WG2 Action Item 19.1

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

Results of the AI 19.1 Study Plan

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with Contributions by
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Institute of Information Science and Technologies

Italian National Research Council

IADC AI 19.1

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

- The IADC AI 19.1 was promoted at the **19th IADC meeting**, 22-23 March, **2001**, DLR, Cologne, Germany, with title: "***Benefits and Risks of using Tethers in Space***".
- At the **20th IADC meeting**, 9-12 April, **2002**, Guildford, Surrey, England, Gerhard Drolshagen presented the AI 19.1 status noting the tools, existing or under development, to study the dynamics and risks of collision of tethers in space.
- At the **21st IADC meeting**, 10-13 March, **2003**, Bangalore, India, Carmen Pardini acquainted the IADC Working Group 2 members with the advanced status of the task giving three presentations:

1. Overview of space tether applications: state-of-the-art knowledge and tools;
2. De-orbiting spacecraft with electrodynamic tether devices;
3. Potential benefits and risks of using electrodynamic tethers for end-of-life de-orbit of LEO spacecraft.

IADC AI 19.1

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

- A proposal to address the Electrodynamic Tether (EDT) systems survivability concern was advanced inside WG2 at the 21st IADC meeting and the AI was renamed:

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

- A study plan was prepared by C. Pardini (Lead, ISTI/CNR – ASI) and sent to all WG2 members on 20 November 2003. Two tests were proposed in the AI 19.1 study plan.
- Three Space Agencies (**ASI**, **JAXA** and **NASA**) participated in the study.
- The **results of Test 1** were presented at the **22nd IADC meeting**, 19-22 April, **2004**, Abano Terme, Italy.
- A summary of the results of Test 1 and the **results of Test 2** are presented at the current IADC meeting.

Proposed Tests

Two tests were proposed in the IADC 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 typical de-orbiting missions of satellites and upper stages from low Earth orbits.

Space Debris Flux Models

TEST 1

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 < 1 mm
ISTI/CNR **CODRM-99R** model for OD ≥ 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 Debris Flux Models

TEST 2

ASI

Meteoroids & Orbital Debris

NASA **DAS 1.5.3** model [M & OD]

NASA **ORDEM 2000** model [OD] + DAS 1.5.3 [M]

ESA **MASTER 2001** model [M & OD]

JAXA

Meteoroids & Orbital Debris

ESA **MASTER 2001** model [M & OD]

Orbital Debris

NASA **ORDEM2000** model

NASA

Meteoroids & Orbital Debris

NASA **ORDEM2000** model [OD] + **Grun, 1985, Meteoroid Flux** [M]

NASA **DAS 1.5.3** model [M & OD]

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, 19-22 April, 2004, Abano Terme, Italy.

JAXA

in "*Assessment of Collision Risk to Electrodynamic Tether Used for De-orbiting*", by A. Oishi et al., *55th International Astronautical Congress*, Vancouver, Canada, Paper IAC-04-IAA.5.12.5.09, October 4-8, 2004, revised and modified by T. Hanada (Kyushu University, Japan) in *"Assessing the vulnerability to debris impacts of electrodynamic tethers during typical de-orbiting missions*", by C. Pardini et al., 4th European Conference on Space Debris, Darmstadt, Germany, 18-20 April 2005.

NASA

in "*A Probability of Sever Model for Tethers in Low Earth Orbit"*, by P. Anz-Meador, 20th IADC Meeting, 9-12 April, 2002, Guildford, Surrey, England.

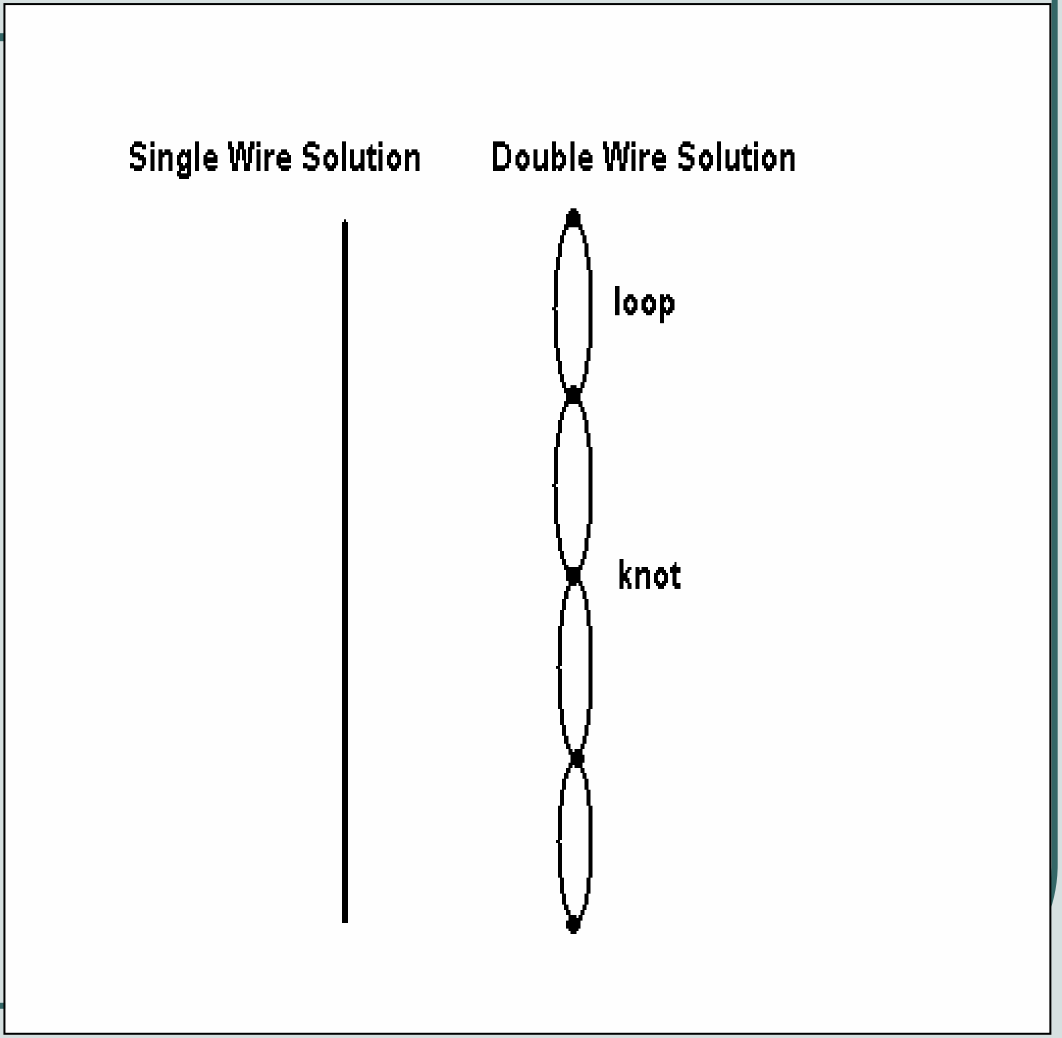
Tether Designs

Two basically different tether designs were considered:

1. **single tether**, with a single wire or a compact cylindrical multi-line structure**;**

2. **Double tether**, in which two cables are separated each other by a distance significantly larger than their diameter and form N loops, tied together in $N + 1$ equidistant knots.

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



Tether Characteristics

TETHERS ARE SUPPOSED TO BE IN CIRCULAR ORBIT AND ALIGNED ALONG THE GRAVITY GRADIENT

TEST 1 – Single-line Tether

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

Tether Length		
5 km	7.5 km	10 km

TEST 2 – Single-line and Double-line, Multi-loop Tether

Diameter of each Line	
0.5 mm	1 mm

Tether Length
7.5 km

Fatal Debris Diameter

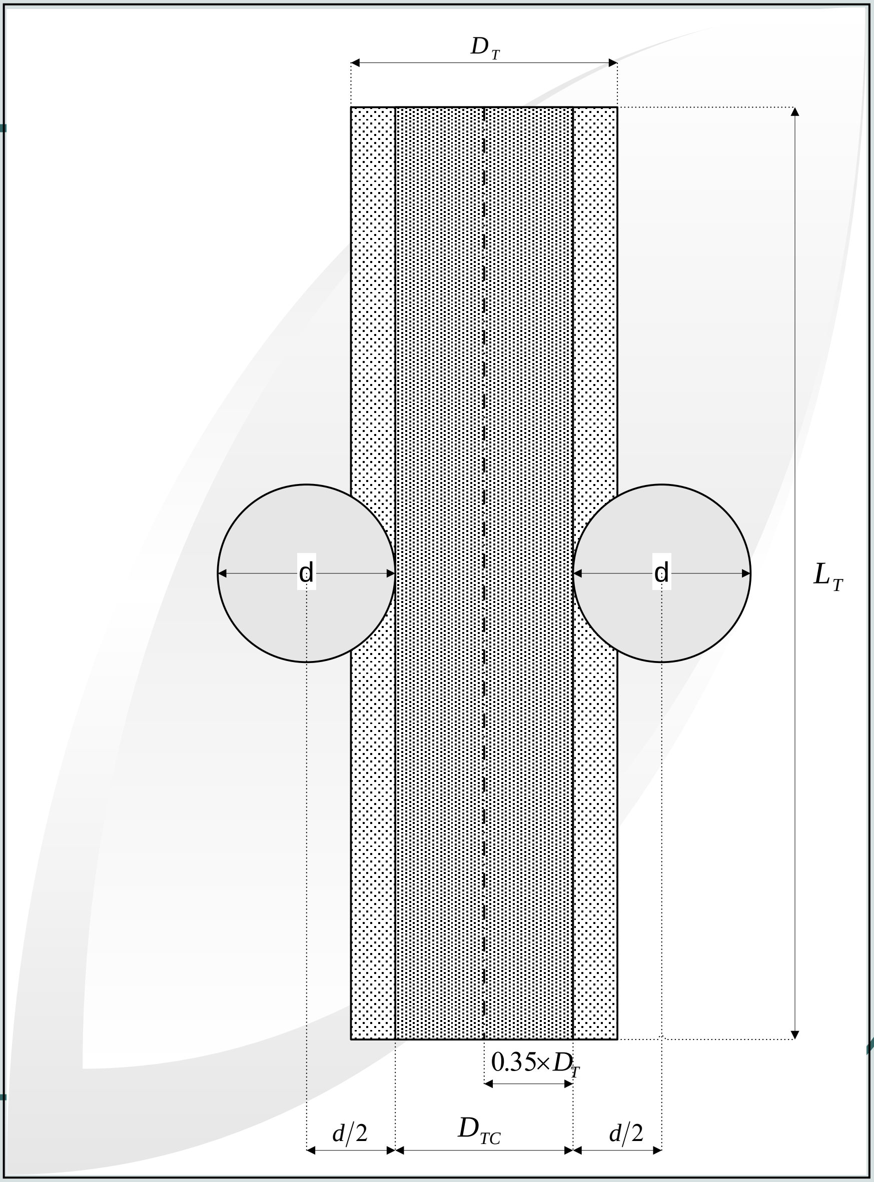
A single tether may be severed by a space debris with a diameter

$$d \geq 0.25 D_T$$

d debris diameter

D_T tether diameter

provided that the debris edge passes within a critical distance: 0.35 D_T from the longitudinal axis of symmetry of the tether.



Test 1
Fatal Impact Rate

The **Fatal Impact Rate**, i.e. the number of impacts able to cut a tether in a given time, 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

Test 1 - Summary
Fatal Impact Rate

Tether diameter: 0.5 mm, 0.75 mm, 1 mm

- The ASI Fatal Impact Rate (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 $D_T \leq 1$ 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

Test 1 - Summary
Fatal Impact Rate

Tether diameters ≥ 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.

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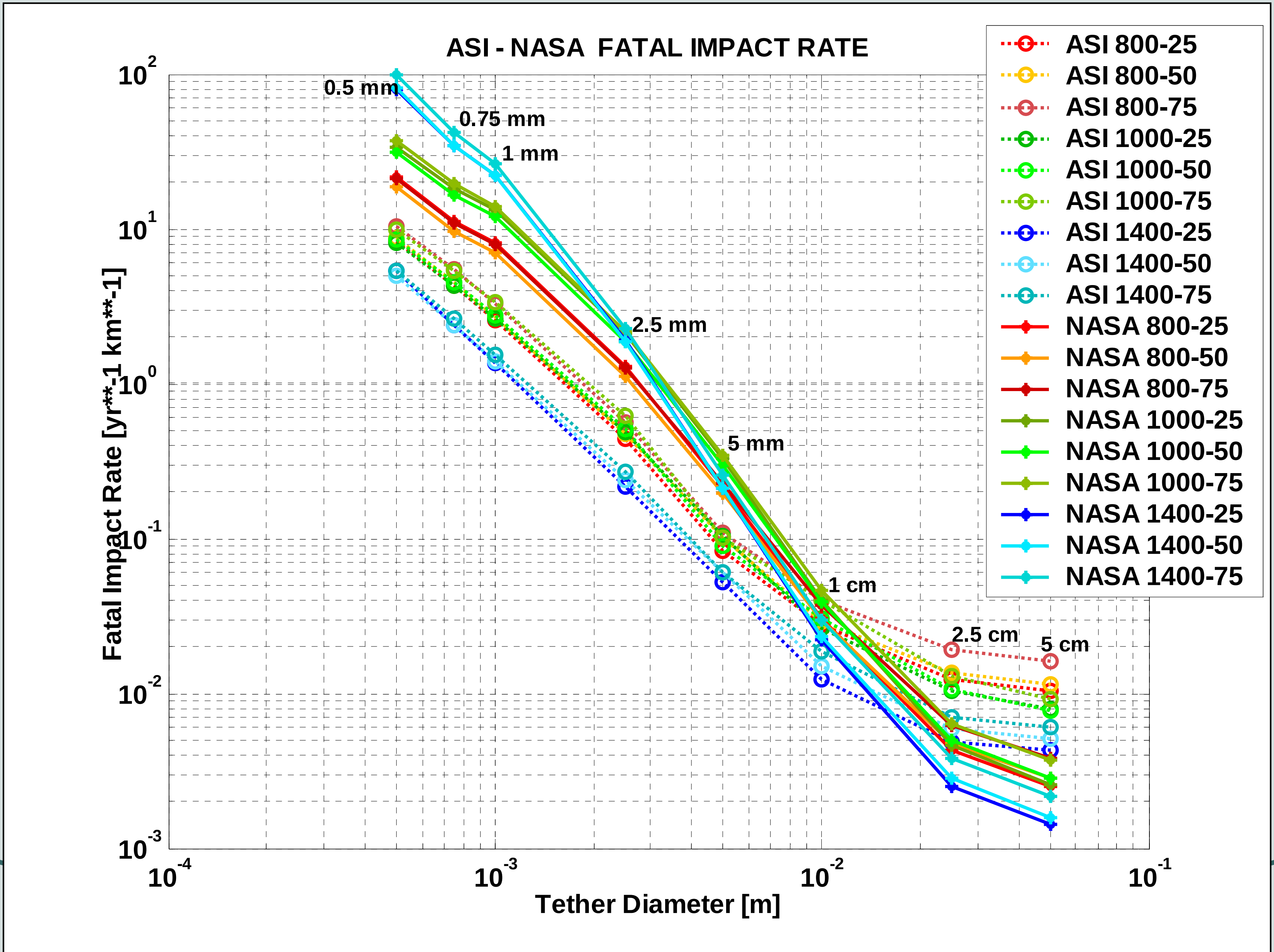
Fatal Impact Rate Analysis

ASI - NASA Fatal Impact Rate Comparison



Test 2
Tether Survival Probability During De-orbiting Missions
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 diameter of 0.5 mm and 1 mm;
- double-line tether with diameter of 0.5 mm and 1 mm for each single wire and with equidistant knots spaced at intervals of 100 m;
- double-line tether with diameter of 0.5 mm and 1 mm for each single wire and with equidistant knots spaced at intervals of 10 m;
- double-line tether with diameter of 0.5 mm and 1 mm for each single wire and with equidistant knots spaced at intervals of 5 m.

Test 2
Tether Survival Probability During De-orbiting Missions
The "Terminator Tether" De-orbiting Times

Time to de-orbit a 1500 kg satellite with a 7.5 km Terminator Tether
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
Tether Survival Probability During De-orbiting Missions
The "Terminator Tether" De-orbiting Times

Altitude Interval [km]	Inclination			
	0°	25°	50°	75°
	De-orbit Time per Altitude Interval [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
Space Debris Fluxes

(1)

ASI

- **ORDEM 2000** (OD) + DAS 1.5.3 (M)

JAXA

- ORDEM 2000

NASA

- ORDEM 2000 (OD) + Grun 1985 (M)

(2)

ASI

- **DAS 1.5.3** (OD & M)

NASA

- DAS 1.5.3 (OD & M)

(3)

ASI

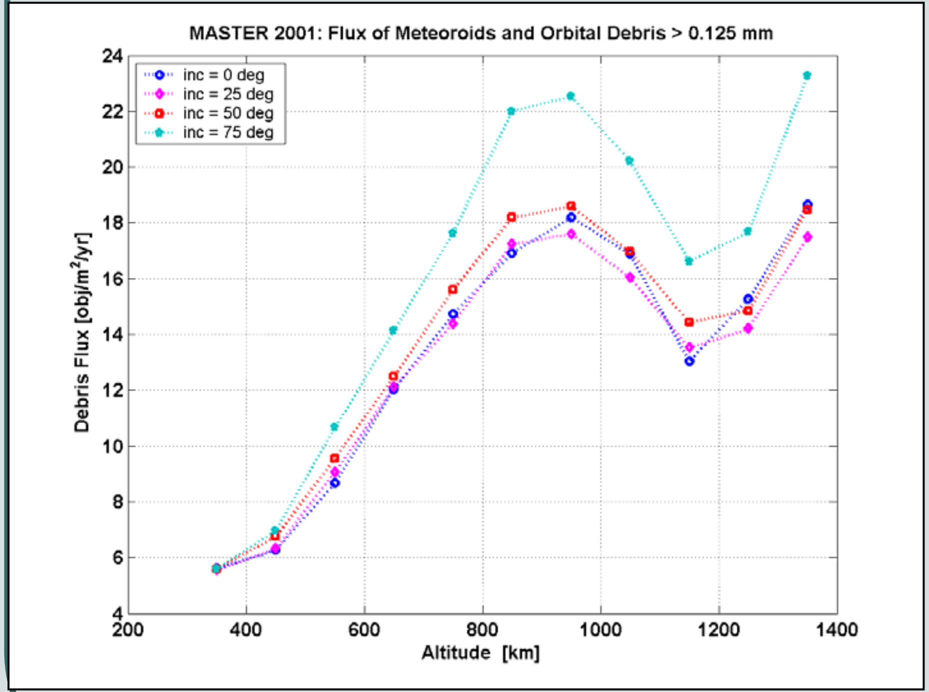
- **MASTER 2001** (OD & M)

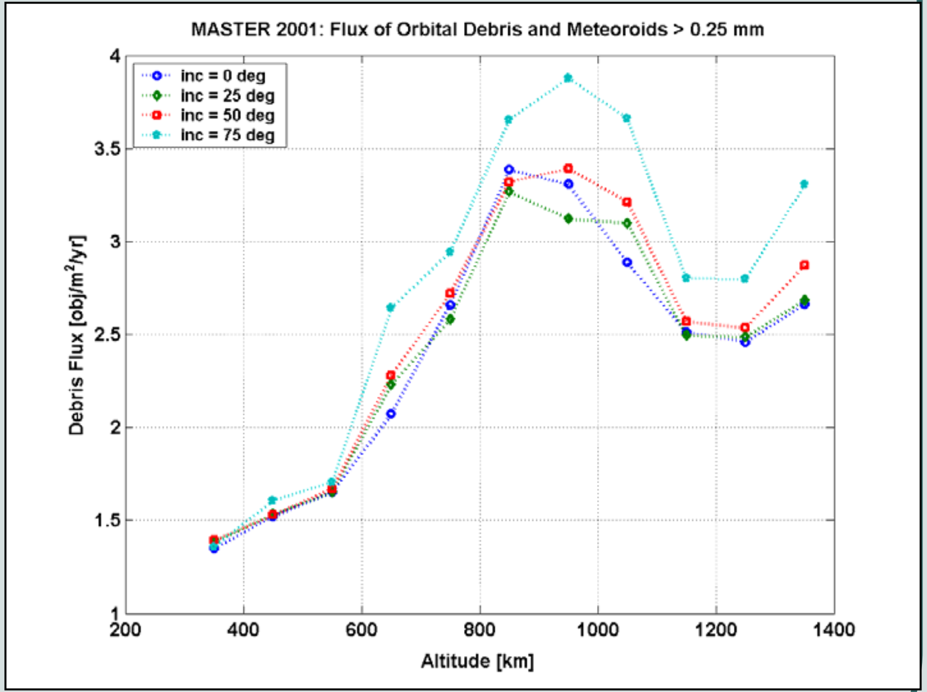
JAXA

- MASTER 2001 (OD & M)

Test 2 - Survivability Analysis
ASI - Debris Flux

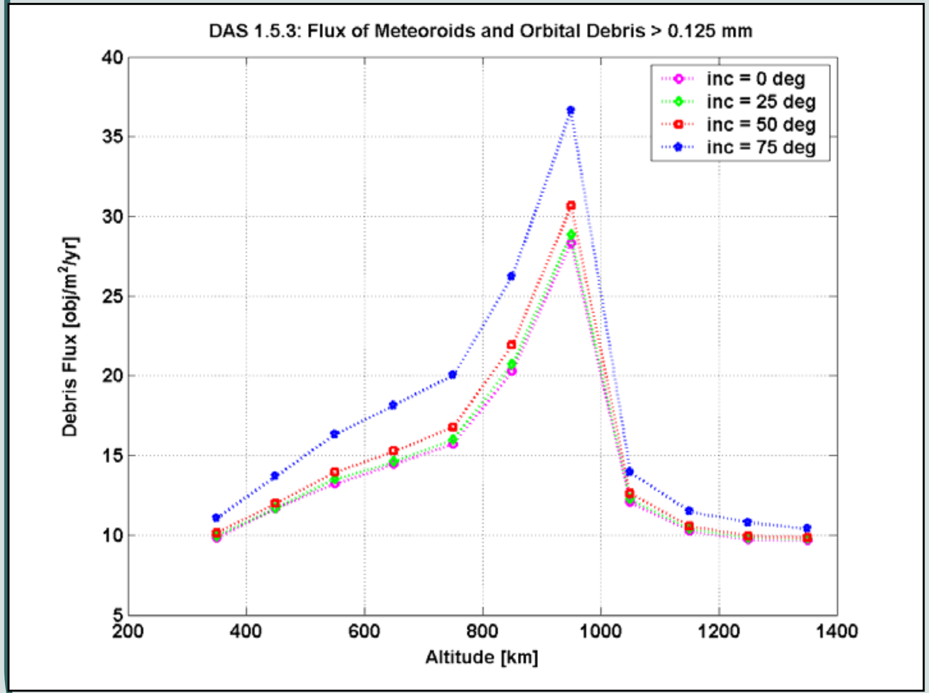
MASTER 2001 – all sources of meteoroids & orbital debris

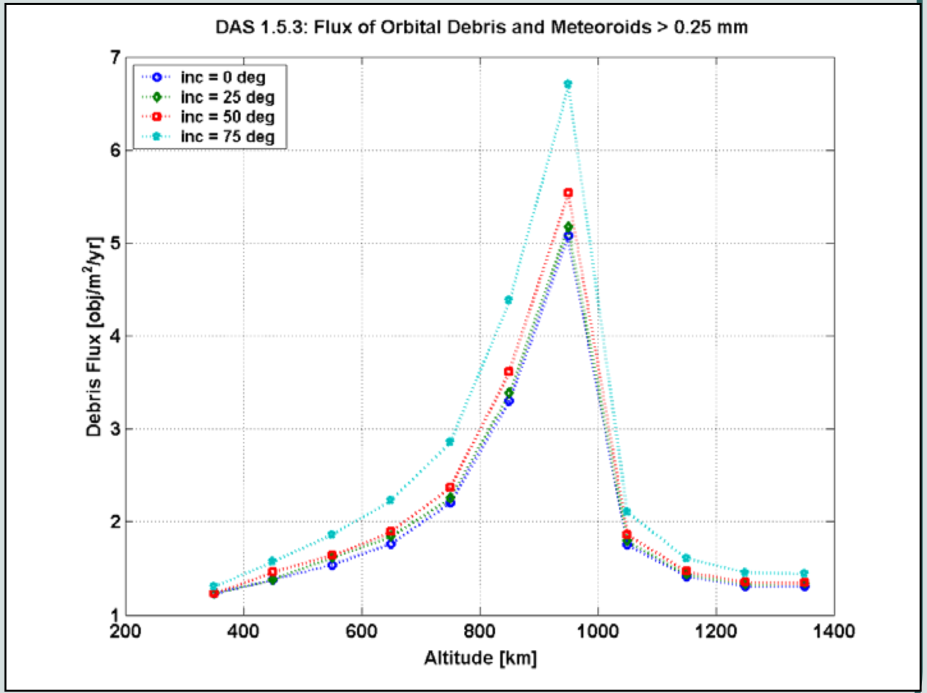




Test 2 - Survivability Analysis
ASI - Debris Flux

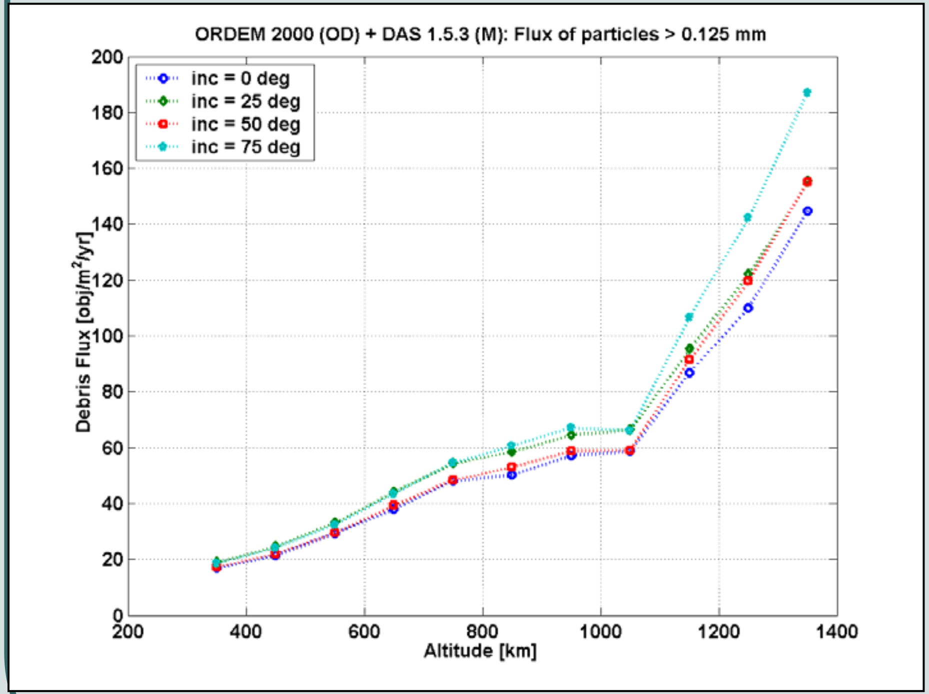
DAS 1.5.3 (Orbital Debris & Meteoroids)

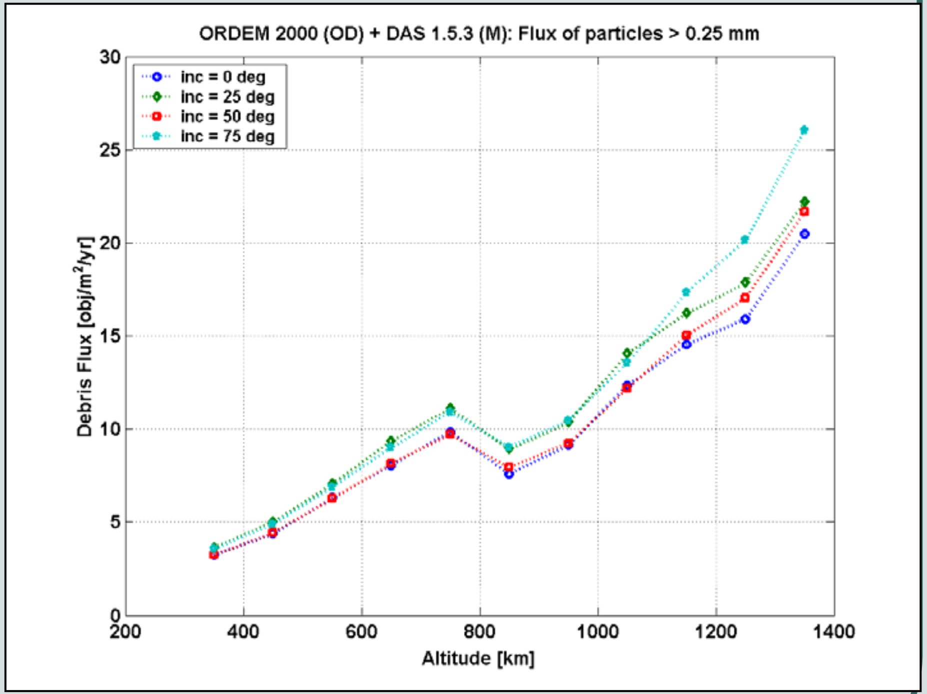




Test 2 - Survivability Analysis
ASI - Debris Flux

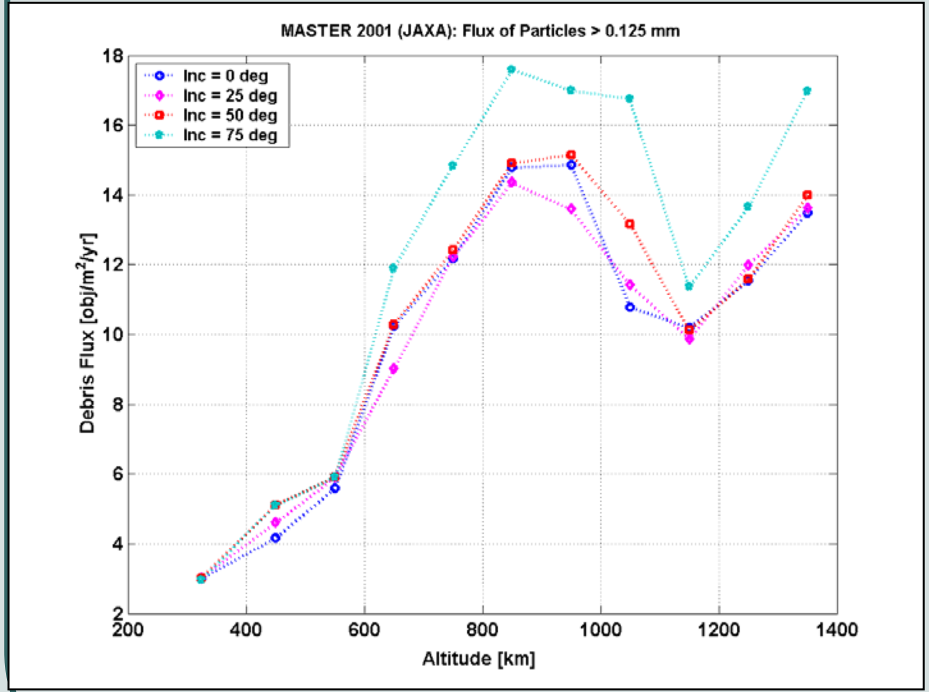
ORDEM 2000 (Orbital Debris) + DAS 1.5.3 (Meteoroids)

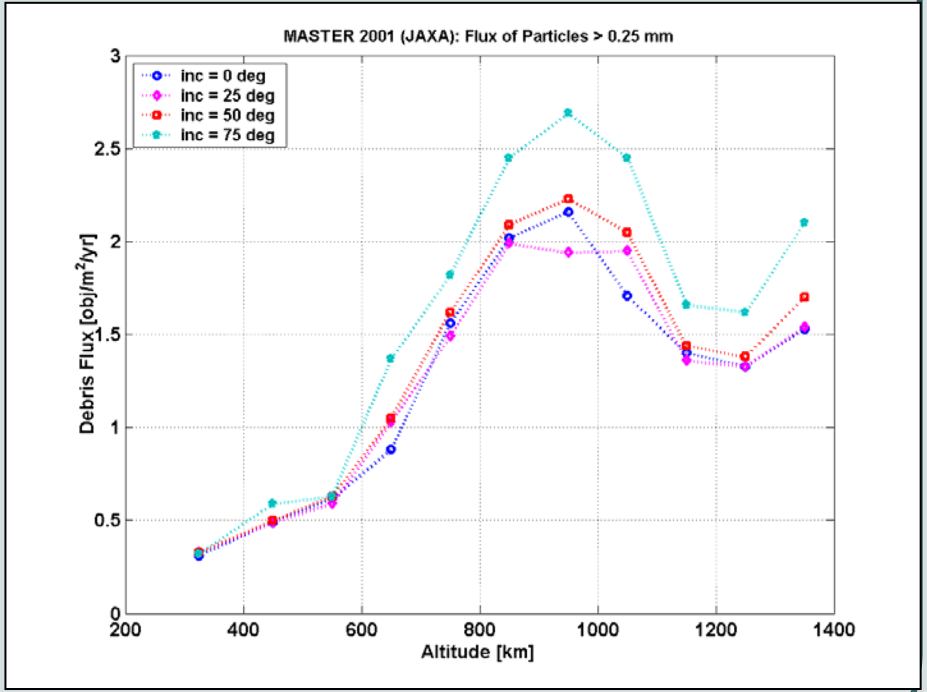




Test 2 - Survivability Analysis
JAXA - Debris Flux

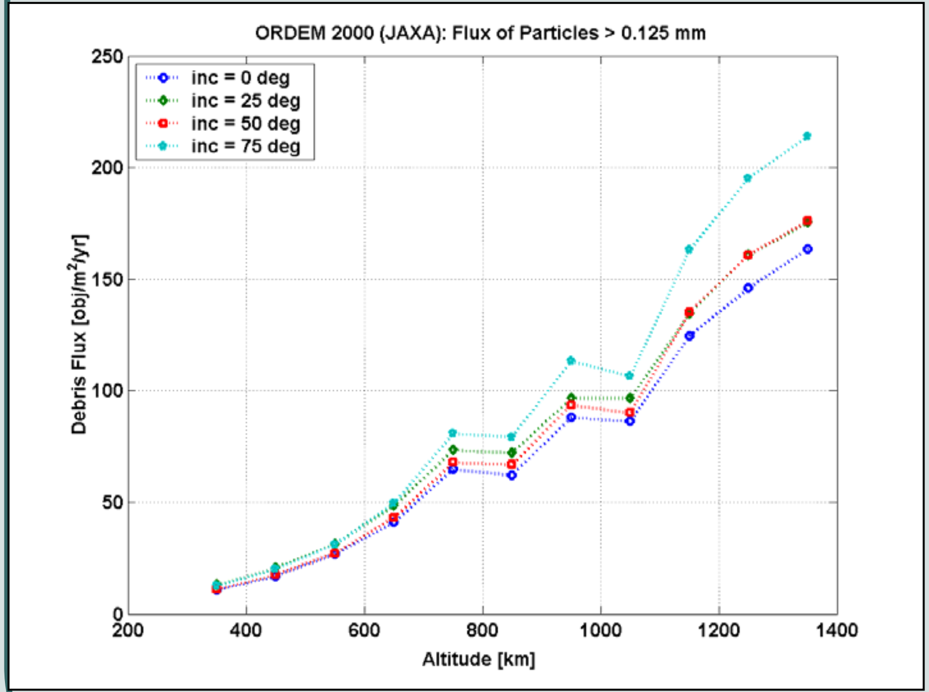
MASTER 2001 –meteoroids & orbital debris

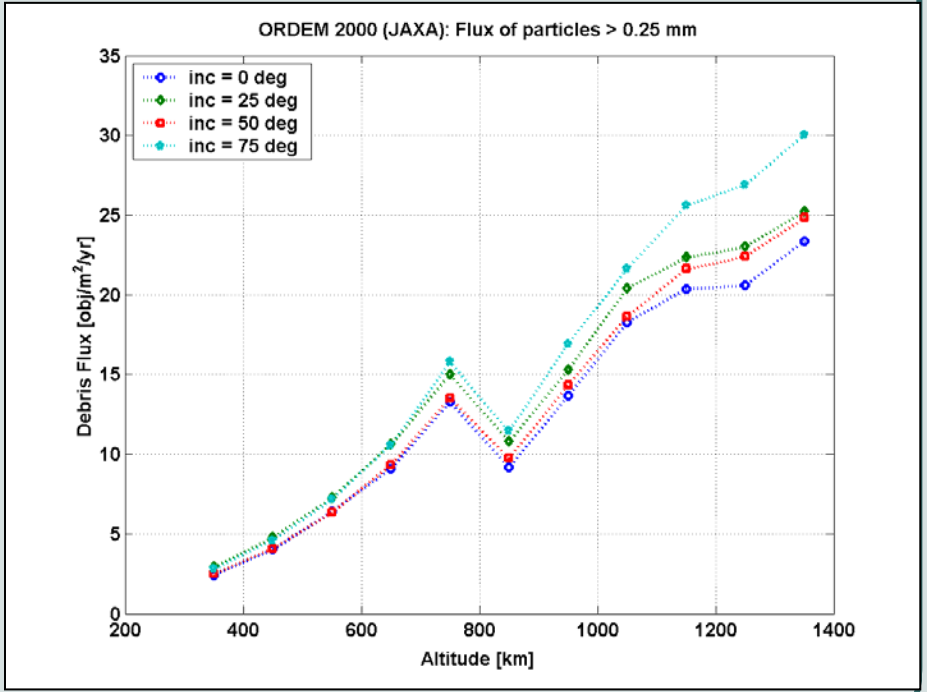




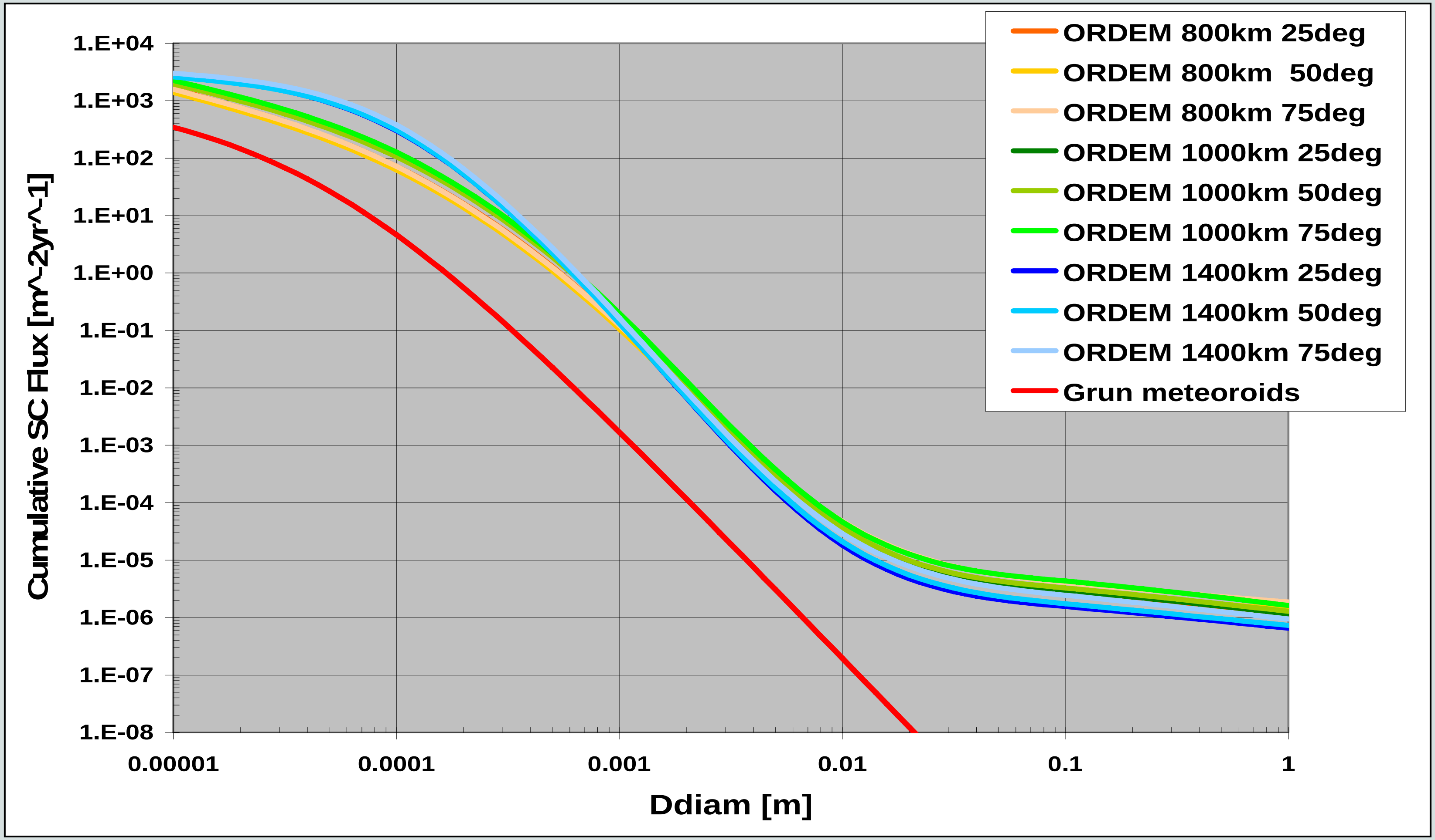
Test 2 - Survivability Analysis
JAXA - Debris Flux

ORDEM 2000 (Orbital Debris)





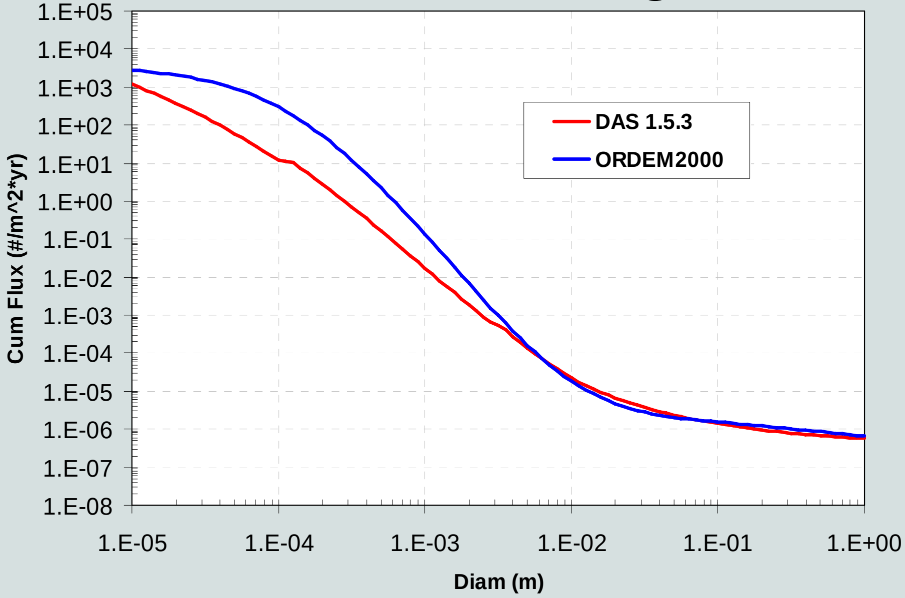
NASA Space Debris Flux



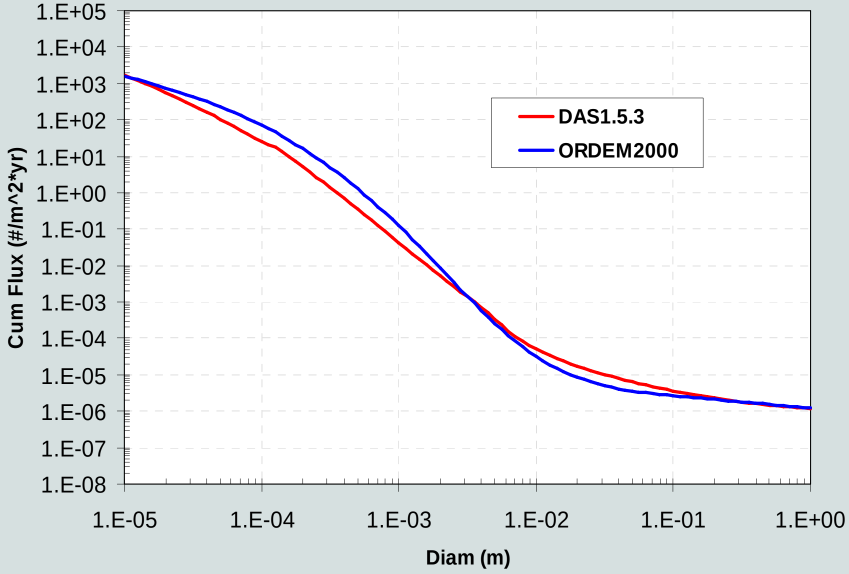
Test 2 - Survivability Analysis
NASA - Debris Flux

ORDEM 2000 & DAS 1.5.3

1400 km, 25 deg



800 km, 25 deg



Test 2 - Survivability Analysis
Single-Line Tether

ASI, JAXA, NASA - Space Debris Flux Model: **ORDEM 2000 + Meteoroids**

Tether diameter: 0.5 mm, 1 mm

Survival Probability = 0 in all cases for NASA, JAXA and ASI

ASI & NASA - Space Debris Flux Model: **DAS 1.5.3**

Tether diameter: 0.5 mm

Survival Probability = 0 in all cases for NASA and ASI

Tether diameter: 1 mm

Inclination	0 deg		25 deg		50 deg		75 deg	
	Survival Probability [%]							
De-orbiting altitude	NASA	ASI	NASA	ASI	NASA	ASI	NASA	ASI
1400 km	0	0	0	0	0	0	-	-
1000 km	0	3	0	0	0	0	0	0
800 km	3	22	1	16	0	6	0	0

Test 2 - Survivability Analysis
Single-Line Tether

ASI & JAXA - Space Debris Flux Model: MASTER 2001

Tether diameter: 0.5 mm

inclination	0 deg		25 deg		50 deg		75 deg	
	Survival Probability [%]							
de-orbiting altitude	JAXA	ASI	JAXA	ASI	JAXA	ASI	JAXA	ASI
1400 km	0	0	0	0	0	0	-	-
1000 km	0	0	0	0	0	0	0	0
800 km	2	1	1	0	0	0	0	0

Tether diameter: 1 mm

inclination	0 deg		25 deg		50 deg		75 deg	
	Survival Probability [%]							
de-orbiting altitude	JAXA	ASI	JAXA	ASI	JAXA	ASI	JAXA	ASI
1400 km	0	1	0	0	0	0	-	-
1000 km	12	27	6	12	1	2	0	0
800 km	39	57	35	51	18	25	1	1

Test 2 - Survivability Analysis
Double-strand, Multi-loop Tether
Knots Spaced by 100 m
(Space Debris Flux Model: ORDEM 2000 + Meteoroids)

Strand diameter: 0.5 mm

Inclination	0 deg			25 deg			50 deg			75 deg		
	Survival Probability [%]											
De-orbiting altitude	NASA	JAXA	ASI	NASA	JAXA	ASI	NASA	JAXA	ASI	NASA	JAXA	ASI
1400 km	0	0	0	0	0	0	0	0	0	-	-	-
1000 km	0	0	13	0	0	0	0	0	0	0	0	0
800 km	4	2	42	1	0	29	0	0	1	0	0	0

Strand diameter: 1 mm

Inclination	0 deg			25 deg			50 deg			75 deg		
	Survival Probability [%]											
De-orbiting altitude	NASA	JAXA	ASI	NASA	JAXA	ASI	NASA	JAXA	ASI	NASA	JAXA	ASI
1400 km	0	0	3	0	0	0	0	0	0	-	-	-
1000 km	22	10	76	2	1	53	0	0	35	0	0	0
800 km	59	45	86	44	28	80	23	10	66	0	0	3

Test 2 - Survivability Analysis
Double-strand, Multi-loop Tether
Knots Spaced by 10 m
(Space Debris Flux Model: ORDEM 2000 + Meteoroids)

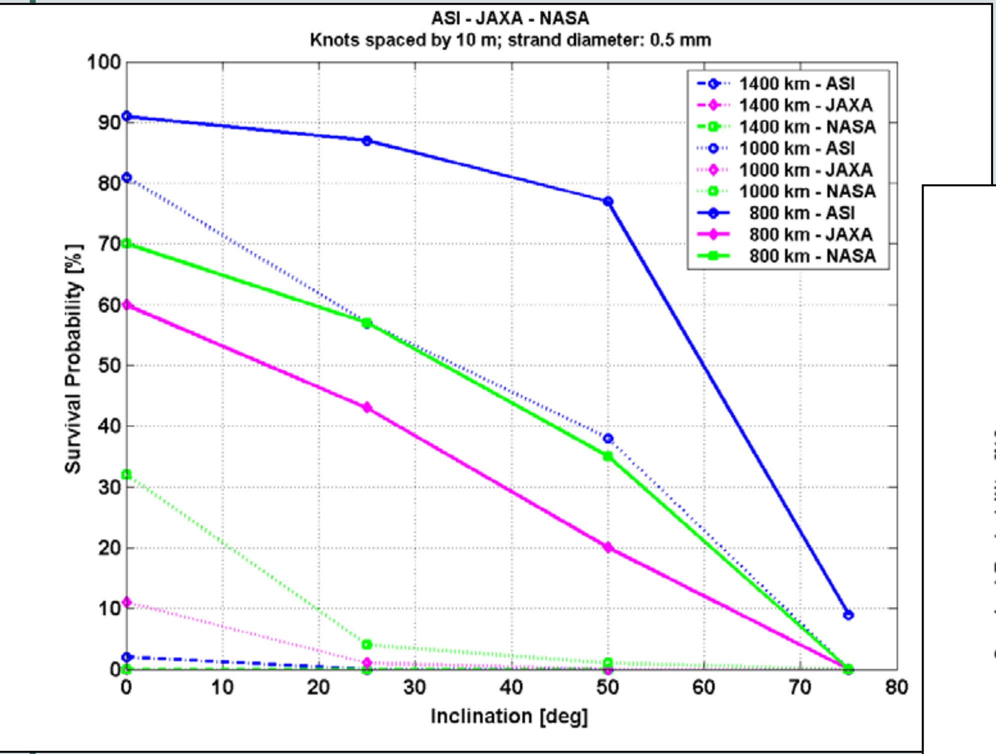
Strand diameter: 0.5 mm

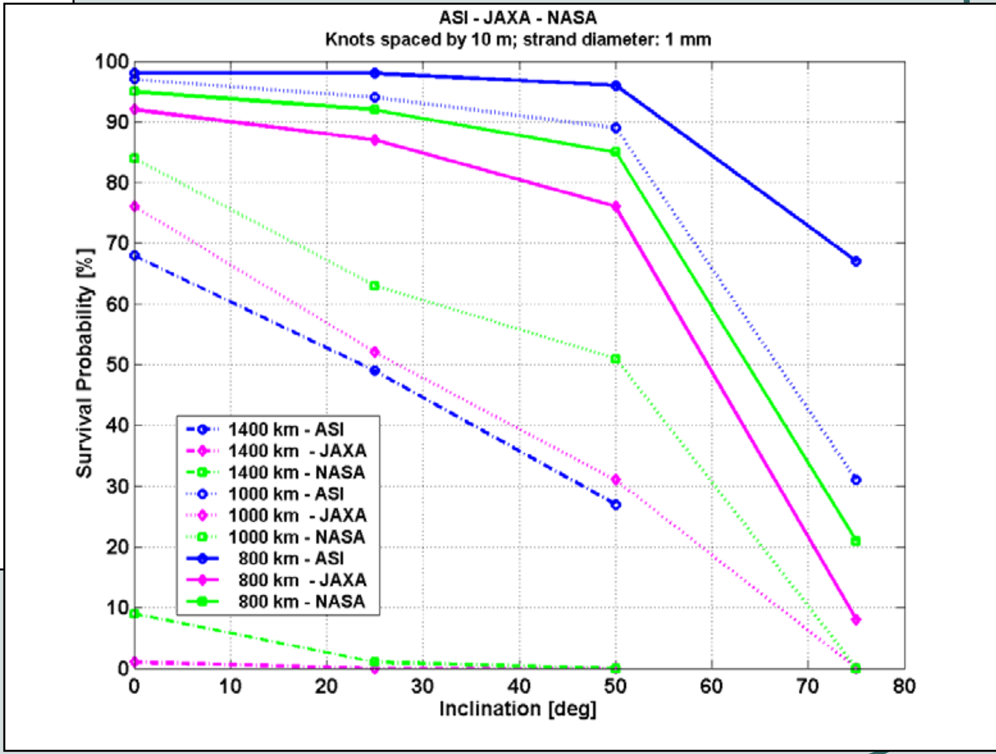
Inclination	0 deg			25 deg			50 deg			75 deg		
	Survival Probability [%]											
De-orbiting altitude	NASA	JAXA	ASI	NASA	JAXA	ASI	NASA	JAXA	ASI	NASA	JAXA	ASI
1400 km	0	0	2	0	0	0	0	0	0	-	-	-
1000 km	32	11	81	4	1	57	1	0	38	0	0	0
800 km	70	60	91	57	43	87	35	20	77	0	0	9

Strand diameter: 1 mm

Inclination	0 deg			25 deg			50 deg			75 deg		
	Survival Probability [%]											
De-orbiting altitude	NASA	JAXA	ASI	NASA	JAXA	ASI	NASA	JAXA	ASI	NASA	JAXA	ASI
1400 km	9	1	68	1	0	49	0	0	27	-	-	-
1000 km	84	76	97	63	52	94	51	31	89	0	0	31
800 km	95	92	98	92	87	98	85	76	96	21	8	67

Test 2 - Survivability Analysis
Double-strand, Multi-loop Tether
Knots Spaced by 10 m
(Space Debris Flux Model: **ORDEM 2000 + Meteoroids**)





Test 2 - Survivability Analysis
Double-strand, Multi-loop Tether
Knots Spaced by 5 m
(Space Debris Flux Model: ORDEM 2000 + Meteoroids)

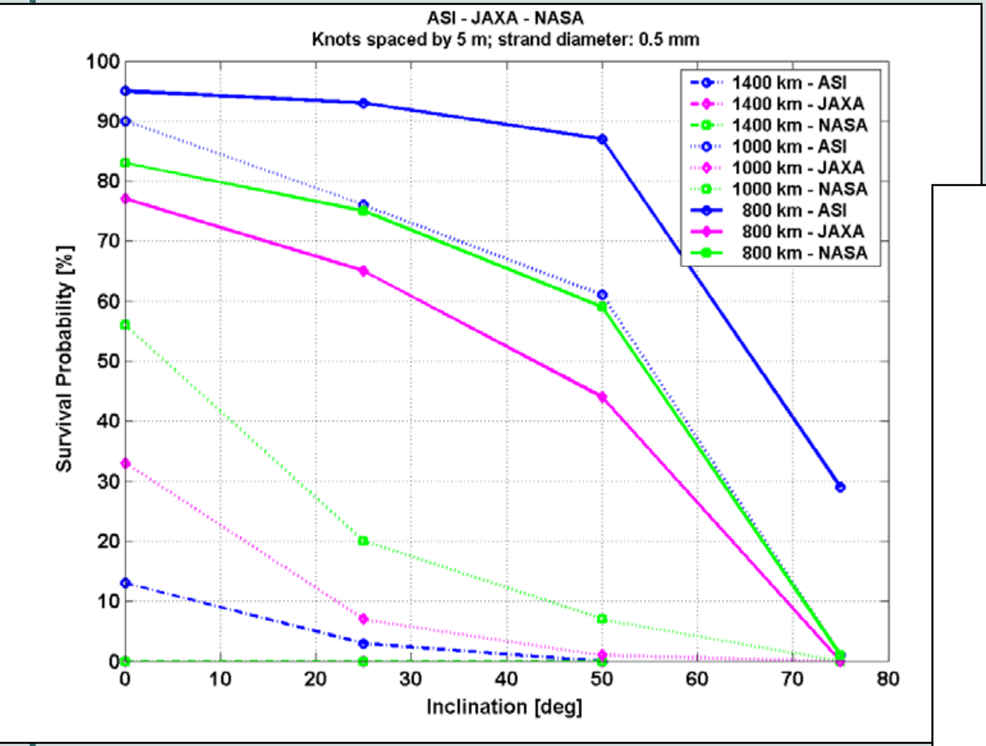
Strand diameter: 0.5 mm

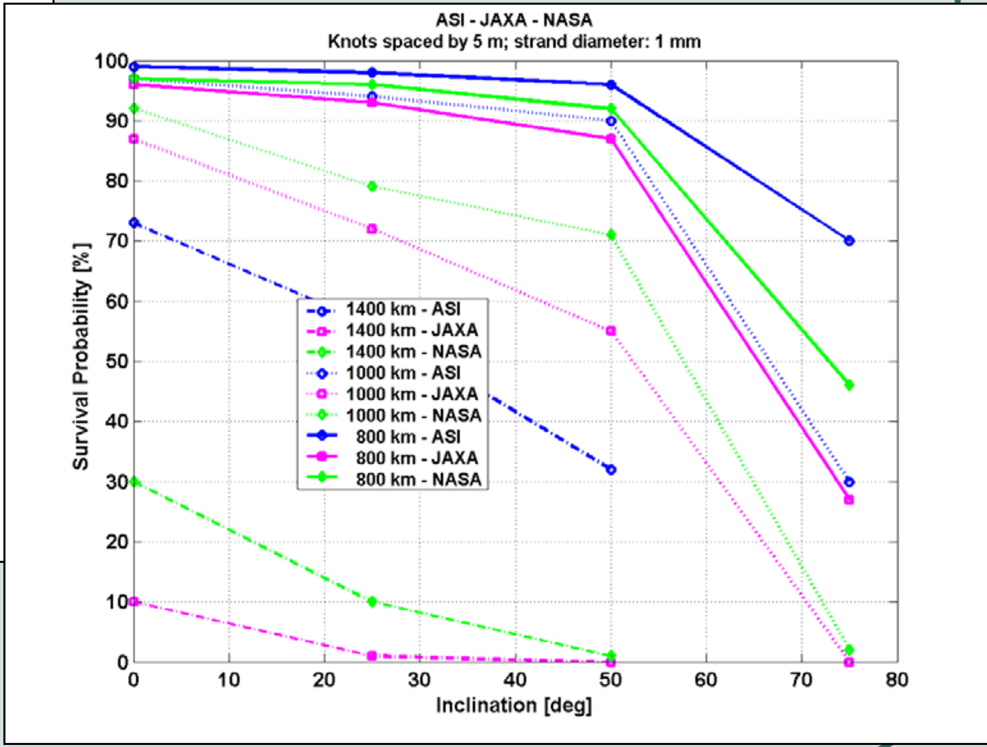
Inclination	0 deg			25 deg			50 deg			75 deg		
	Survival Probability [%]											
De-orbiting altitude	NASA	JAXA	ASI	NASA	JAXA	ASI	NASA	JAXA	ASI	NASA	JAXA	ASI
1400 km	0	0	13	0	0	3	0	0	0	-	-	-
1000 km	56	33	90	20	7	76	7	1	61	0	0	1
800 km	83	77	95	75	65	93	59	44	87	1	0	29

Strand diameter: 1 mm

Inclination	0 deg			25 deg			50 deg			75 deg		
	Survival Probability [%]											
De-orbiting altitude	NASA	JAXA	ASI	NASA	JAXA	ASI	NASA	JAXA	ASI	NASA	JAXA	ASI
1400 km	30	10	73	10	1	56	1	0	32	-	-	-
1000 km	92	87	97	79	72	94	71	55	90	2	0	30
800 km	97	96	99	96	93	98	92	87	96	46	27	70

Test 2 - Survivability Analysis
Double-strand, Multi-loop Tether
Knots Spaced by 5 m
(Space Debris Flux Model: **ORDEM 2000 + Meteoroids**)





Test 2 - Survivability Analysis
Double-strand, Multi-loop Tether

Knots Spaced by 100 m
(Space Debris Flux Model: DAS 1.5.3)

Strand diameter: 0.5 mm

inclination	0 deg		25 deg		50 deg		75 deg	
	Survival Probability [%]							
de-orbiting altitude	NASA	ASI	NASA	ASI	NASA	ASI	NASA	ASI
1400 km	5	48	0	24	0	5	-	-
1000 km	22	68	5	42	0	16	0	0
800 km	53	89	43	86	13	68	0	3

Strand diameter: 1 mm

inclination	0 deg		25 deg		50 deg		75 deg	
	Survival Probability [%]							
de-orbiting altitude	NASA	ASI	NASA	ASI	NASA	ASI	NASA	ASI
1400 km	76	93	60	86	24	73	-	-
1000 km	85	96	72	90	37	80	0	7
800 km	95	99	94	99	84	97	21	77

Test 2 - Survivability Analysis
Double-strand, Multi-loop Tether
Knots Spaced by 10 m
(Space Debris Flux Model: DAS 1.5.3)

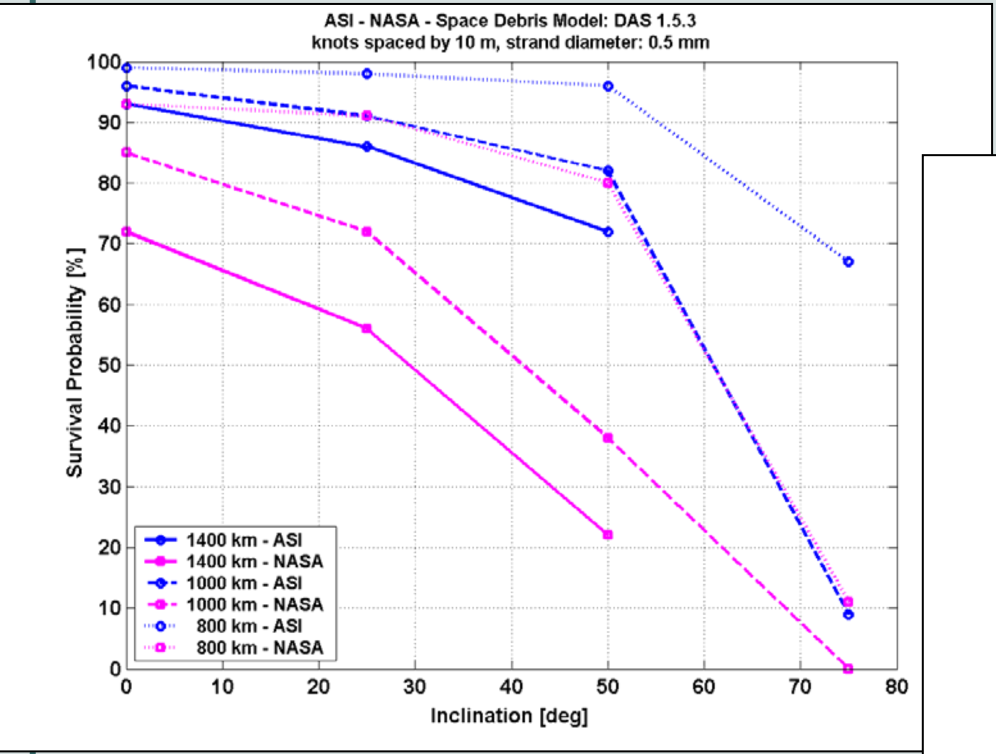
Strand diameter: 0.5 mm

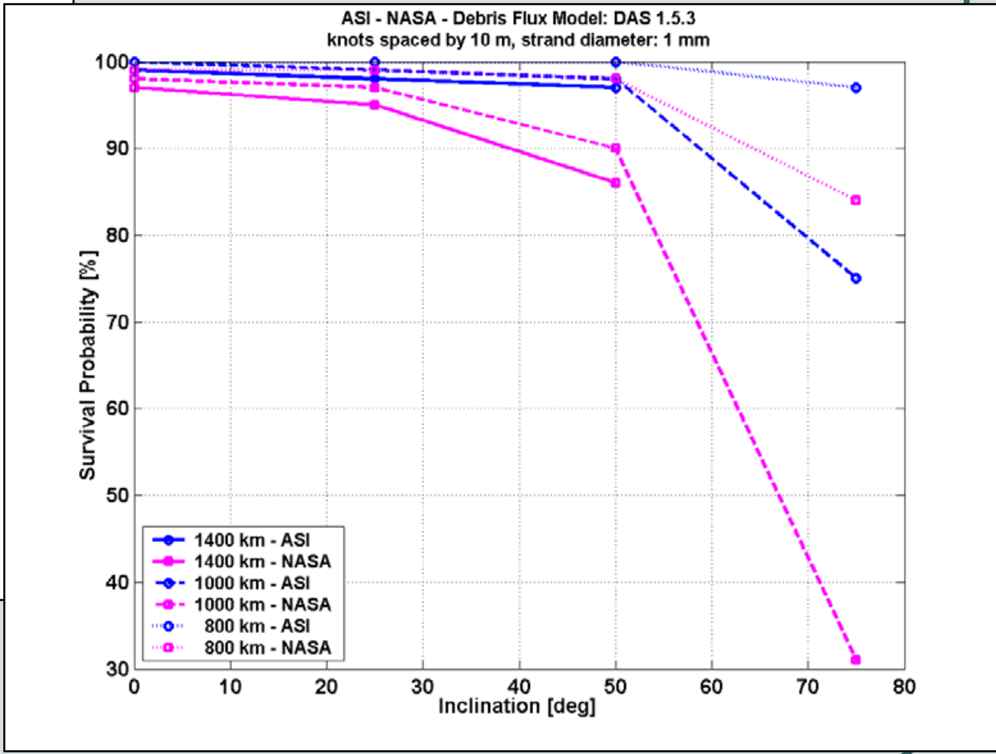
inclination	0 deg		25 deg		50 deg		75 deg	
	Survival Probability [%]							
de-orbiting altitude	NASA	ASI	NASA	ASI	NASA	ASI	NASA	ASI
1400 km	72	93	56	86	22	72	-	-
1000 km	85	96	72	91	38	82	0	9
800 km	93	99	91	98	80	96	11	67

Strand diameter: 1 mm

inclination	0 deg		25 deg		50 deg		75 deg	
	Survival Probability [%]							
de-orbiting altitude	NASA	ASI	NASA	ASI	NASA	ASI	NASA	ASI
1400 km	97	99	95	98	86	97	-	-
1000 km	98	100	97	99	90	98	31	75
800 km	99	100	99	100	98	100	84	97

Test 2 - Survivability Analysis
Double-strand, Multi-loop Tether
Knots Spaced by 10 m
(Space Debris Flux Model: DAS 1.5.3)





Test 2 - Survivability Analysis
Double-strand, Multi-loop Tether
Knots Spaced by 5 m
(Space Debris Flux Model: DAS 1.5.3)

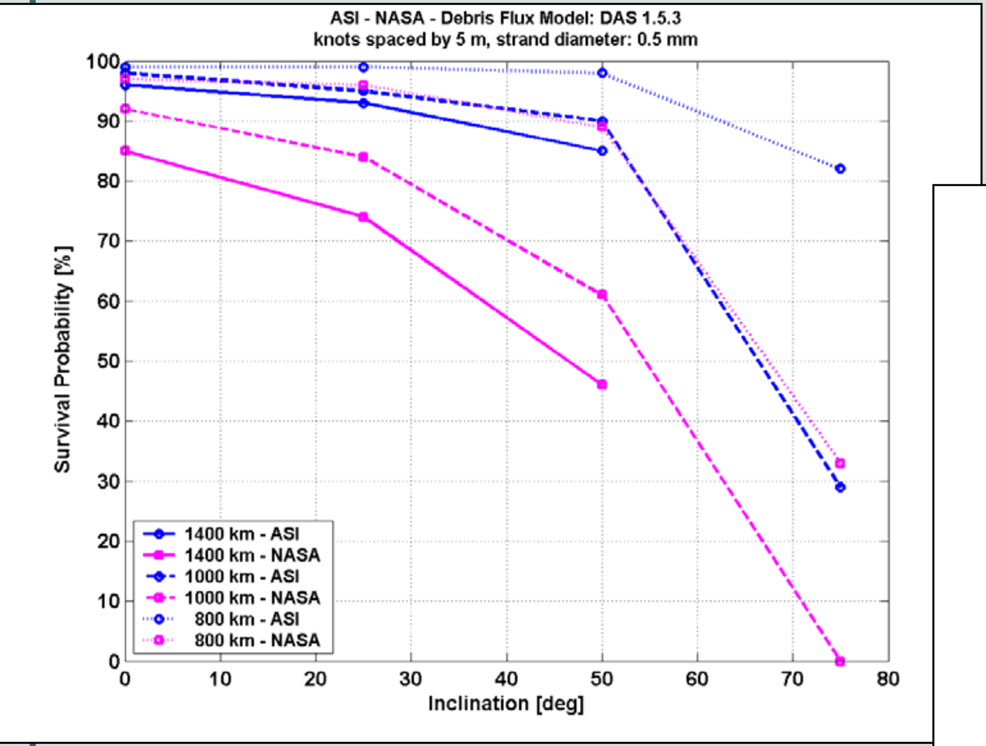
Strand diameter: 0.5 mm

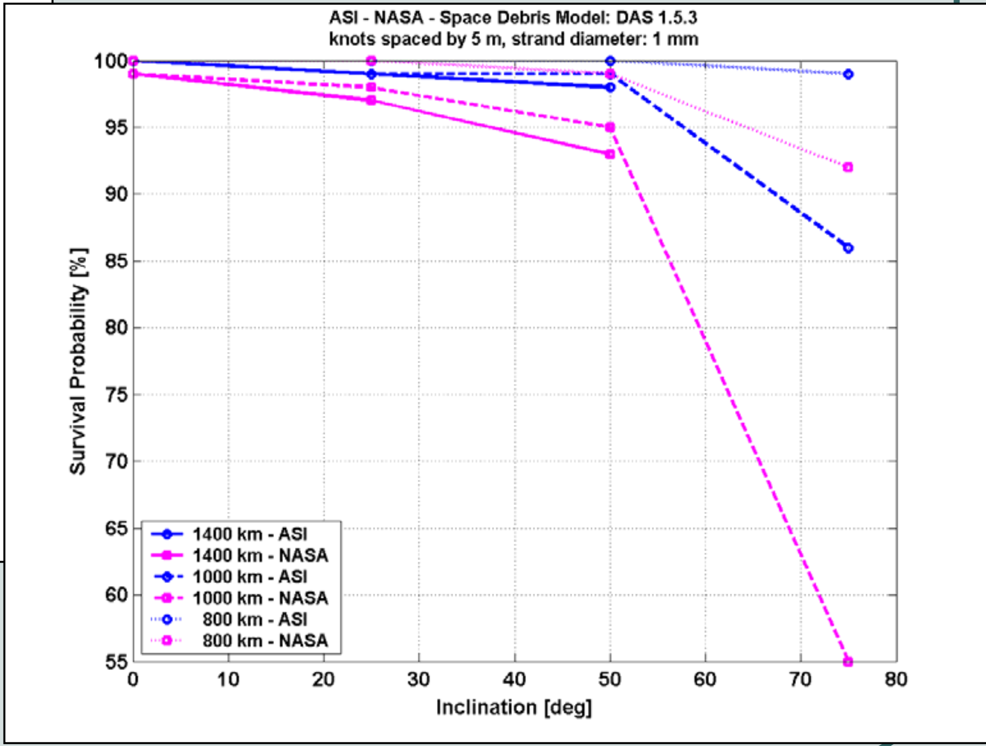
inclination	0 deg		25 deg		50 deg		75 deg	
	Survival Probability [%]							
de-orbiting altitude	NASA	ASI	NASA	ASI	NASA	ASI	NASA	ASI
1400 km	85	96	74	93	46	85	-	-
1000 km	92	98	84	95	61	90	0	29
800 km	97	99	96	99	89	98	33	82

Strand diameter: 1 mm

inclination	0 deg		25 deg		50 deg		75 deg	
	Survival Probability [%]							
de-orbiting altitude	NASA	ASI	NASA	ASI	NASA	ASI	NASA	ASI
1400 km	99	100	97	99	93	98	-	-
1000 km	99	100	98	99	95	99	55	86
800 km	100	100	100	100	99	100	92	99

Test 2 - Survivability Analysis
Double-strand, Multi-loop Tether
Knots Spaced by 5 m
(Space Debris Flux Model: DAS 1.5.3)





Test 2 - Survivability Analysis
Double-strand, Multi-loop Tether

Knots Spaced by 100 m
(Space Debris Flux Model: MASTER 2001)

Strand diameter: 0.5 mm

inclination	0 deg		25 deg		50 deg		75 deg	
	Survival Probability [%]							
de-orbiting altitude	JAXA	ASI	JAXA	ASI	JAXA	ASI	JAXA	ASI
1400 km	1	35	0	21	0	3	-	-
1000 km	44	81	26	66	4	37	0	0
800 km	81	92	78	91	53	76	1	10

Strand diameter: 1 mm

inclination	0 deg		25 deg		50 deg		75 deg	
	Survival Probability [%]							
de-orbiting altitude	JAXA	ASI	JAXA	ASI	JAXA	ASI	JAXA	ASI
1400 km	69	89	54	82	22	63	-	-
1000 km	94	97	90	95	76	87	7	26
800 km	99	99	99	99	96	97	70	74

Test 2 - Survivability Analysis
Double-strand, Multi-loop Tether

Knots Spaced by 10 m

(Space Debris Flux Model: MASTER 2001)

Strand diameter: 0.5 mm

inclination	0 deg		25 deg		50 deg		75 deg	
	Survival Probability [%]							
de-orbiting altitude	JAXA	ASI	JAXA	ASI	JAXA	ASI	JAXA	ASI
1400 km	56	90	37	85	10	68	-	-
1000 km	92	98	86	96	67	90	2	30
800 km	98	99	97	99	93	97	53	77

Strand diameter: 1 mm

inclination	0 deg		25 deg		50 deg		75 deg	
	Survival Probability [%]							
de-orbiting altitude	JAXA	ASI	JAXA	ASI	JAXA	ASI	JAXA	ASI
1400 km	96	99	93	98	84	95	-	-
1000 km	99	100	99	99	97	99	73	87
800 km	100	100	100	100	100	100	96	97

Test 2 - Survivability Analysis
Double-strand, Multi-loop Tether

Knots Spaced by 5 m
(Space Debris Flux Model: MASTER 2001)

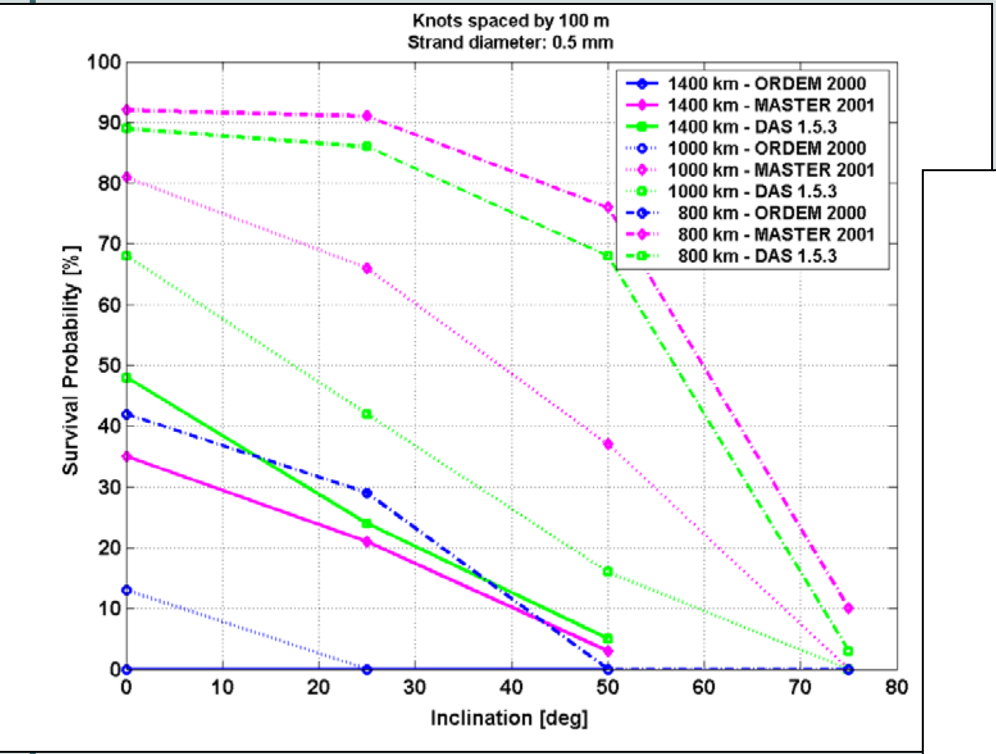
Strand diameter: 0.5 mm

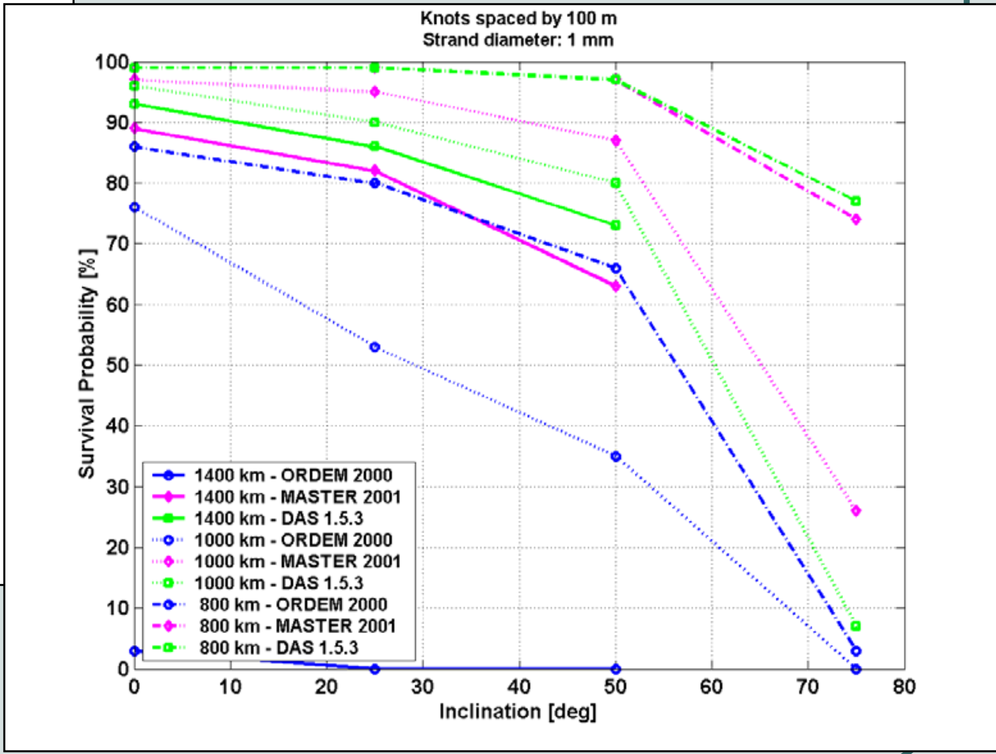
inclination	0 deg		25 deg		50 deg		75 deg	
	Survival Probability [%]							
de-orbiting altitude	JAXA	ASI	JAXA	ASI	JAXA	ASI	JAXA	ASI
1400 km	74	95	62	92	31	82	-	-
1000 km	96	99	93	98	82	95	13	54
800 km	99	100	99	100	97	99	72	88

Strand diameter: 1 mm

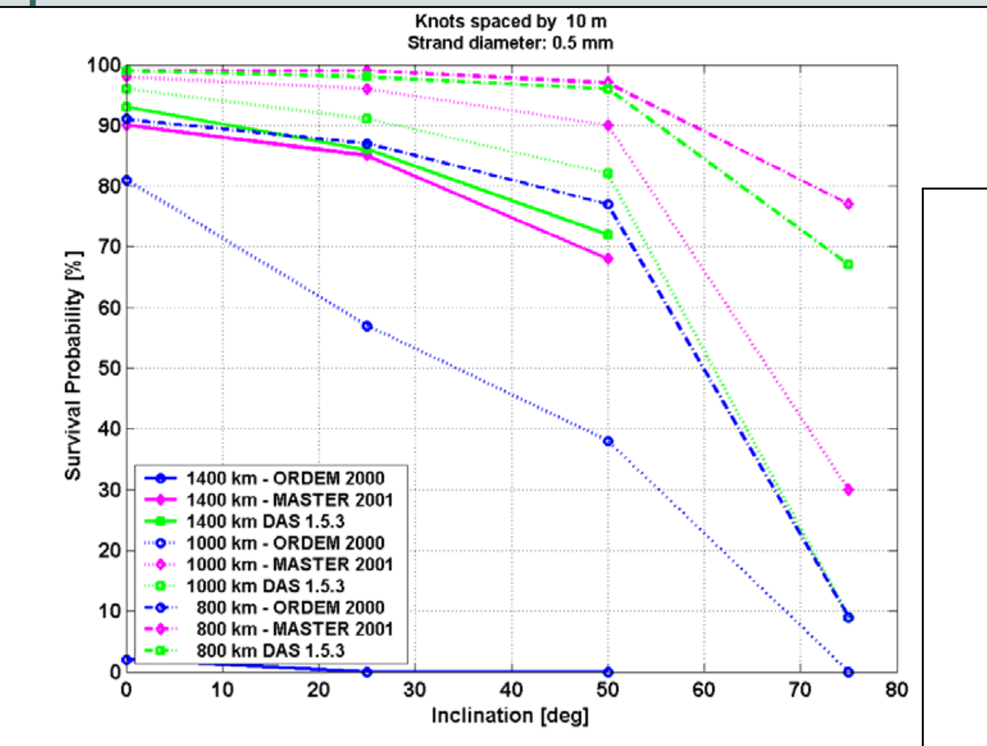
inclination	0 deg		25 deg		50 deg		75 deg	
	Survival Probability [%]							
de-orbiting altitude	JAXA	ASI	JAXA	ASI	JAXA	ASI	JAXA	ASI
1400 km	98	99	97	99	92	98	-	-
1000 km	100	100	100	100	99	99	85	93
800 km	100	100	100	100	100	100	98	98

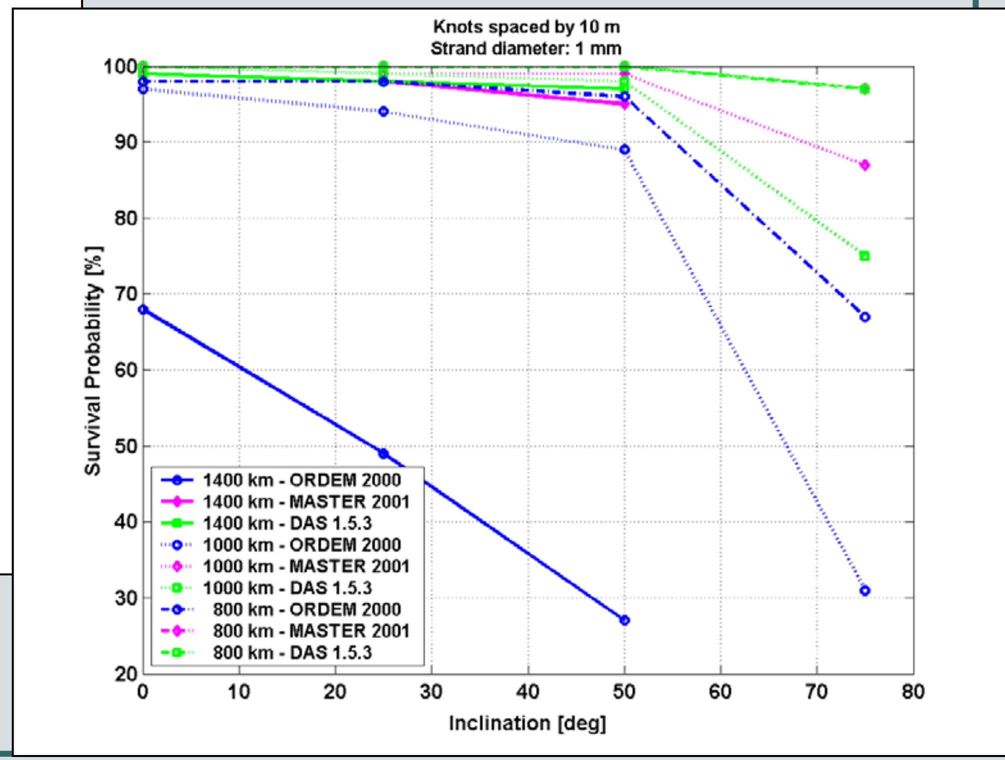
Test 2 - Survivability Analysis
Double-strand, Multi-loop Tether
Knots Spaced by 100 m
ASI – Results dependence on the debris flux model



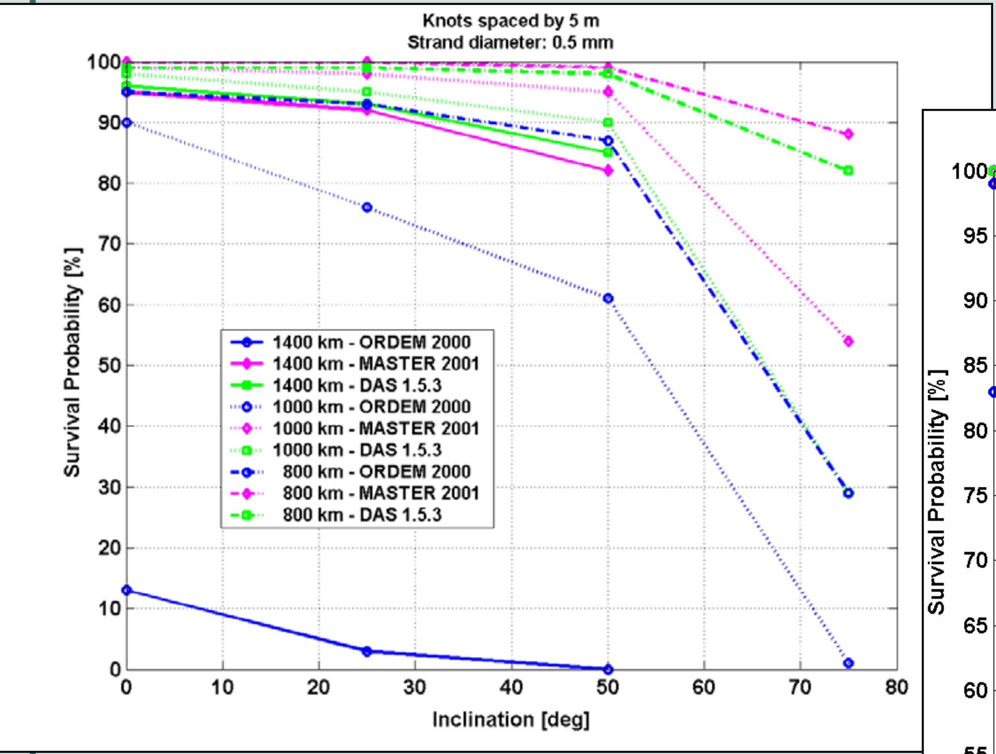


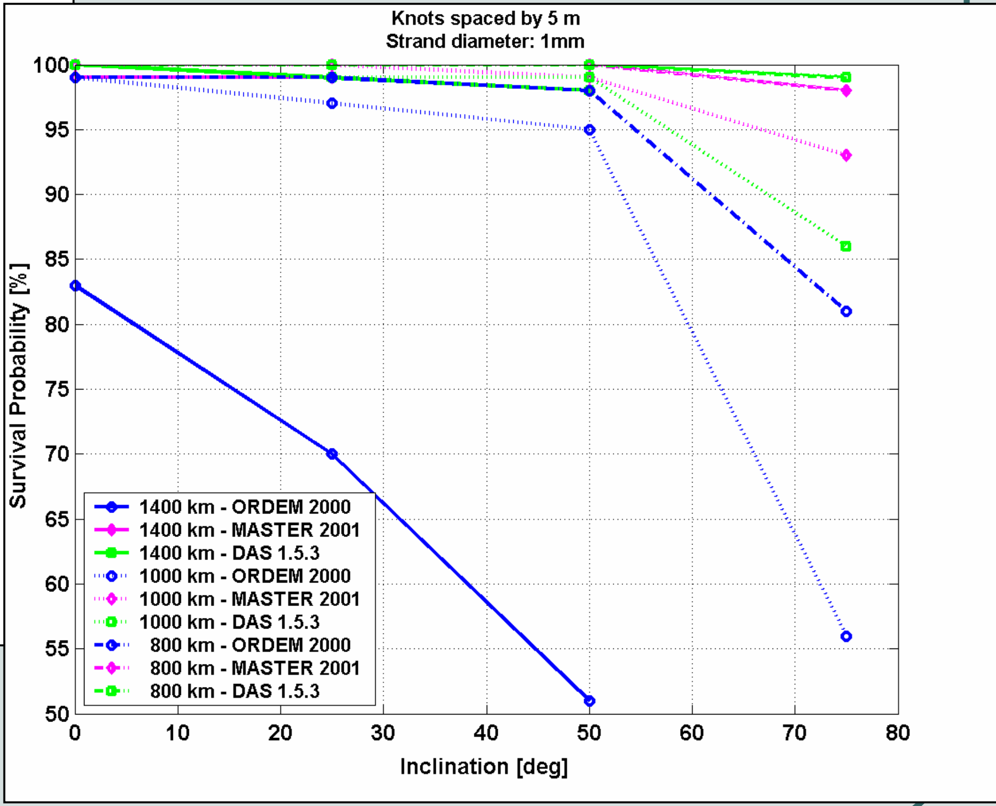
Test 2 - Survivability Analysis
Double-strand, Multi-loop Tether
Knots Spaced by 10 m
ASI – Results dependence on the debris flux model





Test 2 - Survivability Analysis
Double-strand, Multi-loop Tether
Knots Spaced by 5 m
ASI – Results dependence on the debris flux model





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

Taking into account the Terminator Tether de-orbiting times, ASI, JAXA and NASA found that no de-orbiting mission from the altitudes and inclinations considered is possible using a single-line tether with diameter of 0.5 mm or 1 mm

ORDEM 2000 (ASI – JAXA – NASA)

Tether diameter D_T = 0.5 mm, 1 mm: Survival Probability (SP) = 0 in all cases

DAS 1.5.3 (ASI – NASA)

D_T = 0.5 mm: SP = 0 in all cases

D_T = 1 mm: maximum SP: 22% (ASI, 800 km and 0°); 3% (NASA, 800 km and 0°)

MASTER 2001 (ASI – JAXA)

D_T = 0.5 mm: maximum SP: 1% (ASI, 800 km and 0°); 2% (JAXA, 800 km and 0°)

D_T = 1 mm: maximum SP: 57% (ASI, 800 km and 0°); 39% (JAXA, 800 km and 0°)

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

Different techniques to compute the tether survival probability were adopted

1) ASI – JAXA - NASA: Space debris flux model: ORDEM 2000 + Meteoroids

According to ASI, JAXA & NASA no de-orbiting mission is possible if the strand diameter is 0.5 mm for each tether configuration assumed.

If the strand diameter is 1 mm:

Number of loops: 750 (knots spaced by 10 m)

- **ASI – SP > 96% from 800 km (0°, 25°, 50°) and 1000 km (0°)**
- **NASA – SP = 95% from 800 km (0°)**

Number of loops: 1500 (knots spaced by 5 m)

- **ASI – SP > 96% from 800 km (0°, 25°, 50°) and 1000 km (0°)**
- **NASA – SP ≥ 96% from 800 km (0°, 25°)**
- **JAXA – SP = 96% from 800 km (0°)**

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

2) ASI – NASA: Space debris flux model: DAS 1.5.3

The DAS 1.5.3 fluxes result in higher survival probabilities than ORDEM 2000

Number of loops 1500, strand diameter = 1 mm

According to ASI and NASA, a survival probability > 97% results during de-orbiting missions from 1400 km, 1000 km and 800 km and inclinations 0° and 25°. If the inclination is 50°, de-orbiting missions are possible from 800 km.

3) ASI – JAXA: Space debris flux model: MASTER 2001

The MASTER 2001 fluxes result in higher survival probabilities than ORDEM 2000 and in SP similar to DAS 1.5.3

Number of loops 1500, strand diameter = 1 mm

According to ASI and JAXA, a survival probability > 97% results during de-orbiting missions from 1400 km, 1000 km and 800 km and inclinations 0° and 25°; SP > 99% from 1000 km up to inc = 50°. If the inclination is 75°, de-orbiting missions are possible from 800 km.

Conclusions
Test 2 – Survival Probability

- **Detailed computations and comparisons were carried out for the simulated de-orbiting missions of a 1500 kg satellite , with initial altitudes of 800, 1000 and 1400 km, and orbital inclinations of 0, 25, 50 and 75 deg.**

- **Tethers with a length of 7.5 km, of both single and double line designs, were considered adopting conducting wires with diameter of 0.5 and 1 mm.**

- **For the double line tether design, three configurations were assumed with each segment length of 5, 10 and 100 m.**

- **To assess the tether vulnerability, the following assumptions were made:**

  d **(minimum debris diameter able to sever a tether)** $\geq 0.25D_T$

  D_{TC} **(critical tether diameter)** $= 0.7D_T$.

Conclusions
Test 2 – Survival Probability

According to ASI, JAXA and NASA, provided the hypotheses assumed in the AI 19.1 study plan are correct:

- **THE SURVIVABILITY CONCERN IS FULLY JUSTIFIED FOR A SINGLE LINE TETHER**

  No de-orbiting mission is possible, from the altitudes and inclinations considered, using a single line tether with a diameter of 0.5 mm or 1 mm.

- **THE SURVIVAL PROBABILITY MAY SIGNIFICANTLY GROW FOR A DOUBLE LINE CONFIGURATION WITH A SUFFICIENTLY HIGH NUMBER OF KNOTS AND LOOPS**

  For a double-line tether, the survival probability increases:

  - **By decreasing the initial de-orbit altitude;**
  - **By decreasing the orbital inclination;**
  - **By increasing the number of tether loops and strand diameter.**

Conclusions
Test 2 – Survival Probability

- **THE RESULTS STRONGLY DEPEND ON THE DEBRIS MODEL ADOPTED, THE MORE PESSIMISTIC ESTIMATIONS WERE OBTAINED WITH ORDEM 2000**

The MASTER 2001 and DAS 1.5.3 fluxes result in comparable survival probabilities higher than ORDEM 2000.

If ORDEM 2000 is used, an acceptable survival probability (> 95%) exists to de-orbit S/C from 800 km, at low inclinations, using a double-line tether with 1500 loops and strand diameter of 1 mm. On the contrary, using DAS 1.5.3, or MASTER 2001, the same tether system allows the majority of the de-orbiting missions proposed, except at high inclination (75°).

Status of AI 19.1

- **The**
  - **State-of-the-art knowledge on space tether applications;**
  - **Use of electrodynamic tethers (EDT) devices to de-orbit spacecraft;**
  - **Potential benefits and risks of using EDT to de-orbit spacecraft,**

  were presented.

- **The two tests proposed in the AI 19.1 Study Plan were concluded and the results were compared. General agreement was found between ASI, JAXA and NASA and differences can be explained.**

- **Not exactly the same debris flux values were adopted by ASI, JAXA and NASA when using the same environment model. Additional tests using the same debris fluxes might be necessary (open to discussion).**

- **The final report will be compiled by ASI, with contributions of JAXA and NASA, by the next Steering Group meeting in Fukuoka, Japan, October 2005, provided all results required are available.**