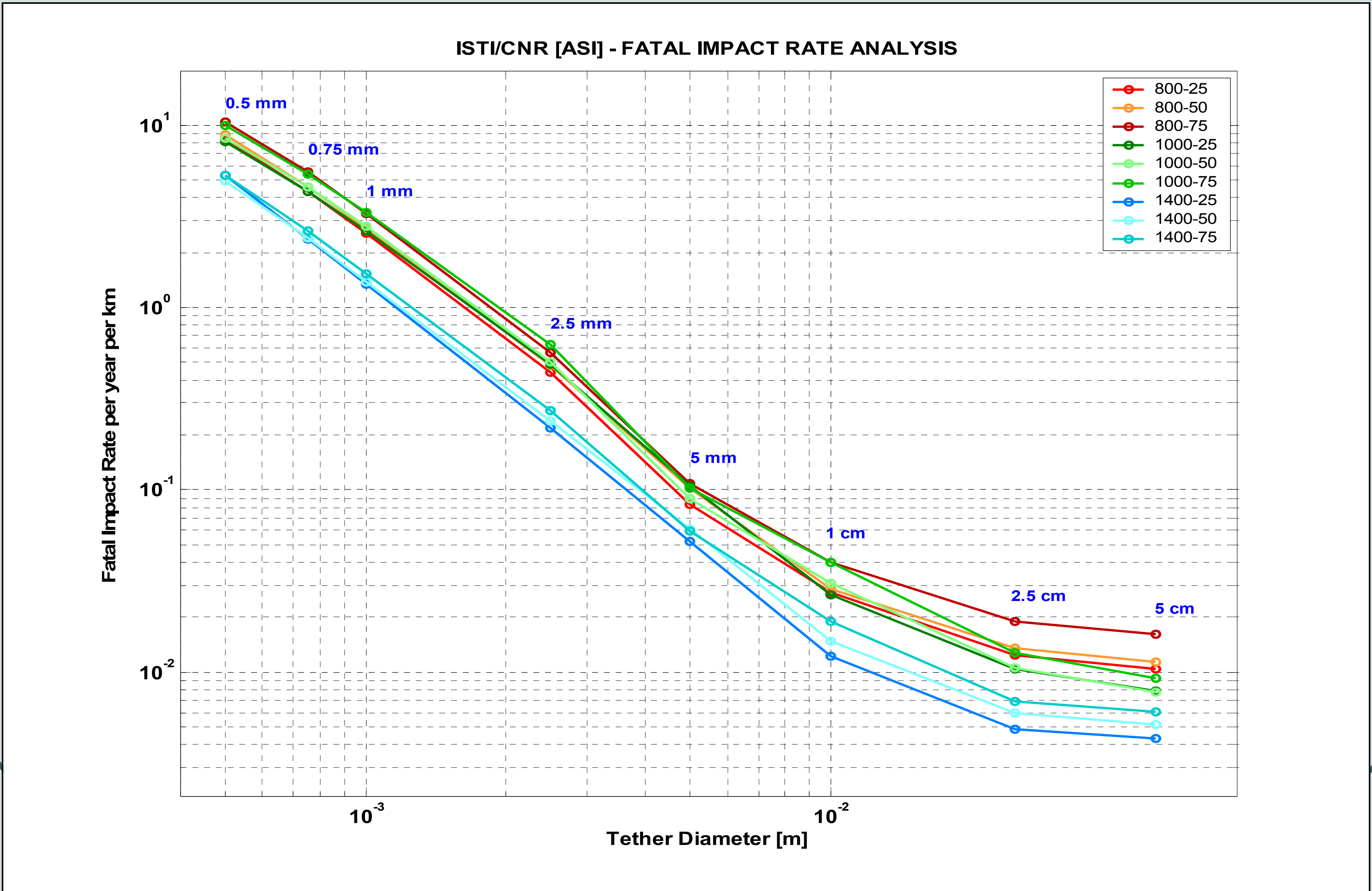
Test 1

Fatal Impact Rate Analysis: ASI Results

All Tether Diameters between 0.5 mm and 5 cm

Altitude and Inclination	Tether Diameter							
	0.50 mm	0.75 mm	1.00 mm	2.50 mm	5.00 mm	1.00 cm	2.50 cm	5.00 cm
	Fatal Debris Diameter [mm]							
	0.125	0.1875	0.25	0.625	1.25	2.5	6.25	12.5
	Critical Tether Diameter [mm]							
	0.35	0.525	0.7	1.75	3.5	7	17.5	35
	FATAL IMPACT RATE [yr^{-1} km^{-1}]							
800 km, 25°	8.38	4.31	2.55	0.441	0.083	0.027	0.012	0.010
800 km, 50°	8.80	4.56	2.69	0.479	0.102	0.029	0.013	0.011
800 km, 75°	10.41	5.50	3.26	0.566	0.108	0.040	0.019	0.016
1000 km, 25°	8.11	4.33	2.63	0.491	0.104	0.027	0.010	0.008
1000 km, 50°	8.52	4.56	2.78	0.506	0.090	0.031	0.010	0.008
1000 km, 75°	9.90	5.40	3.33	0.625	0.102	0.040	0.013	0.009
1400 km, 25°	5.30	2.37	1.35	0.218	0.052	0.012	0.005	0.004
1400 km, 50°	4.92	2.41	1.37	0.237	0.061	0.015	0.006	0.005
1400 km, 75°	5.30	2.64	1.53	0.271	0.060	0.019	0.007	0.006

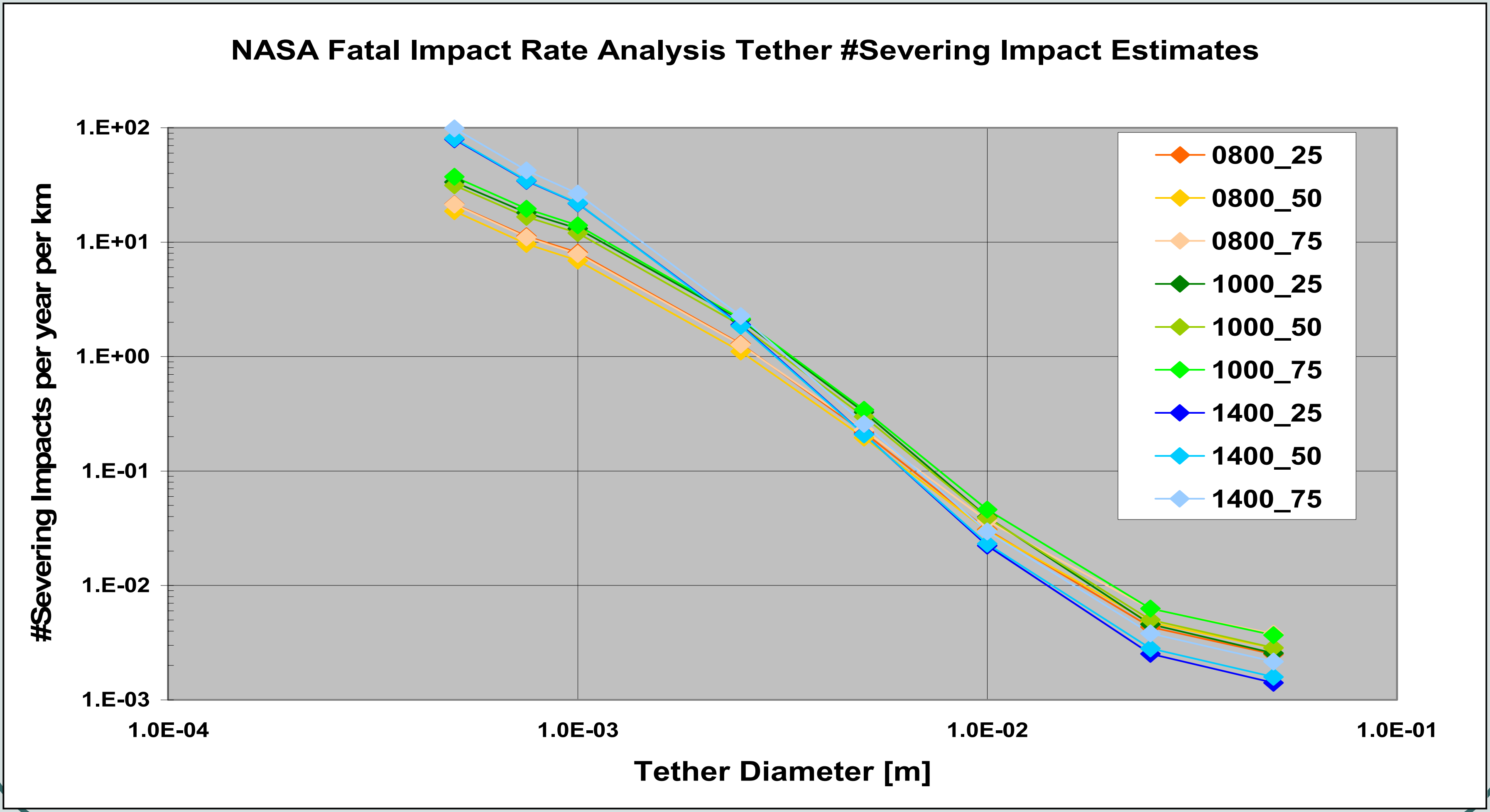
Test 1
Fatal Impact Rate Analysis
ASI Fatal Impact Rate



Test 1
Fatal Impact Rate Analysis: NASA Results
All Tether Diameters between 0.5 mm and 5 cm

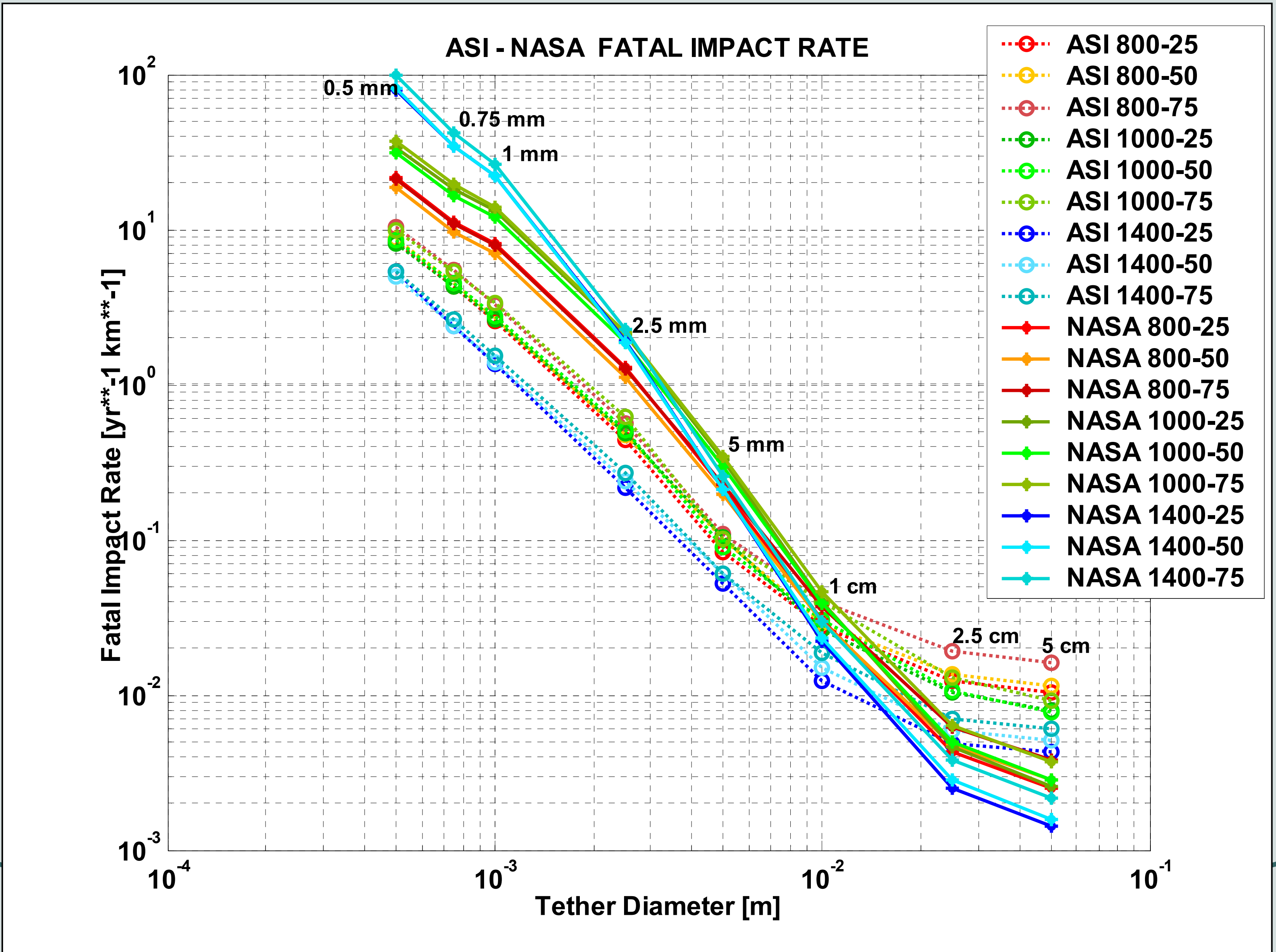
Tether Diameter [m]	ORBIT [altitude in km _ inclination in deg]								
	0800_25	0800_50	0800_75	1000_25	1000_50	1000_75	1400_25	1400_50	1400_75
	Fatal Impact Rate [yr^{-1} km^{-1}]								
5.00E-04	2.16E+01	1.87E+01	2.13E+01	3.35E+01	3.15E+01	3.73E+01	7.93E+01	8.08E+01	9.87E+01
7.50E-04	1.13E+01	9.68E+00	1.10E+01	1.81E+01	1.67E+01	1.96E+01	3.45E+01	3.47E+01	4.23E+01
1.00E-03	8.11E+00	6.93E+00	7.89E+00	1.32E+01	1.20E+01	1.40E+01	2.19E+01	2.19E+01	2.66E+01
2.50E-03	1.30E+00	1.11E+00	1.27E+00	2.10E+00	1.88E+00	2.14E+00	1.90E+00	1.86E+00	2.26E+00
5.00E-03	2.18E-01	1.96E-01	2.29E-01	3.27E-01	3.00E-01	3.43E-01	2.11E-01	2.09E-01	2.58E-01
1.00E-02	3.08E-02	3.01E-02	3.67E-02	3.97E-02	3.91E-02	4.60E-02	2.22E-02	2.31E-02	2.97E-02
2.50E-02	4.33E-03	4.76E-03	6.24E-03	4.59E-03	5.02E-03	6.30E-03	2.53E-03	2.82E-03	3.81E-03
5.00E-02	2.50E-03	2.83E-03	3.80E-03	2.56E-03	2.86E-03	3.68E-03	1.41E-03	1.59E-03	2.17E-03

Test 1
Fatal Impact Rate Analysis
NASA Fatal Impact Rate



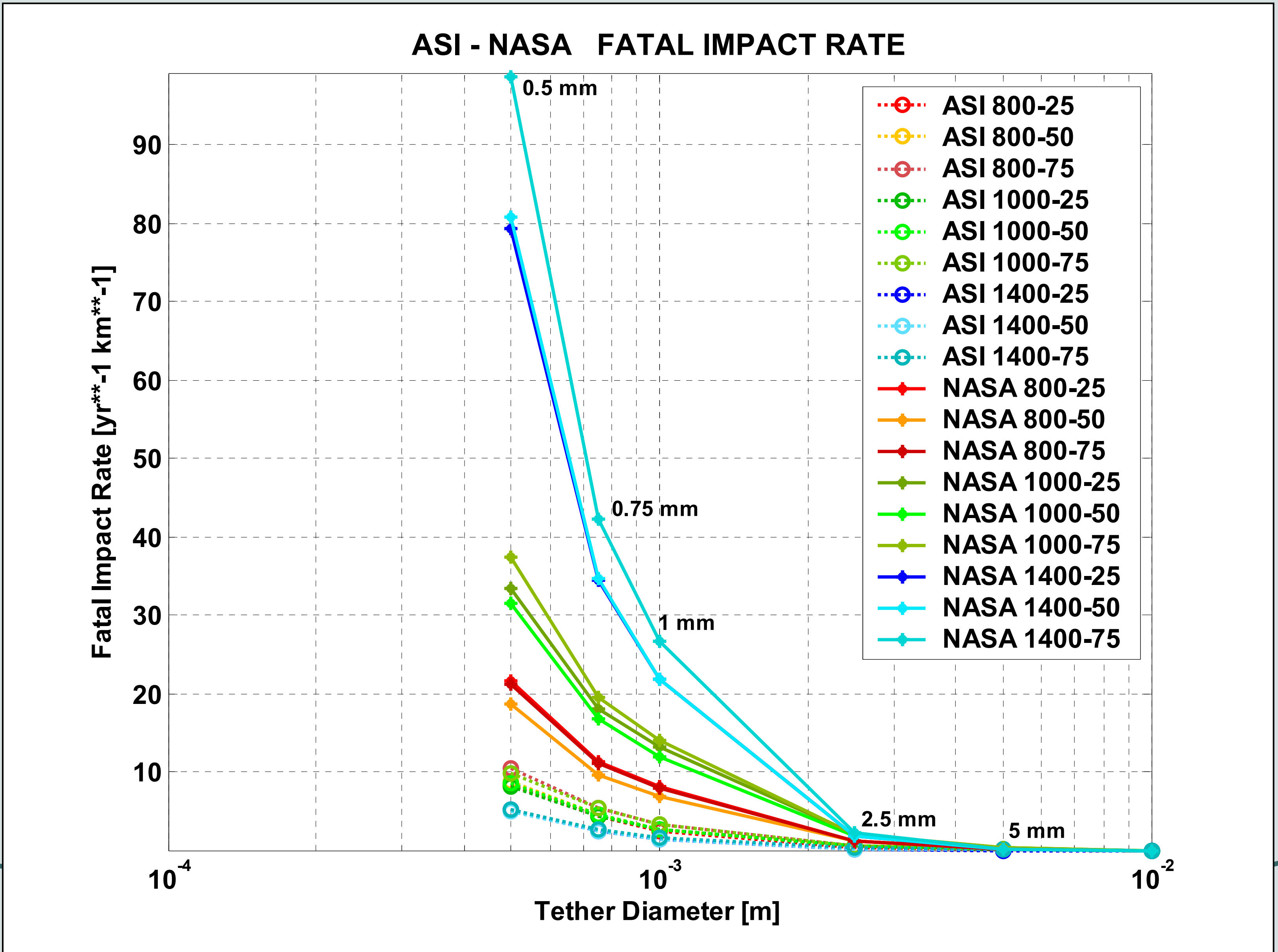
Fatal Impact Rate Analysis

ASI - NASA Fatal Impact Rate Comparison

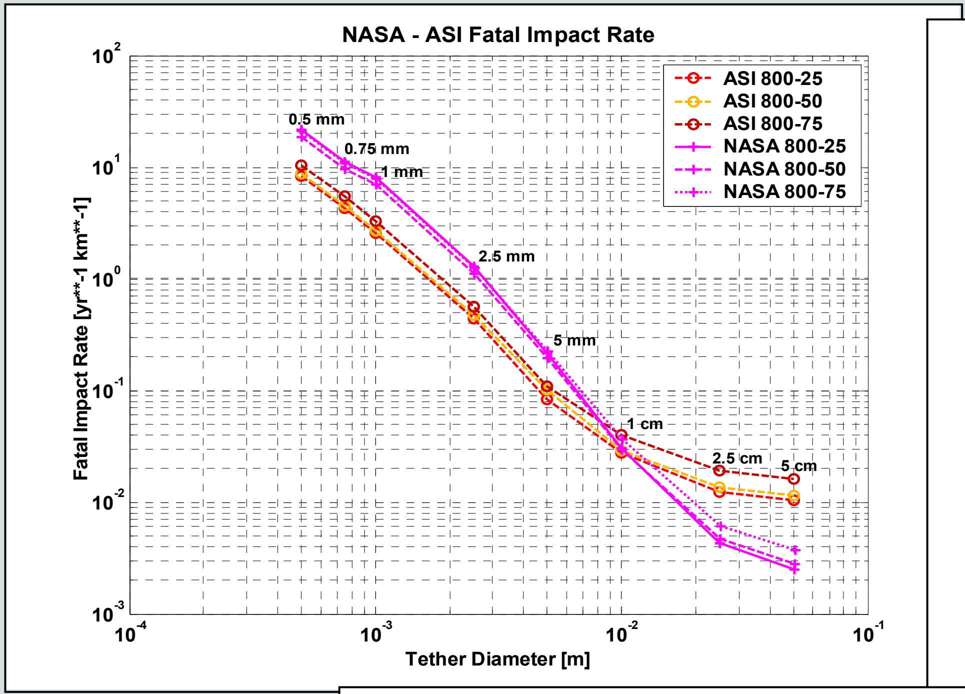


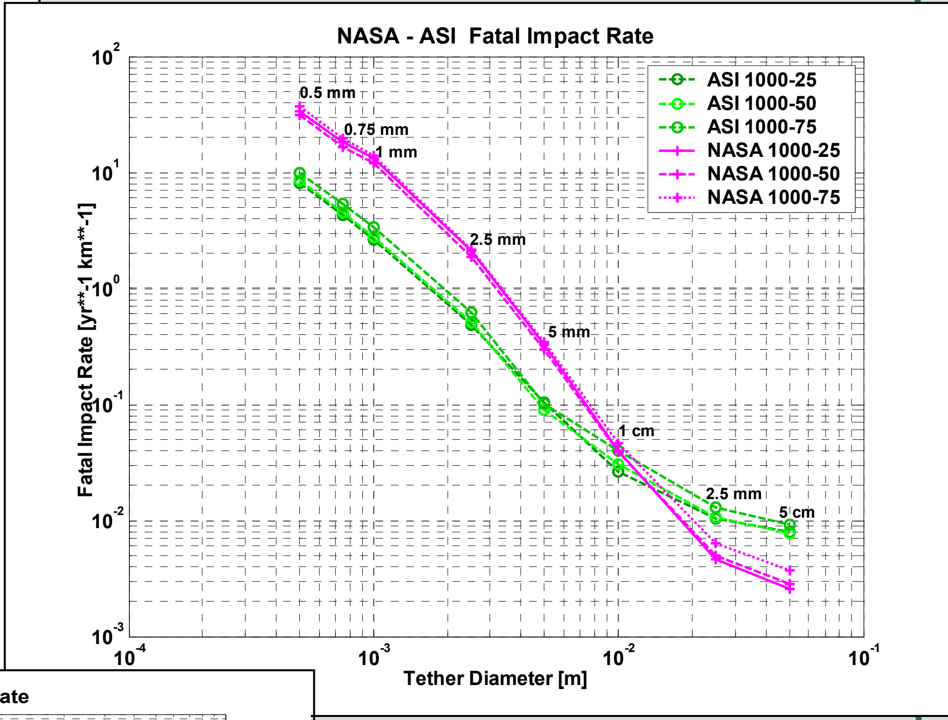
Fatal Impact Rate Analysis

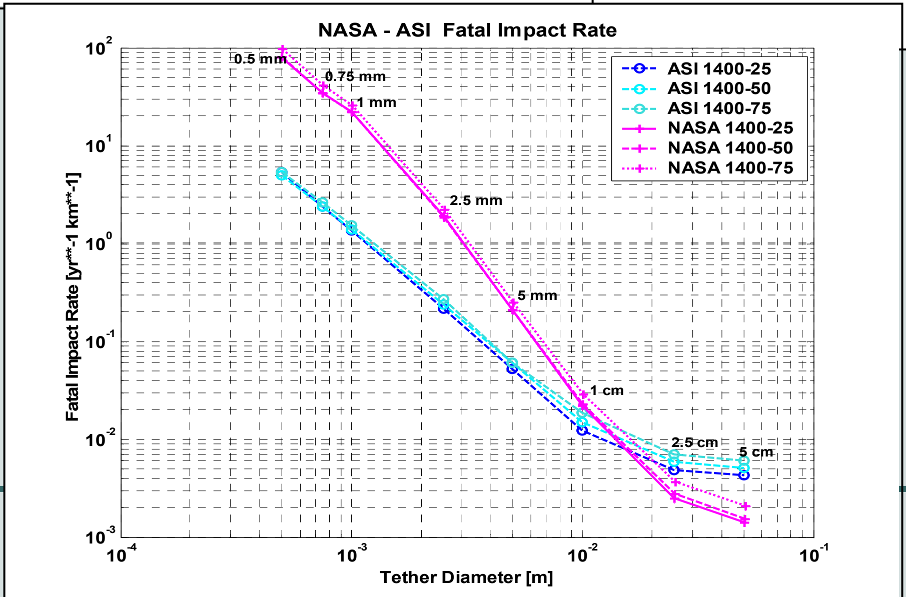
ASI - NASA Fatal Impact Rate Comparison



ASI - NASA Fatal Impact Rate Comparison





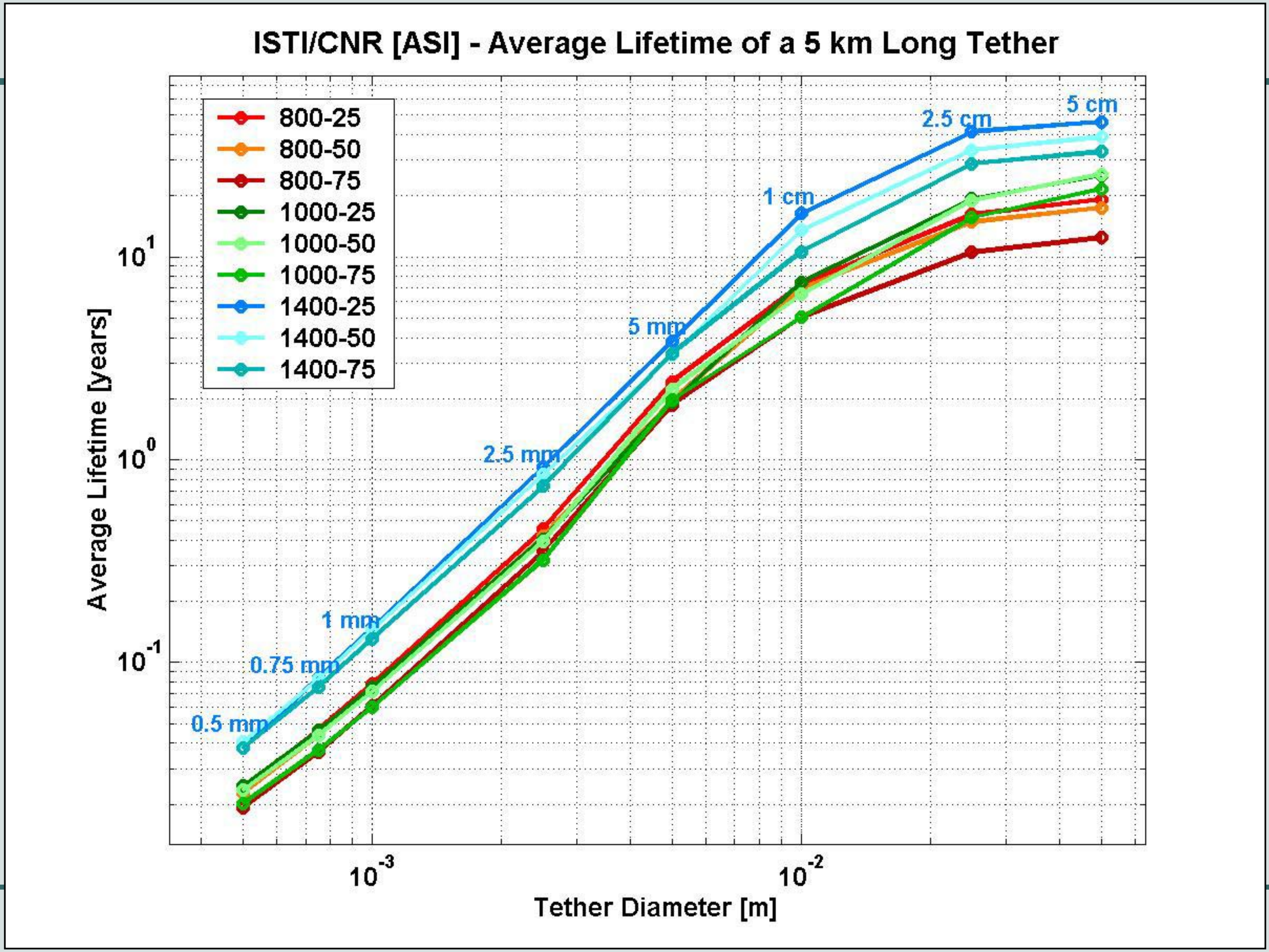


Fatal Impact Rate Analysis

ASI – Average Lifetime of a 5 km Long Tether

AVERAGE LIFETIME of a 5 km Long Tether								
	Tether Diameter							
Altitude and Inclination	0.5 mm	0.75mm	1 mm	2.5 mm	5 mm	1 cm	2.5 cm	5 cm
	Days				**Years**			
800 km, 25°	8.7	16.9	28.7	165.6	2.42	7.30	16.13	19.21
800 km, 50°	8.3	16.0	27.2	152.6	1.96	6.96	14.85	17.48
800 km, 75°	7.0	13.3	22.4	128.9	1.85	5.03	10.51	12.44
1000 km, 25°	9.0	16.9	27.7	148.7	1.91	7.51	19.25	25.28
1000 km, 50°	8.6	16.0	26.3	144.3	2.23	6.54	18.97	25.57
1000 km, 75°	7.4	13.5	21.9	116.8	1.96	5.03	15.55	21.67
1400 km, 25°	13.8	30.8	54.2	335.6	3.86	16.30	41.24	46.40
1400 km, 50°	14.8	30.3	53.1	308.6	3.27	13.51	33.50	38.99
1400 km, 75°	13.8	27.6	47.8	270.0	3.34	10.61	28.78	33.06

Fatal Impact Rate Analysis
ASI – Average Lifetime of a 5 km Long Tether



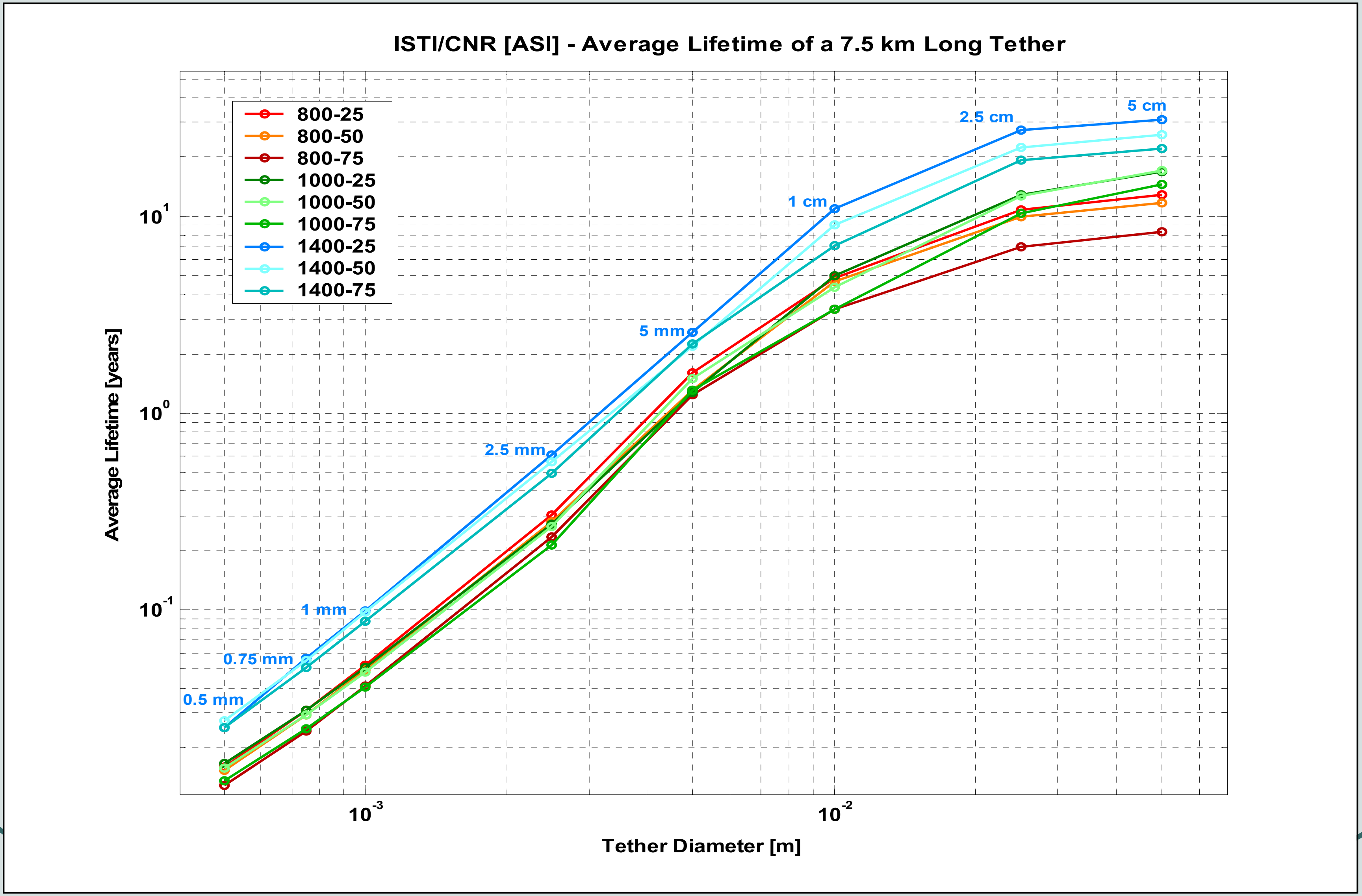
Fatal Impact Rate Analysis

ASI – Average Lifetime of a 7.5 km Long Tether

AVERAGE LIFETIME of a 7.5 km Long Tether								
	Tether Diameter							
Altitude and Inclination	0.5 mm	0.75mm	1 mm	2.5 mm	5 mm	1 cm	2.5 cm	5 cm
	Days				Years			
800 km, 25°	5.8	11.3	19.1	110.4	1.61	4.87	10.75	12.81
800 km, 50°	5.5	10.7	18.1	101.8	1.30	4.64	9.90	11.65
800 km, 75°	4.7	8.8	14.9	86.0	1.24	3.36	7.01	8.29
1000 km, 25°	6.0	11.2	18.5	99.1	1.28	5.01	12.83	16.86
1000 km, 50°	5.7	10.7	17.5	96.2	1.49	4.36	12.65	17.05
1000 km, 75°	4.9	9.0	14.6	77.9	1.31	3.35	10.37	14.44
1400 km, 25°	9.2	20.5	36.1	223.7	2.57	10.87	27.49	30.94
1400 km, 50°	9.9	20.2	35.4	205.8	2.18	9.01	22.33	26.00
1400 km, 75°	9.2	18.4	31.8	180.0	2.23	7.07	19.18	22.04

Fatal Impact Rate Analysis

ASI – Average Lifetime of a 7.5 km Long Tether



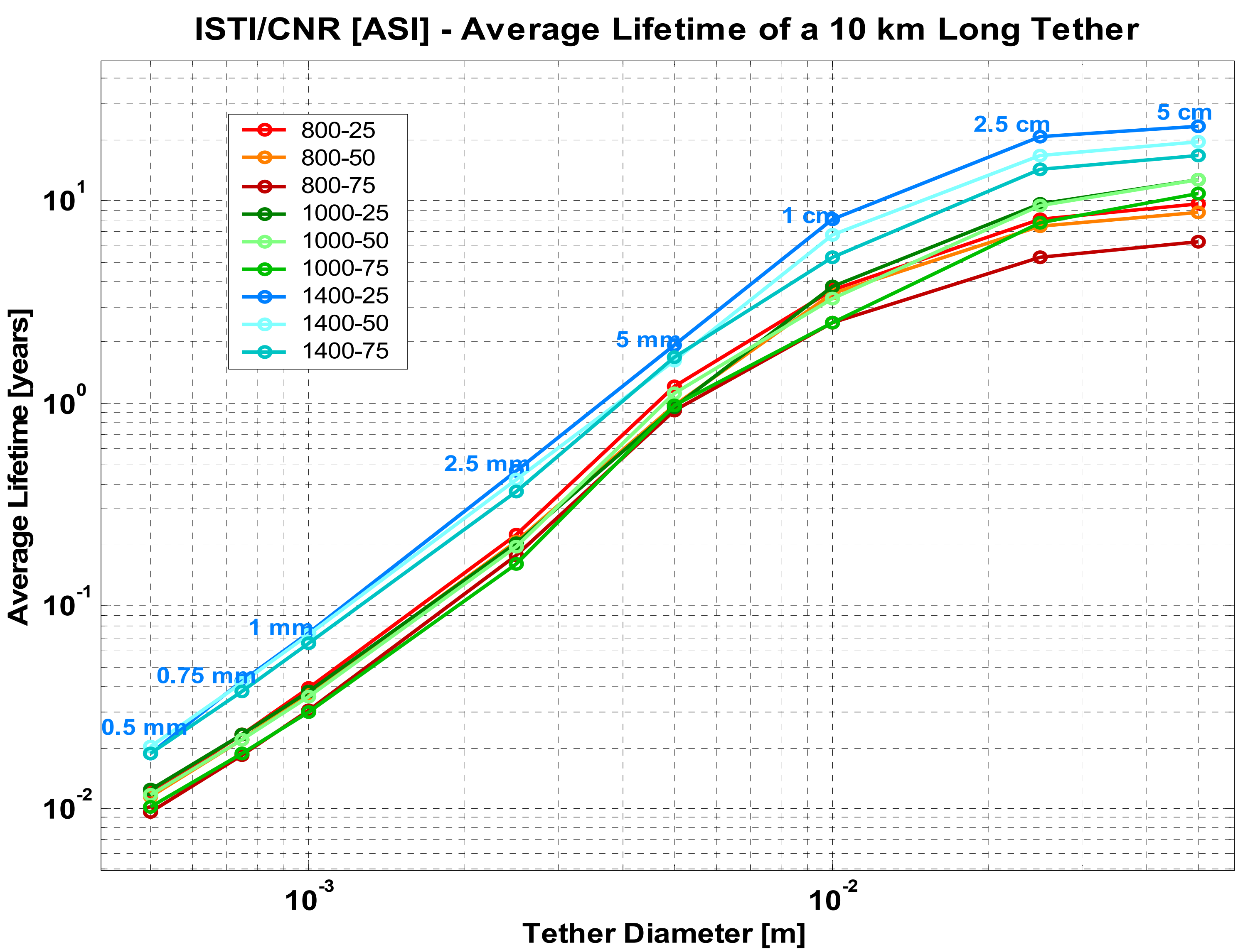
Fatal Impact Rate Analysis

ASI – Average Lifetime of a 10 km Long Tether

AVERAGE LIFETIME of a 10 km Long Tether								
	Tether Diameter							
Altitude and Inclination	0.5 mm	0.75mm	1 mm	2.5 mm	5 mm	1 cm	2.5 cm	5 cm
	Days				**Years**			
800 km, 25°	4.4	8.5	14.3	82.8	1.21	3.65	8.06	9.61
800 km, 50°	4.1	8.0	13.6	76.3	0.98	3.48	7.42	8.74
800 km, 75°	3.5	6.6	11.2	64.5	0.93	2.52	5.26	6.22
1000 km, 25°	4.5	8.4	13.9	74.4	0.96	3.75	9.62	12.64
1000 km, 50°	4.3	8.0	13.1	72.1	1.12	3.27	9.49	12.79
1000 km, 75°	3.7	6.8	11.0	58.4	0.98	2.52	7.78	10.83
1400 km, 25°	6.9	15.4	27.1	167.8	1.93	8.15	20.62	23.20
1400 km, 50°	7.4	15.1	26.6	154.3	1.64	6.76	16.75	19.49
1400 km, 75°	6.9	13.8	23.9	135.0	1.67	5.30	14.39	16.53

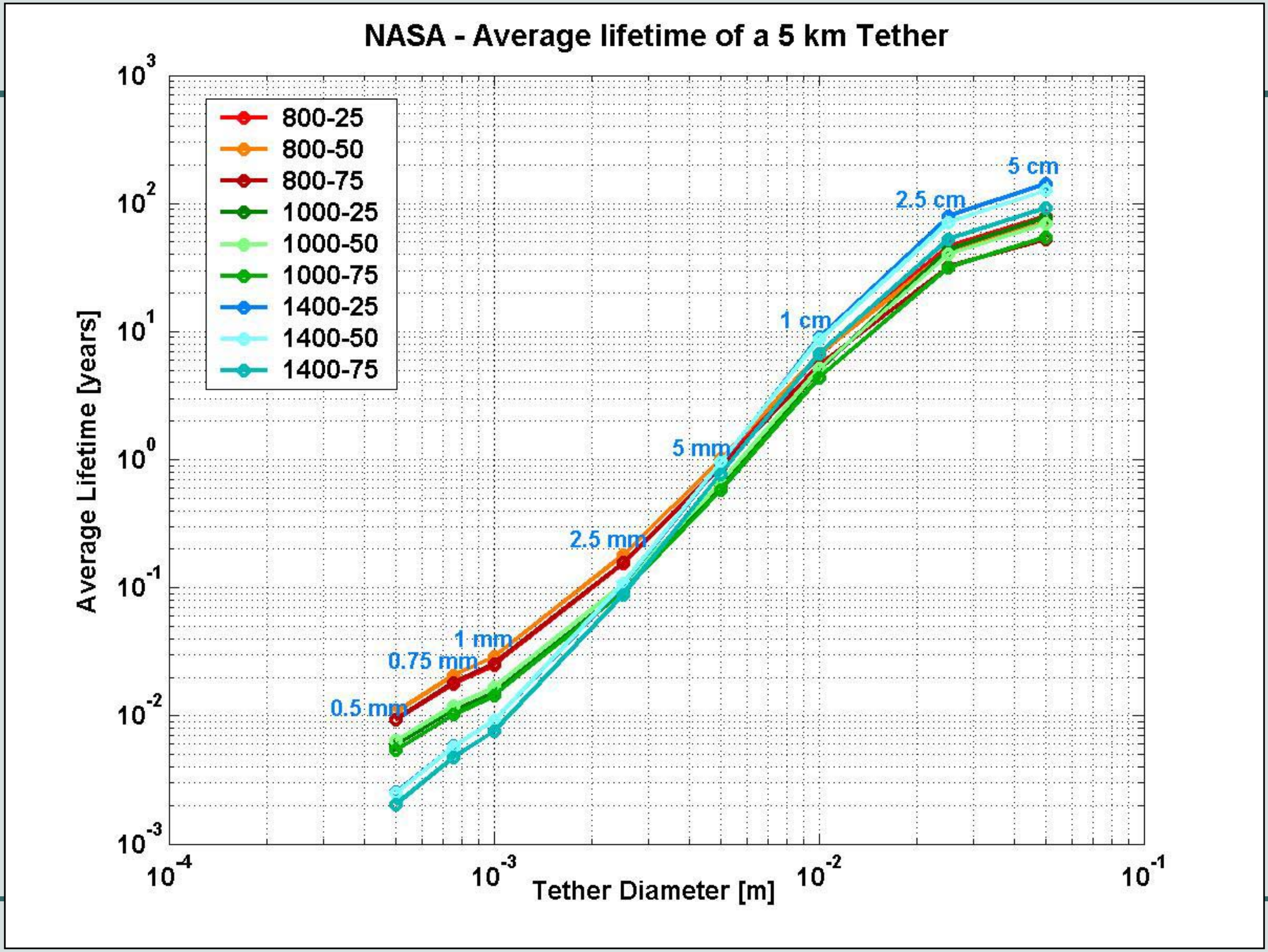
Fatal Impact Rate Analysis

ASI – Average Lifetime of a 10 km Long Tether



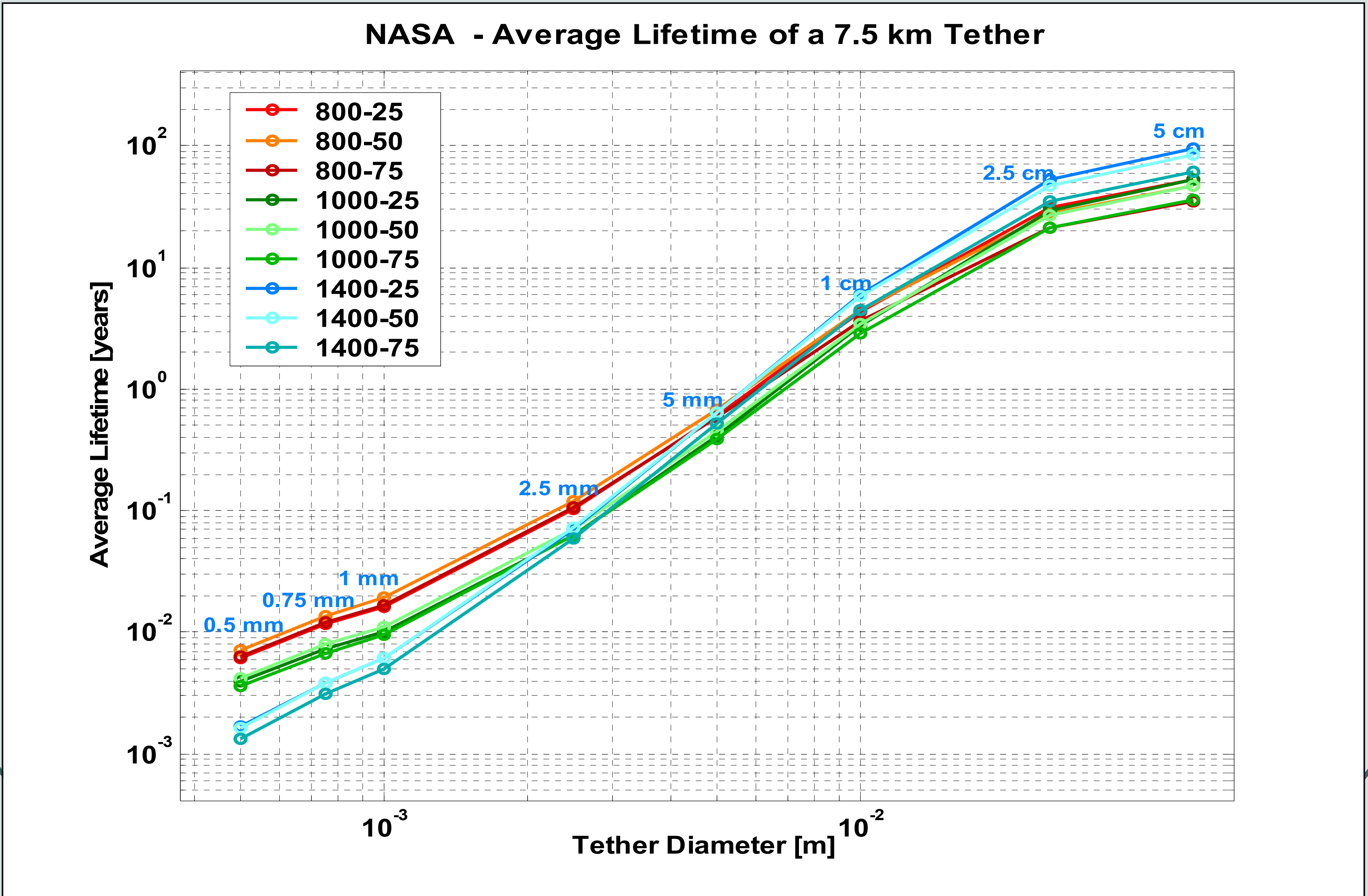
Fatal Impact Rate Analysis

NASA – Average Lifetime of a 5 km Long Tether



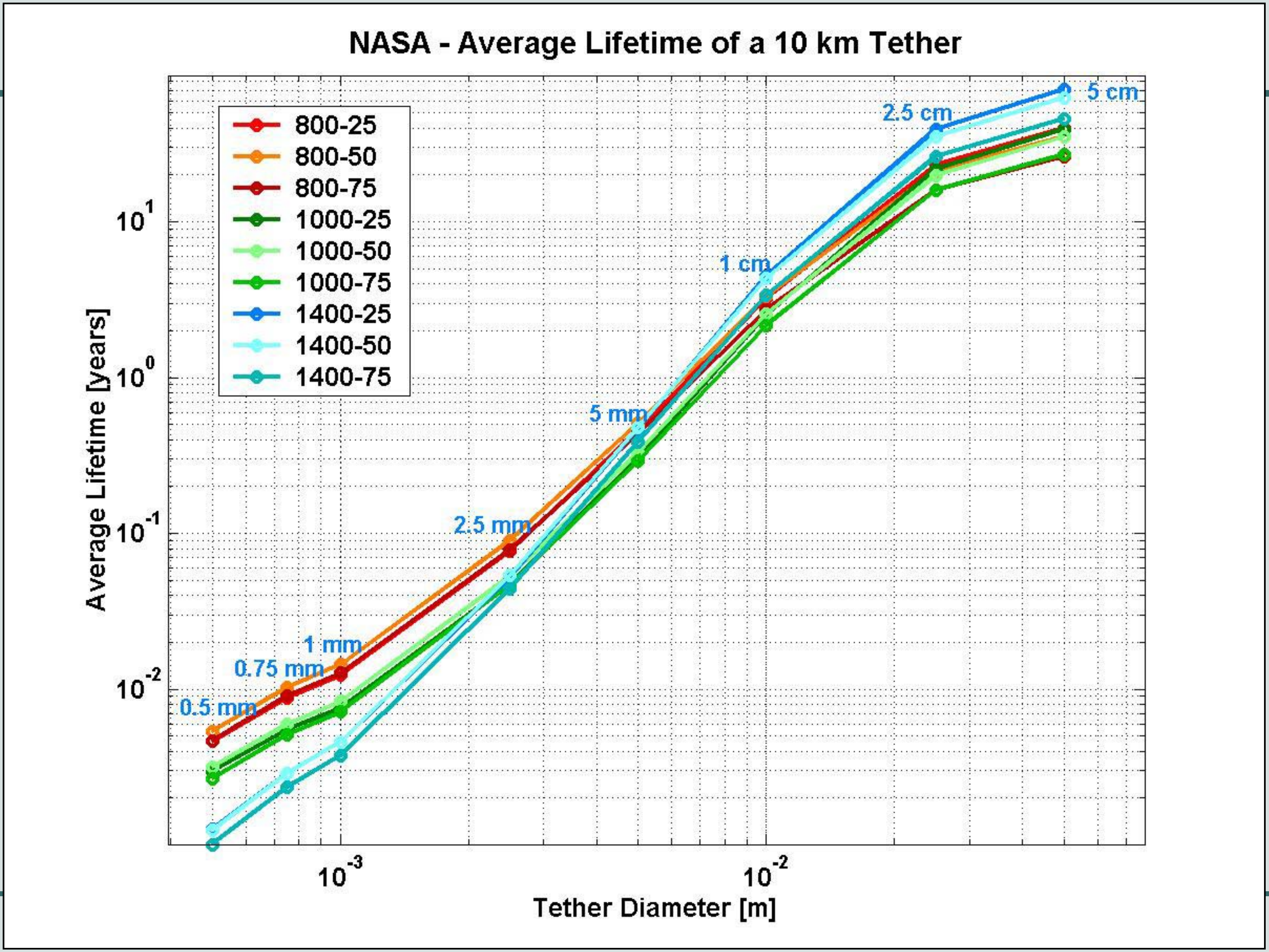
Fatal Impact Rate Analysis

NASA – Average Lifetime of a 7.5 km Long Tether



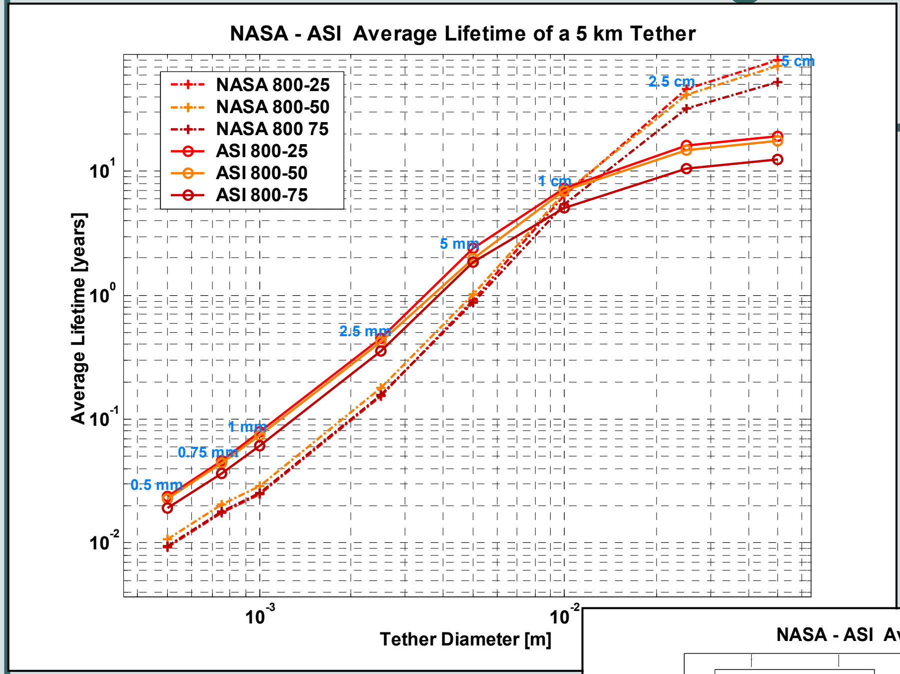
Fatal Impact Rate Analysis

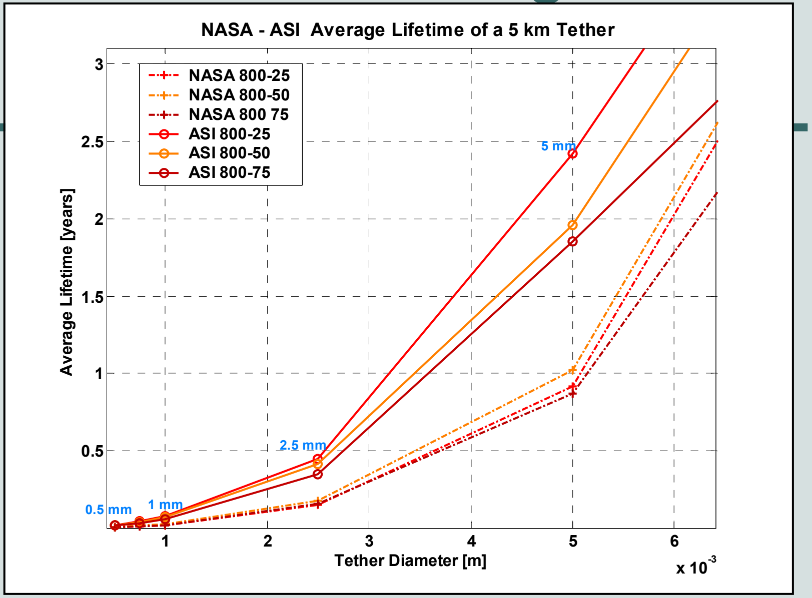
NASA – Average Lifetime of a 10 km Long Tether

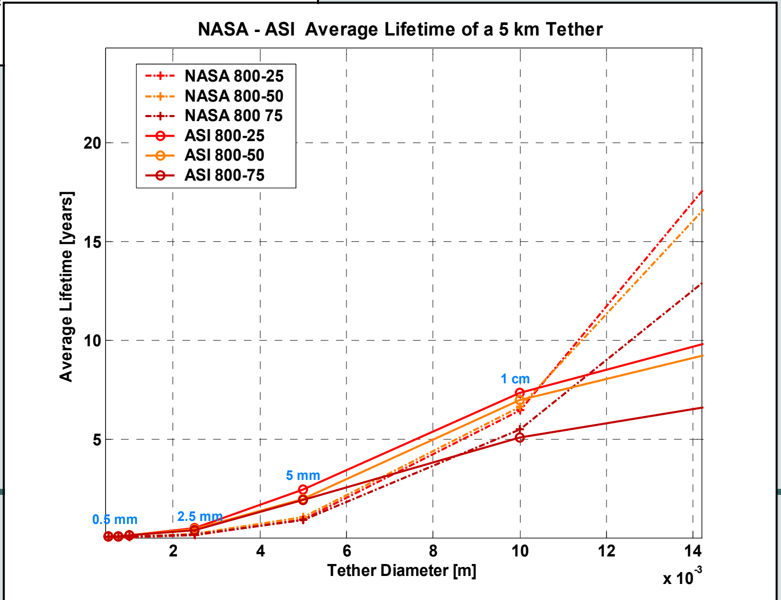


Fatal Impact Rate Analysis

ASI - NASA – Average Lifetime of a 5 km Long Tether



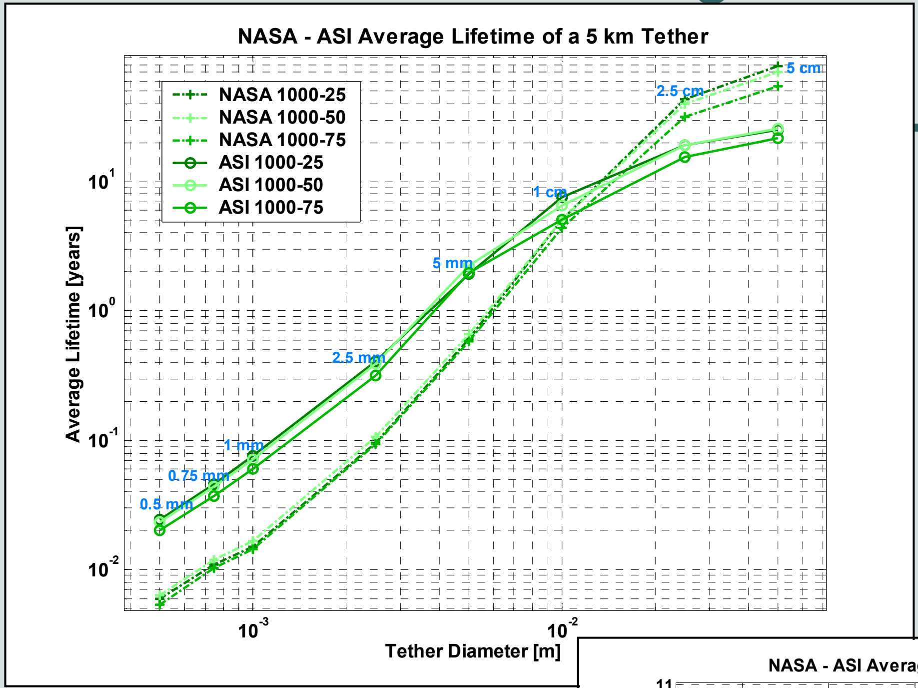


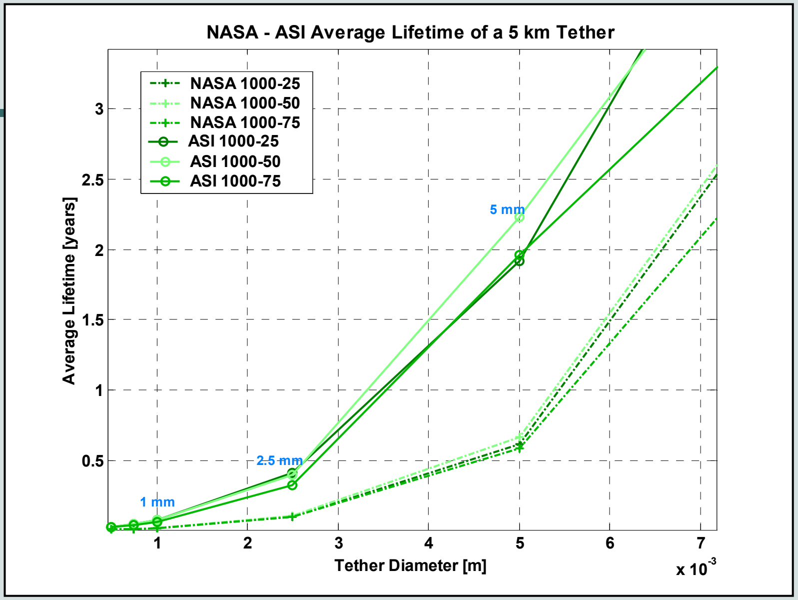


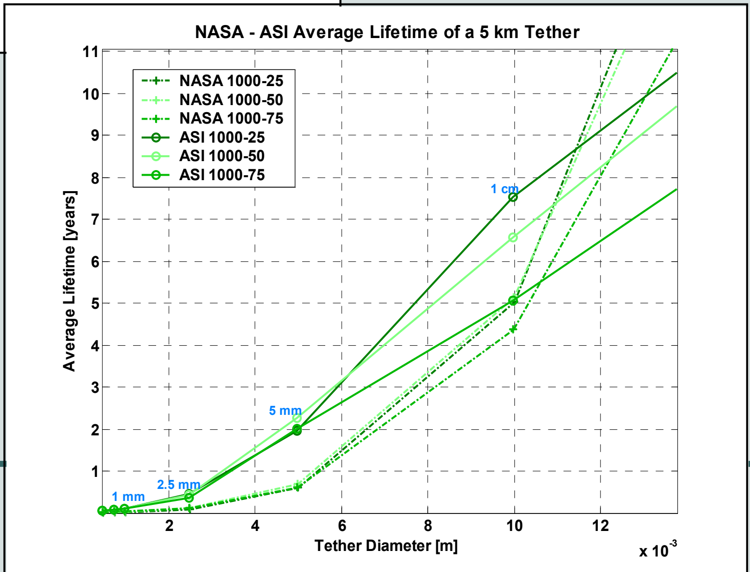
Orbit Altitude 800 km

Fatal Impact Rate Analysis

ASI - NASA – Average Lifetime of a 5 km Long Tether



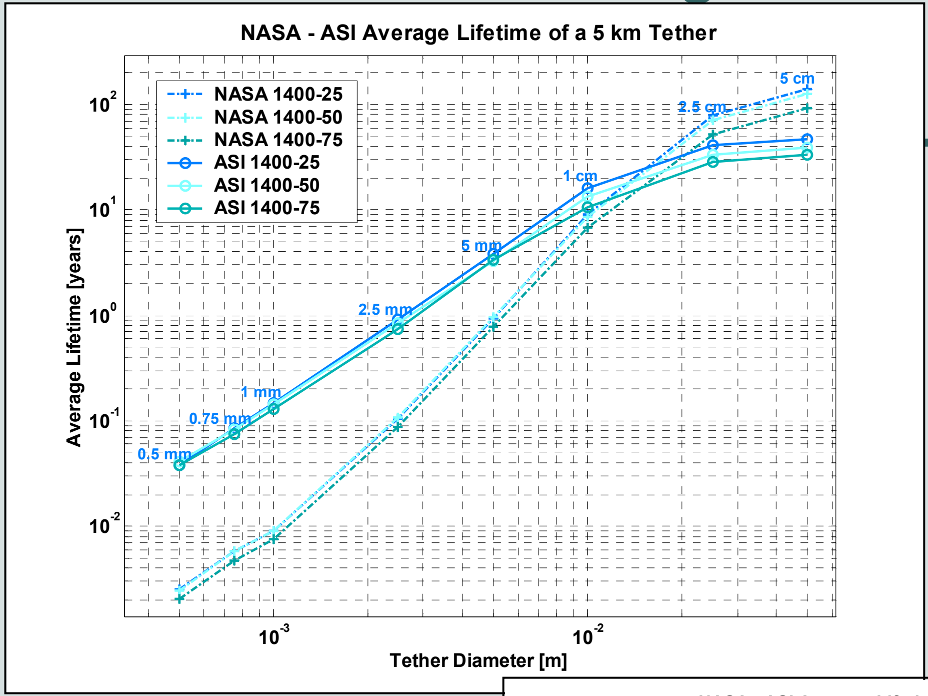


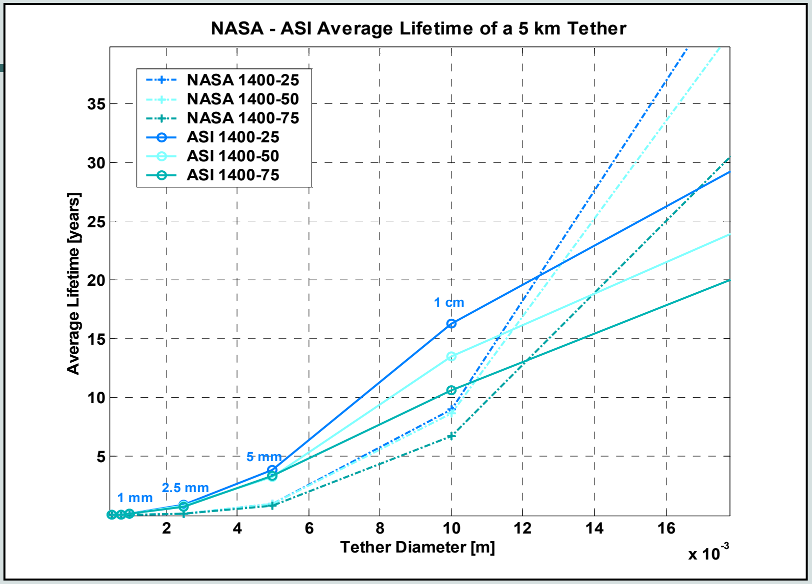


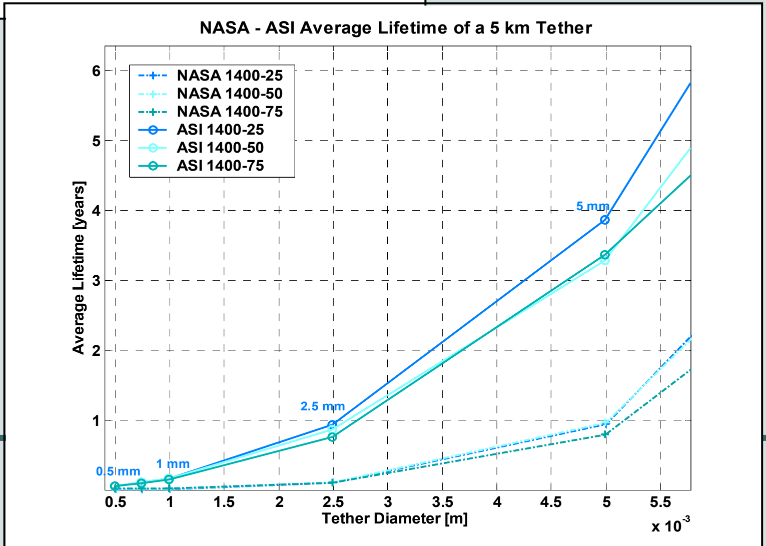
Orbit Altitude
1000 km

Fatal Impact Rate Analysis

ASI - NASA – Average Lifetime of a 5 km Long Tether







Orbit Altitude
1400 km

Fatal Impact Rate Analysis

ASI – Impact Rate with Large Space Objects

Altitude & Inclination	Impact Rate [yr^{-1} km^{-1}] with Space Debris ≥ 10 cm
800 km, 25° 800 km, 50° 800 km, 75°	9.2E-3 9.8E-3 1.4E-2
1000 km, 25° 1000 km, 50° 1000 km, 75°	6.5E-3 6.2E-3 6.8E-3
1400 km, 25° 1400 km, 50° 1400 km, 75°	3.8E-3 4.5E-3 5.2E-3

Altitude & Inclination	Impact Rate [$yr^{-1}km^{-1}$] with Space Debris ≥ 1 m
800 km, 25° 800 km, 50° 800 km, 75°	8.1E-3 8.7E-3 1.3E-2
1000 km, 25° 1000 km, 50° 1000 km, 75°	5.8E-3 5.4E-3 5.6E-3
1400 km, 25° 1400 km, 50° 1400 km, 75°	3.5E-3 4.2E-3 4.7E-3

Survivability Analysis

JAXA – Survival Probability [%] of a 7.5 km Long Single-Line Tether

ORDEM 2000				
Initial Altitude [km]	Inclination			
	0°	25°	50°	75°
Tether Diameter = 0.5 mm				
1400	0.0	0.0	0.0	–
1000	0.0	0.0	0.0	0.0
800	0.0	0.0	0.0	0.0
Tether Diameter = 0.75 mm				
1400	0.0	0.0	0.0	–
1000	0.0	0.0	0.0	0.0
800	0.0	0.0	0.2	0.0
Tether Diameter = 1 mm				
1400	0.0	0.0	0.0	–
1000	0.0	0.0	0.0	0.0
800	2.5	1.7	5.7	0.0

MASTER 2001				
Initial Altitude [km]	Inclination			
	0°	25°	50°	75°
Tether Diameter = 0.5 mm				
1400	0.0	0.0	0.0	–
1000	0.3	0.0	0.0	0.0
800	6.2	3.5	0.5	0.0
Tether Diameter = 0.75 mm				
1400	0.0	0.0	0.0	–
1000	3.8	0.8	0.0	0.0
800	20.5	15.7	5.1	0.0
Tether Diameter = 1 mm				
1400	0.0	0.6	0.0	–
1000	15.7	6.3	1.0	0.0
800	41.0	36.2	19.2	0.6

Survivability Analysis

JAXA – Double-Line Tether Design

The Risk Analysis of Space Debris on Space Tethers

1. Method

Single Tether

Number of times of cutting the tether by space debris can be expressed as

$$N_{cuts} = \int P_c(D) \cdot A \cdot dF(D)$$

where P_c is the cutting efficiency, A is the collision area, and dF is the debris flux between D and D+dD.

The debris diameter to sever the tether is

$$d \geq 0.25\delta$$

where δ is tether's diameter.

Double Tether

Fig.1 shows schematic diagram of the double tether. M is the numbers of the knots.

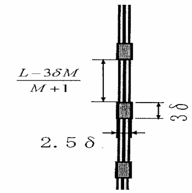
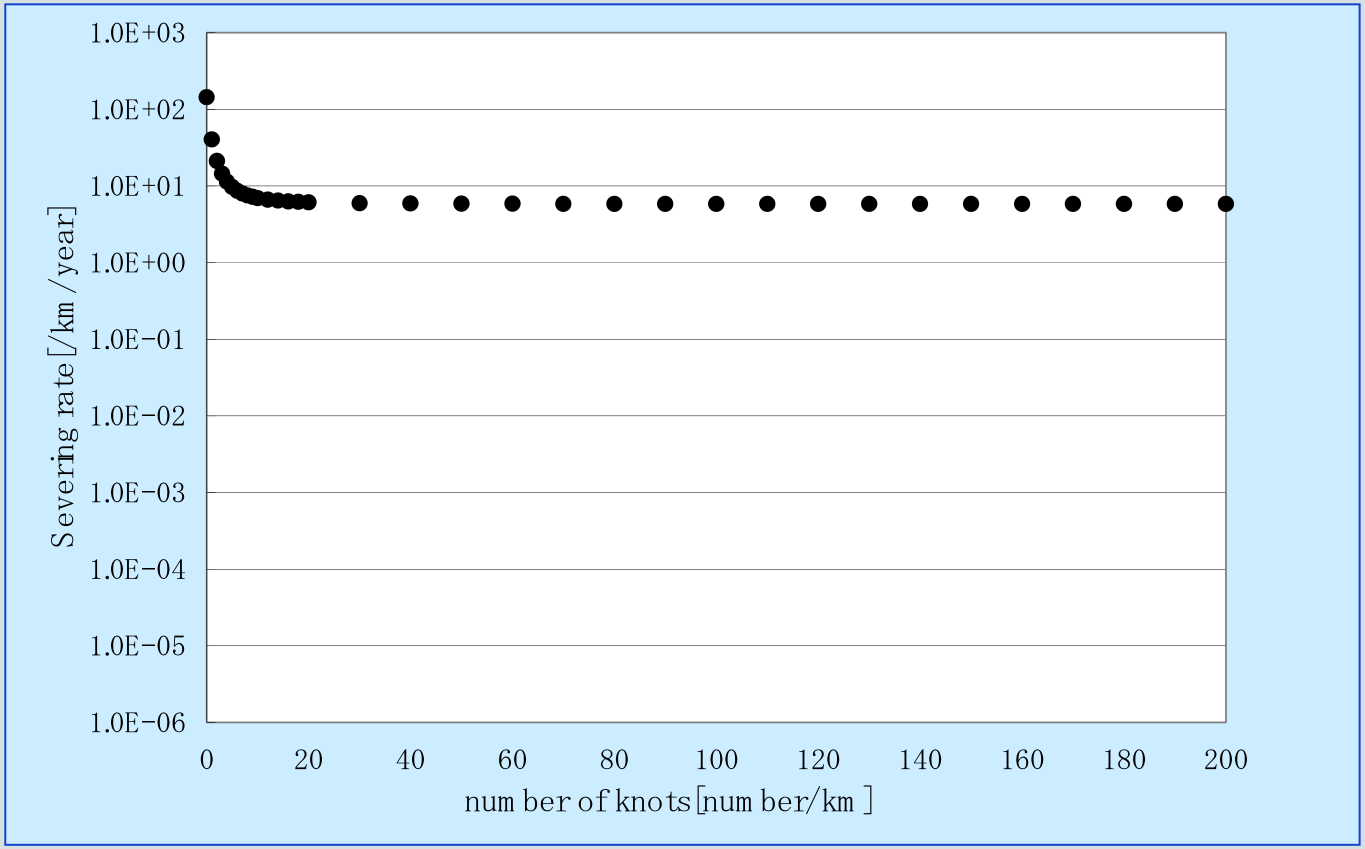


Fig.1 Double tether

Double tether will be severed for the three cases, 1)the knot is severed, 2)the two tethers are severed by one impact, 3)the two tethers are severed by two different debris each. The distance between the two tethers is 0mm.

Survivability Analysis

JAXA – Effect of Number of Knots on a Double-Line Tether (Altitude = 800 km, Inclination = 0°, Tether ∅ = 0.5 mm]



Survivability Analysis

JAXA – Survival Probability [%] of a 7.5 km Double-Line Tether Knots Spaced by 10 m

ORDEM 2000				
Initial Altitude [km]	Inclination			
	0°	25°	50°	75°
Tether Diameter = 0.5 mm				
1400	0.0	0.0	0.0	–
1000	0.1	0.0	0.0	0.0
800	15.4	12.8	23.3	0.9
Tether Diameter = 0.75 mm				
1400	0.4	0.0	0.0	–
1000	9.4	2.6	2.3	0.0
800	52.2	48.9	59.4	18.6
Tether Diameter = 1 mm				
1400	8.4	3.3	0.1	–
1000	33.8	19.0	17.4	0.2
800	74.1	71.9	78.3	45.5

MASTER 2001				
Initial Altitude [km]	Inclination			
	0°	25°	50°	75°
Tether Diameter = 0.5 mm				
1400	2.2	0.5	0.0	–
1000	25.9	13.3	3.8	0.0
800	51.5	45.4	27.9	1.8
Tether Diameter = 0.75 mm				
1400	13.5	6.2	1.1	–
1000	49.3	35.0	17.7	0.3
800	71.0	67.3	52.6	13.3
Tether Diameter = 1 mm				
1400	33.9	22.1	8.7	–
1000	67.7	55.5	37.6	3.6
800	83.0	80.6	69.9	32.7

Survivability Analysis

ASI – Survival Probability [%] of a 7.5 km Long Single-Line Tether (DAS 1.5.3)

Tether Diameter: 0.5 mm

Inclination	0°	25°	50°	75°
De-orbiting Altitude	Survival Probability [%]			
1400 km	0	0	0	-
1000 km	0	0	0	0
800 km	0	0	0	0

Tether Diameter: 1 mm

Inclination	0°	25°	50°	75°
De-orbiting Altitude	Survival Probability [%]			
1400 km	0	0	0	-
1000 km	3	0	0	0
800 km	22	16	6	0

Survivability Analysis

ASI – Survival Probability [%] of a 7.5 km Long Double-Line Tether Knots Spaced by 100 m (DAS 1.5.3)

Line Diameter: 0.5 mm

Inclination	0°	25°	50°	75°
De-orbiting Altitude	**Survival Probability [%]**			
1400 km	48	24	5	-
1000 km	68	42	16	0
800 km	89	86	68	3

Inclination	0°	25°	50°	75°
De-orbiting Altitude	**Sever Probability [%]**			
1400 km	52	76	95	-
1000 km	32	58	84	100
800 km	11	14	32	97

Survivability Analysis

ASI – Survival Probability [%] of a 7.5 km Long Double-Line Tether Knots Spaced by 10 m (DAS 1.5.3)

Line Diameter: 0.5 mm

Inclination	0°	25°	50°	75°
De-orbiting Altitude	**Survival Probability [%]**			
1400 km	93	86	72	-
1000 km	96	91	82	9
800 km	99	98	96	67

Inclination	0°	25°	50°	75°
De-orbiting Altitude	**Sever Probability [%]**			
1400 km	7	14	28	-
1000 km	4	9	18	91
800 km	1	2	4	33

Survivability Analysis

ASI – Survival Probability [%] of a 7.5 km Long Double-Line Tether Knots Spaced by 5 m (DAS 1.5.3)

Line Diameter: 0.5 mm

Inclination	0°	25°	50°	75°
De-orbiting Altitude	Survival Probability [%]			
1400 km	96	93	85	-
1000 km	98	95	90	29
800 km	99	99	98	82

Inclination	0°	25°	50°	75°
De-orbiting Altitude	Sever Probability [%]			
1400 km	4	7	15	-
1000 km	2	5	10	71
800 km	1	1	2	18

Survivability Analysis

ASI – Survival Probability [%] of a 7.5 km Long Double-Line Tether Knots Spaced by 5 m (DAS 1.5.3)

Line Diameter: 1 mm

Inclination	0°	25°	50°	75°
De-orbiting Altitude	Survival Probability [%]			
1400 km	100	99	98	-
1000 km	100	99	99	86
800 km	100	100	100	99

Inclination	0°	25°	50°	75°
De-orbiting Altitude	Sever Probability [%]			
1400 km	0	1	2	-
1000 km	0	1	1	14
800 km	0	0	0	1

Survivability Analysis

ASI – Survival Probability [%] of a 7.5 km Long Double-Line Tether Knots Spaced by 5 m (MASTER 2001)

Line Diameter: 1 mm

Inclination	0°	25°	50°	75°
De-orbiting Altitude	Survival Probability [%]			
1400 km	100	100	99	-
1000 km	100	100	100	98
800 km	100	100	100	100

Inclination	0°	25°	50°	75°
De-orbiting Altitude	Sever Probability [%]			
1400 km	0	0	1	-
1000 km	0	0	0	2
800 km	0	0	0	0

Survivability Analysis

ASI – Survival Probability [%] of a 7.5 km Long Double-Line Tether Knots Spaced by 5 m (ORDEM 2000)

Line Diameter: 1 mm

Inclination	0°	25°	50°	75°
De-orbiting Altitude	Survival Probability [%]			
1400 km	84	73	56	-
1000 km	99	97	96	62
800 km	99	99	98	85

Inclination	0°	25°	50°	75°
De-orbiting Altitude	Sever Probability [%]			
1400 km	16	27	44	-
1000 km	1	3	4	38
800 km	1	1	2	15

Conclusions

A massive and detailed study was carried out by **ASI**, **JAXA** and **NASA**

1. To estimate the **Fatal Impact Rate (FIR)** of meteoroids & OD on space tethers, at different altitudes & inclinations, as a function of the tether diameter;

2. To assess the **Survival Probability (SP)** of a particular Electrodynamic Tether system during some baseline de-orbiting missions,

by assuming specific fatal debris diameters and tether severing conditions.

- A single-line tether was adopted for test 1, with diameter in between 0.5 mm and 5 cm.
- Both single-line and double-line tethers were considered for test 2 with diameter of 0.5 mm or 1 mm for each single-line. A particular tether design was assumed in the double-line configuration.

Conclusions
Test 1 – Fatal Impact Rate

ASI and NASA estimated the FIR for all proposed tether diameters, i.e. from 0.5 mm to 5 cm
JAXA estimated the FIR for tether diameters of 0.5 mm, 0.75 mm and 1 mm.

For tether diameters of 0.5 mm, 0.75 mm and 1 mm

- The ASI FIR is in good agreement with the JAXA FIR using MASTER 2001 for all orbit altitudes & inclinations considered;
- The ASI & JAXA (MASTER 2001) FIR are lower than the NASA FIR by a factor 2-3 at 800 and 1000 km and by one order of magnitude at 1400 km for a tether diameter of 0.5 mm;
- The ASI average lifetime of a 5 km long tether is less than 1 month at 800 km and 1000 km for all orbit inclinations considered and less than 2 months at 1400 km, the lifetime computed by NASA is still smaller.

Provided the hypotheses assumed are correct, the FIR on a single-line tether with $\varnothing \leq 1$ mm is rather high and the tether lifetime might be too short to enable the feasibility of typical de-orbiting missions using electrodynamic tether devices

Conclusions
Test 1 – Fatal Impact Rate

For tether diameters larger than 2.5 mm

- The ASI FIR is smaller than the NASA FIR if the tether diameter is less than 1 cm while it is larger for tether diameters of 2.5 cm and 5 cm;
- The average lifetime of a 5 km tether with diameter of 2.5 mm is less than 1 year, both according to ASI and NASA, at each altitude & inclination considered;
- The average lifetime of a 5 km tether with diameter of 5 mm can vary in between 1.85 years (800 km, 75°) and 3.86 years (1400 km, 25°) according to ASI, but it results to be less than 1 year according to NASA;
- A 5 km tether with diameter of 1 cm may survive more than 4 years, both according to ASI and NASA, while if the tether diameter is 5 cm the average lifetime goes up to more than 10 years.

Provided the hypotheses assumed are correct, the diameter of a single-line tether should be larger than 2.5 mm (2.5 mm $< \varnothing \leq$ 5 mm) for ASI and 5 mm (5 mm $< \varnothing \leq$ 1 cm) for NASA to allow the feasibility of typical de-orbiting missions using electrodynamic tether devices

Conclusions
Test 2 – Survival Probability of a Single-Line Tether

Taking into account the Terminator Tether de-orbit times, ASI and JAXA found that no de-orbit mission from the altitudes and inclinations proposed in the study is possible using a 7.5 km long single-line tether with diameter of 0.5 mm or 1 mm

JAXA (MASTER 2001) computed a maximum survival probability of 41% for a single-line tether with ∅ = 1 mm to de-orbit a S/C from a circular orbit with altitude of 800 km and inclination of 0°;

ASI as well obtained that the maximum survival probability corresponds to the above conditions, but its computed survival probability reduced to 22%.

Conclusions
Test 2 – Survival Probability of a Double-Line Tether

ASI adopted the tether design in which the two cables are separated each other by a distance significantly larger than each line diameter.

JAXA used its own tether design with a distance of 0 mm between the two lines.

THEREFORE, RESULTS CANNOT BE DIRECTLY COMPARED DUE TO DIFFERENT ASSUMPTIONS ON THE TETHER DESIGN

JAXA

JAXA demonstrated that the sever probability is independent on the number of knots for its tether design, then only knots spaced by 10 m were assumed.

Using the JAXA tether design, a relatively low survival probability was computed for all de-orbiting missions proposed: in between 0% and 78% using ORDEM 2000, in between 0% and 83% using MASTER 2001.

The maximum survival probability of 83% (MASTER 2001) corresponded to a tether with each line diameter of 1 mm to de-orbit from [800 km, 0°].

Conclusions
Test 2 – Survival Probability of a Double-Line Tether

ASI

1. The survival probability of a double-line tether with diameter of **0.5 mm** for each single-line and knots spaced by 100 m, 10 m and 5 m was computed using DAS 1.5.3 as debris flux model;

2. The survival probability was estimated for a double-line tether with diameter of **1 mm** for each single line and knots spaced by 5 m using DAS 1.5.3, MASTER 2001 and ORDEM 2000 as debris flux models.

CASE 1 – **Distance between knots: 100 m**

maximum SP: 89% - de-orbit from [800 km, 0°].

CASE 1 – **Distance between knots: 10 m**

SP ≥ 96% - de-orbit from [1000 km, 0°], [800 km, 0°, 25°, 50°].

CASE 1 – **Distance between knots: 5 m**

SP ≥ 95% - de-orbit from [1400 km, 0°], [1000 km, 0°, 25°], [800 km, 0°, 25°, 50°].

Conclusions
Test 2 – Survival Probability of a Double-Line Tether

ASI

CASE 2 – **Distance between knots: 5 m [DAS 1.5.3]**

SP ≥ 98% - always, apart from de-orbit [1000 km, 75°] where SP = 86%.

CASE 2 – **Distance between knots: 5 m [MASTER 2001]**

SP ≥ 98% always.

CASE 2 – **Distance between knots: 5 m [ORDEM 2000]**

SP ≥ 96% - de-orbit from [1000 km, 0°, 25°, 50°], [800 km, 0°, 25°, 50°].

If the hypotheses assumed are correct, a variety of de-orbiting missions is possible using double-line tethers with diameter of 0.5 mm for each single-line and with knots spaced by 10 m or less.

A distance between knots of 5 m and line diameter of 1 mm allows the majority of de-orbiting missions proposed.