IADC AI 19.1

"POTENTIAL BENEFITS AND RISKS OF USING ELECTRODYNAMIC TETHERS FOR END-OF-LIFE DE-ORBIT OF LEO SPACECRAFT"

Final Results & Draft Report

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24th IADC Plenary Meeting, Tsukuba, Japan, 10-13 April 2006

The IADC AI 19.1

De-orbiting devices based on the use of conducting tethers have been proposed as innovative solutions to mitigate the growth of orbital debris

But

Tethers in space introduce unusual problems when viewed from the space debris perspective

- **They present a much greater risk to operating spacecraft due to their considerably large collision cross-sectional area**
- **Because of their small diameter, tethers of normal design may have a high probability of being severed by impacts with relatively small meteoroids and orbital debris**
- **The resulting tether fragments may pose additional risks to operating spacecraft**

Such space debris related concerns prompted the Inter-Agency Space Debris Coordination Committee to recognize this task and to open, in March 2001, a new Action Item (AI 19.1) with the purpose of investigating the

"Potential Benefits and Risks of using Tethers in Space"

IADC AI 19.1 - A Short History [1]

- The AI 19.1 was opened at the 19th IADC meeting held in Cologne, Germany, from 22 to 23 March 2001, and it was assigned to WG2

- At the 20th IADC meeting held in Guilford, Surrey, England, from 9 to 12 April 2002, Gerhard Drolshagen [ESA] introduced the existing and under development tools to analyse the dynamics of tethers in space and to estimate the collision risk of tethers with space debris and operative spacecraft

- At the 21th IADC meeting held in Bangalore, India, from 10 to 13 March 2003, Carmen Pardini [ASI] gave 3 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

At the same meeting, the specifics of the task were formulated and a proposal to address the Electrodynamic Tether (EDT) systems survivability concern was advanced inside WG 2

The original AI designation, i.e. “Benefits and Risks of using Space Tethers”, was then changed in:

“***Potential Benefits and Risks of using Electrodynamic Tethers for end-of-life De-orbit of LEO Spacecraft***”

IADC AI 19.1 - A Short History [2]

Two independent studies were proposed by C. Pardini (Lead) and sent to all WG 2 members on 20 November 2003:

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 survivability of a specific electrodynamic tether system during typical de-orbiting missions**

IADC members of three countries volunteered to participate in the study:

- The Space Flight Dynamics Laboratory of ISTI, an institute of the Italian National Research Council (CNR), on behalf of the Italian Space Agency (**ASI**)
- The Department of Aeronautics and Astronautics of the Kyushu University (KU), on behalf of the Japan Aerospace Exploration Agency (**JAXA**)
- The Johnson Space Center (JSC) of the US National Aeronautics and Space Administration (**NASA**)

Different computational approaches were specifically developed in the framework of this IADC task; other techniques, coming from past research and experience in the field, were instead revised and improved.

IADC AI 19.1 - A Short History [3]

In the AI 19.1 Study Plan of 30 November 2003, all participating members were asked to use the space environment and impact probability models of their own choice

- The study plan and some preliminary results of test 1 were presented at the 22th IADC meeting held in Abano Terme, Italy, from 19 to 22 April 2004
- Preliminary results for test 2 were given at the 23th IADC meeting held in Darmstadt, Germany, from 21 to 22 April 2005

At the 23th IADC, for consistency and comparisons of the results all participating members were tasked to use two particular space environments, including both orbital debris and meteoroids, based on MASTER-2001 and ORDEM2000 coupled with the Grün meteoroids model

The two AI 19.1 tests were thus repeated and the final results will be herein presented

A draft Final Report (Version 1.0) of the IADC AI 19.1 was also compiled and it will be introduced and discussed in this session meeting

IADC AI 19.1 – Space Debris Flux Models [1]

IADC AI 19.1 TEST 1

The environment model used for the **first AI 19.1 test** was the NASA's **ORDEM2000** model, **coupled with** the **Grün** meteoroids model. The fluxes were computed at epoch January 2003

IADC AI 19.1 TEST 2

For the second AI 19.1 test on the survivability analysis, two different representations of the environment were assumed:

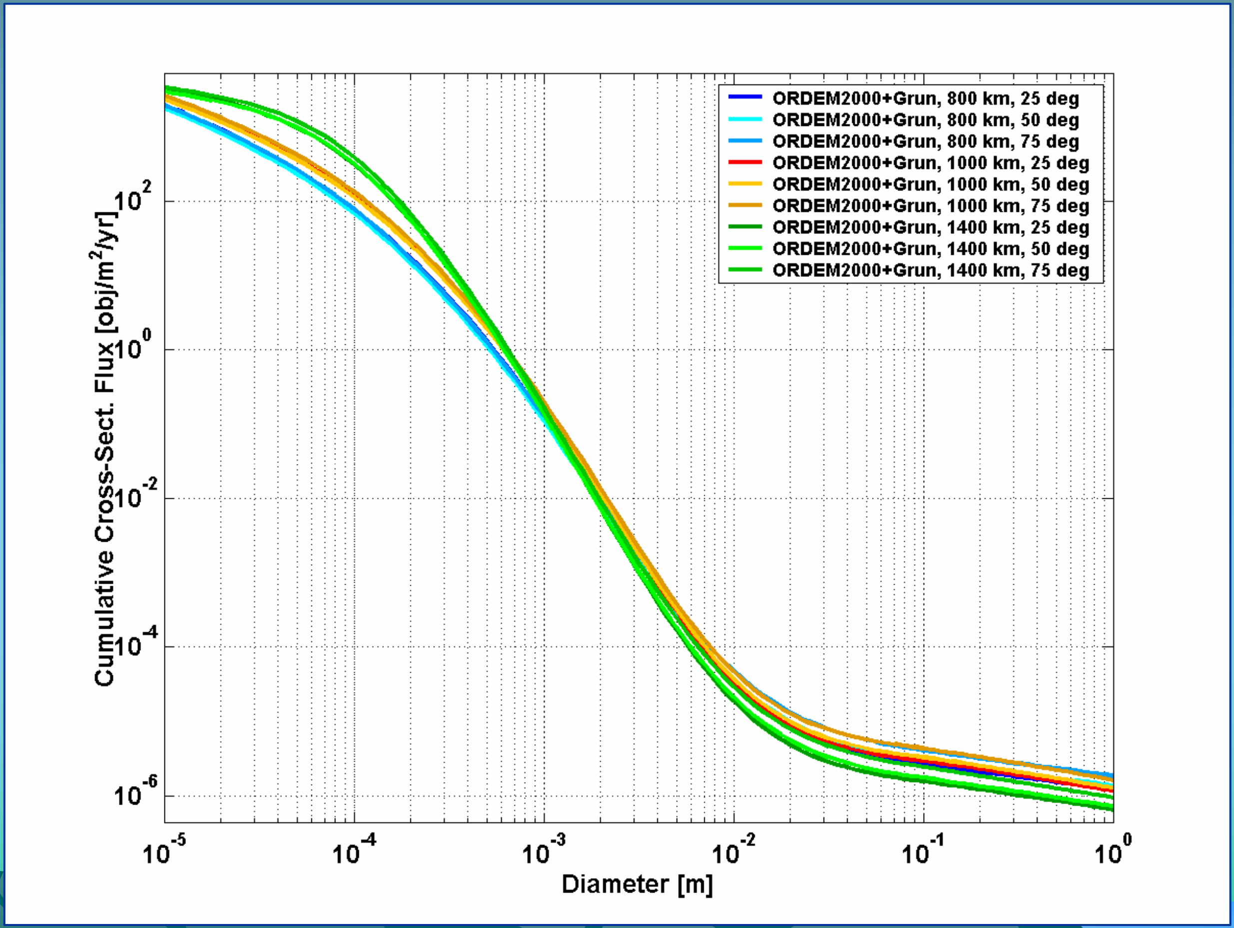
- **ORDEM2000 (orbital debris) coupled with Grün (meteoroids) at epoch January 2001**
- **MASTER-2001 (orbital debris and meteoroids). The analyst application was used to obtain more accurate debris fluxes at the reference epoch of the model, i.e. May 5th, 2001**

Large differences exist in the flux versus particle diameter distribution computed by the ESA and NASA models, with ORDEM2000 predicting fluxes up to one order of magnitude higher than MASTER-2001 in the significant diameter region of less than 1 mm

IADC AI 19.1 – Space Debris Flux Models [2]

IADC AI 19.1 TEST 1

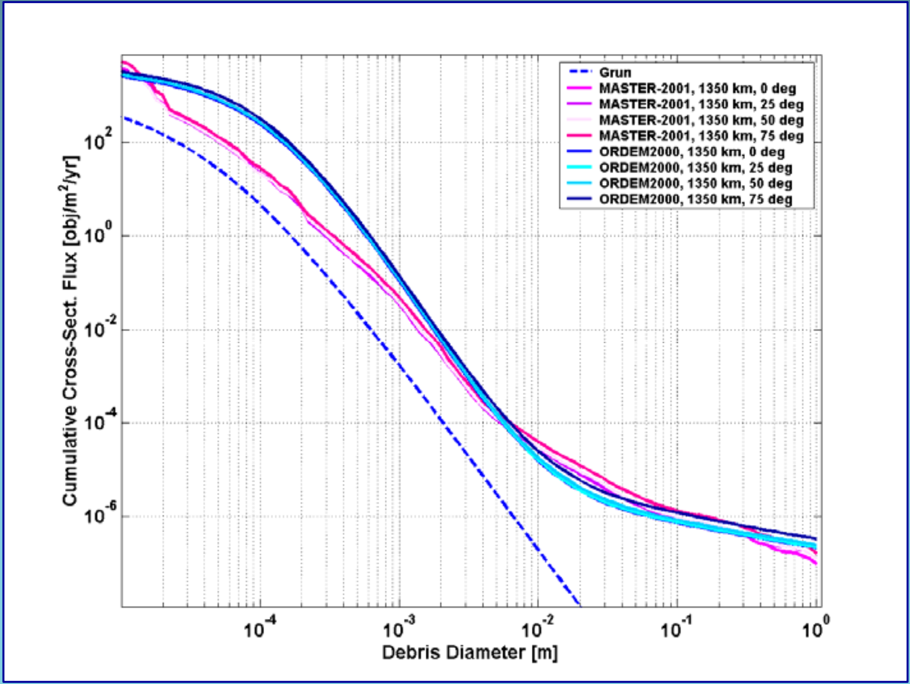
Cumulative flux of orbital debris (ORDEM2000) and meteoroids (Grün) at 800, 1000, 1400 km, i = 25˚, 50˚, 75˚, versus debris diameter. Reference epoch: January 2003.

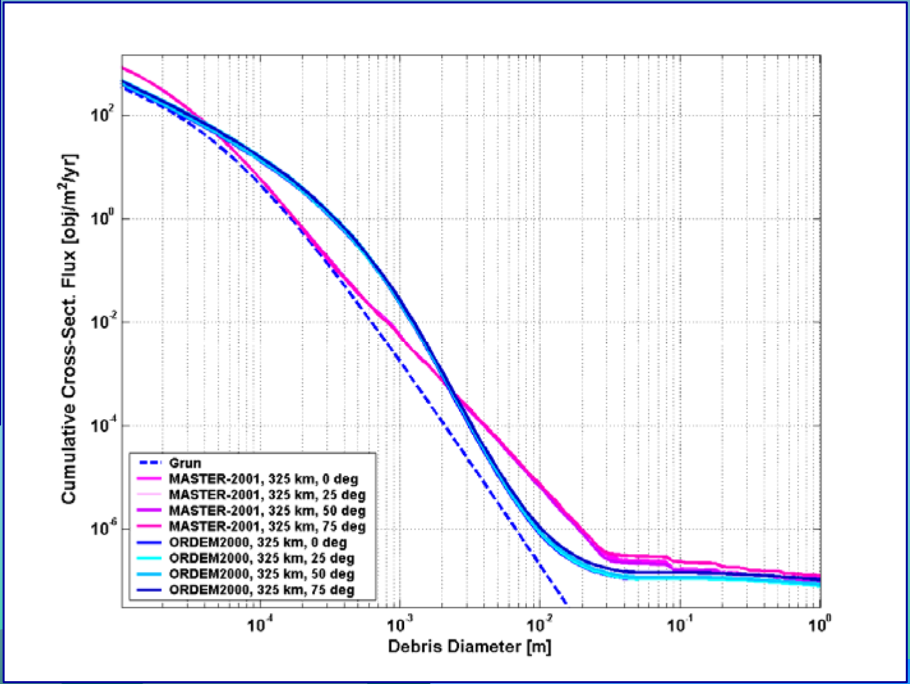


IADC AI 19.1 – Space Debris Flux Models [3]

IADC AI 19.1 TEST 2

For the second AI 19.1 test, the debris flux was estimated in the middle of each altitude shell crossed during the de-orbiting mission, i.e. :1350, 1250, 1150, 1050, 950, 850, 750, 650, 550, 450, 325 km, and inclinations of 0°, 25°, 50° and 75°





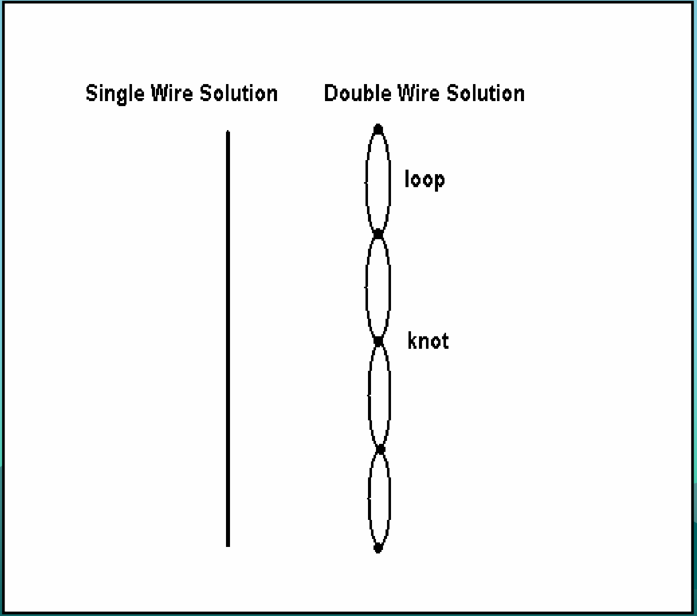
IADC AI 19.1 – Tether Orbital Configuration & Design

The tether orbital configurations and designs assumed in the AI 19.1 study plan were very simple.

Tethers were supposed to be in circular orbit and aligned along the gravity gradient.

Two basically different and very simple designs were considered:

- **Single tether, with a single wire or a compact cylindrical multi-line structure**
- **Double tethers, in which two cables are separated from each other by a distance significantly larger than their diameter and form *N* loops, tied together in *N* + 1 equidistant knots**



TEST 1

Tethers with a length of 5 km, 7.5 km and 10 km, of single line design, were considered in the first AI 19.1 test, adopting wires with diameters of 0.50 mm, 0.75 mm, 1 mm, 2.5 mm, 5 mm, 1 cm, 2.5 cm and 5 cm

TEST 2

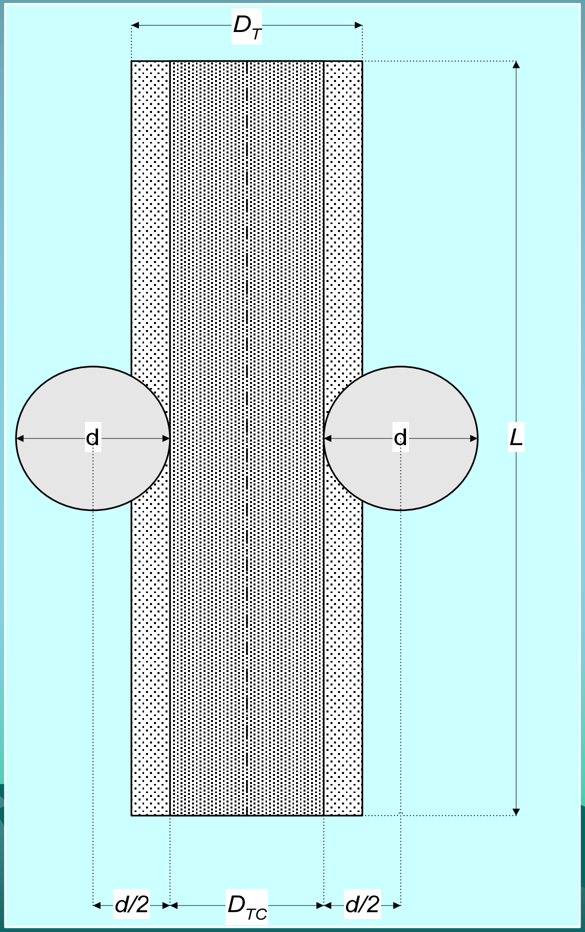
Tethers of length 7.5 km, with both single and double line designs, were considered in the second AI 19.1 test, adopting conducting wires with diameter of 0.5 mm and 1 mm. With regards to the double line solution, three configurations, where the length of each tether loop was 5 m, 10 m and 100 m, were simulated.

IADC AI 19.1 – Tether Vulnerability to Space Debris Impacts

A single tether was assumed to be severed by a space debris with a diameter d larger than a certain fraction f of the tether diameter D_T

$$d \geq d_C = f \cdot D_T$$

where d_C is defined as the minimum fatal debris diameter, provided that the debris edge passes within a critical distance $D_{TC}/2$ from the longitudinal axis of symmetry of the tether



IADC AI 19.1 TEST 1

The following conjecture on the tether vulnerability was considered in the first test

$$d_C = 0.25 \cdot D_T \text{ and } D_{TC} = 0.7 \cdot D_T$$

IADC AI 19.1 TEST 2

The following two conjectures were adopted in the second test

1. $d_C = 0.25 \cdot D_T$ and $D_{TC} = 0.7 \cdot D_T$
2. $d_C = 0.33 \cdot D_T$ and $D_{TC} = 0.7 \cdot D_T$

Moreover, a negligible cross-sectional area of the knots, and a distance between the two cables much greater than d_C was assumed for double line systems

IADC AI 19.1 – Test 1
Fatal Impact Rates & Average Lifetimes

The fatal impact rate, in ($yr^{-1}km^{-1}$), was computed for each selected orbital 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

Single line tethers were considered

One specific tether vulnerability conjecture was considered, that of limiting the minimum fatal debris diameter to 1/4 of the tether diameter

The Average Lifetimes of tethers with different lengths (5 km, 7.5 km, 10 km) were estimated

Results of the First IADC AI 19.1 Test
Fatal Impact Rates

The approaches developed at ISTI/CNR, Kyushu University and Johnson Space Center for a single line tether were applied to compute the fatal impact rate of meteoroids and orbital debris on space tethers

The conjecture on the tether vulnerability was applied to obtain the fatal debris diameter and the critical tether diameter

Tether Diameter [mm]	Fatal Debris Diameter [mm]	Critical Tether Diameter [mm]
0.50	0.1250	0.350
0.75	0.1875	0.525
1.00	0.2500	0.700
2.50	0.6250	1.750
5.00	1.2500	3.500
10.00	2.5000	7.000
25.00	6.2500	17.50
50.00	12.500	35.00

For tether diameters in between 0.5 and 5 mm, the JSC's fatal impacts rates are generally lower than those computed by ISTI and KU

The differences reduce to a few percent as the tether size exceeds 1 mm

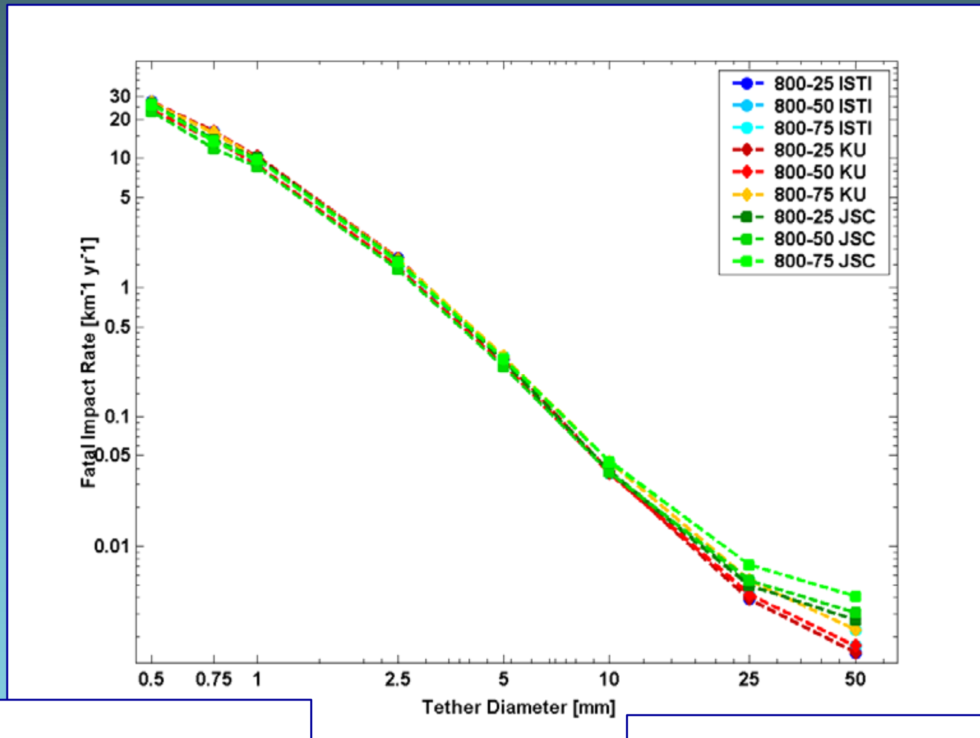
At 1 cm, the differences are still very small and the JSC results are somewhat higher at 800 km and slightly lower elsewhere

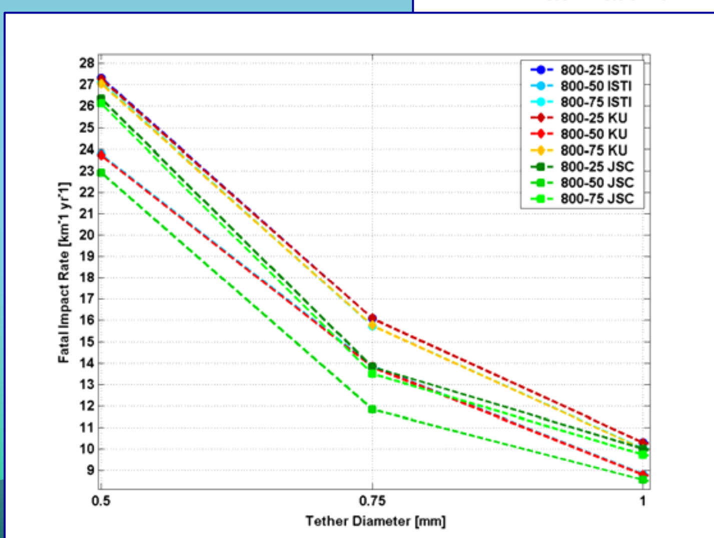
For the largest tether diameters (2.5 cm and 5 cm), the fatal impact rates obtained by JSC are typically higher than those by ISTI and KU

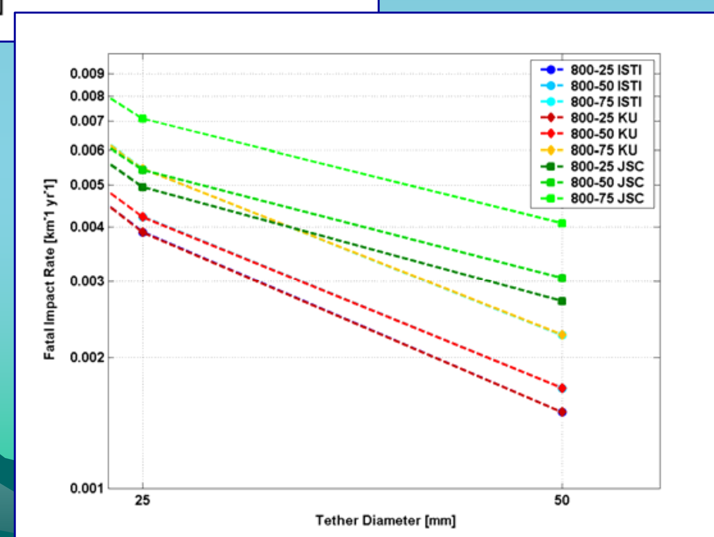
Results of the First IADC AI 19.1 Test

Altitude and Inclination	Tether Diameter [mm]							
	0.5	0.75	1	2.5	5	10	25	50
	Fatal Debris Diameter [mm]							
	0.125	0.1875	0.25	0.625	1.25	2.5	6.25	12.5
	Tether Critical Diameter [mm]							
	0.35	0.525	0.7	1.75	3.5	7	17.5	35
	ISTI / KU / JSC FATAL IMPACT RATE [yr^{-1} km^{-1}]							
800 km, 25°	27.32 27.27 26.35	16.08 16.09 13.81	10.30 10.28 10.00	1.683 1.681 1.607	0.2826 0.2820 0.2710	0.03783 0.03780 0.03782	0.003893 0.003889 0.004947	0.001497 0.001496 0.002695
800 km, 50°	23.76 23.71 22.91	13.85 13.82 11.84	8.81 8.79 8.55	1.444 1.443 1.380	0.2528 0.2523 0.2428	0.03670 0.03663 0.03685	0.004217 0.004217 0.005415	0.001697 0.001698 0.003044
800 km, 75°	27.10 27.05 26.13	15.74 15.75 13.48	10.02 10.00 9.73	1.651 1.648 1.576	0.2947 0.2942 0.2834	0.04455 0.04448 0.04495	0.005446 0.005445 0.007085	0.002251 0.002252 0.004082
1000 km, 25°	42.48 42.39 40.98	25.72 25.69 22.12	16.65 16.64 16.19	2.722 2.723 2.601	0.4248 0.4239 0.4066	0.04942 0.04939 0.04896	0.004288 0.004274 0.005246	0.001622 0.001621 0.002751
1000 km, 50°	39.90 39.84 38.51	23.79 23.79 20.44	15.33 15.31 14.89	2.446 2.441 2.332	0.3891 0.3882 0.3708	0.04842 0.04835 0.04808	0.004672 0.004662 0.005741	0.001832 0.001833 0.003078
1000 km, 75°	47.36 47.25 45.67	28.01 27.98 24.00	17.80 17.80 17.31	2.777 2.781 2.656	0.4452 0.4442 0.4262	0.05678 0.05671 0.05653	0.005807 0.005795 0.007176	0.002378 0.002377 0.003961
1400 km, 25°	101.30 101.00 97.53	51.09 51.06 42.49	27.95 27.91 27.10	2.491 2.487 2.363	0.2752 0.2745 0.2623	0.02769 0.02767 0.02742	0.002343 0.002341 0.002895	0.000878 0.000875 0.001516
1400 km, 50°	103.32 103.10 99.52	51.59 51.59 42.84	28.03 27.98 27.17	2.440 2.435 2.313	0.2726 0.2722 0.2603	0.02874 0.02872 0.02852	0.002612 0.002610 0.003228	0.000999 0.000998 0.001711
1400 km, 75°	126.51 126.10 121.77	62.87 62.89 52.20	34.11 34.03 33.05	2.968 2.968 2.821	0.3364 0.3360 0.3213	0.03677 0.03676 0.03651	0.003588 0.003576 0.004367	0.001425 0.001423 0.002338

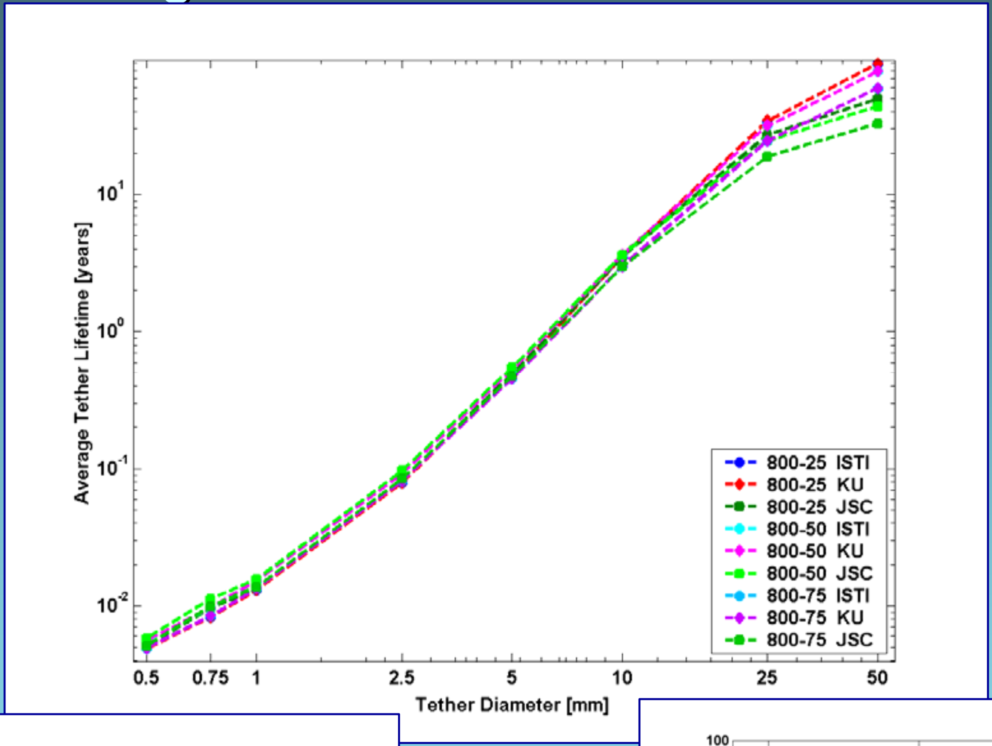
Results of the First IADC AI 19.1 Test
Fatal Impact Rates

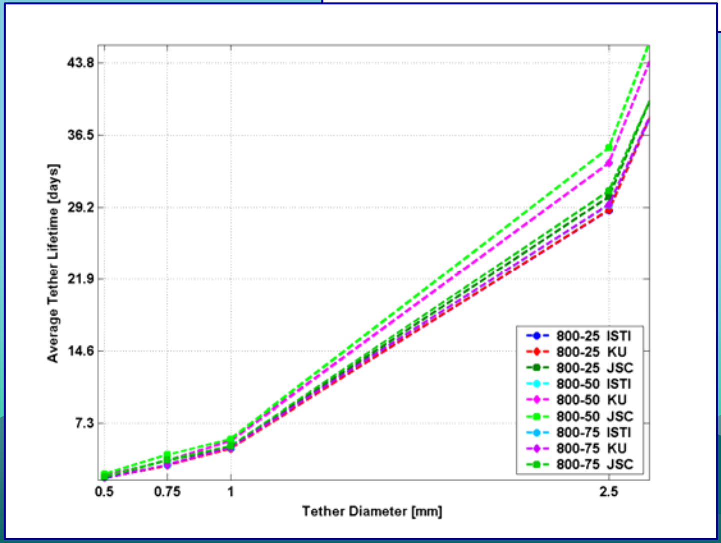


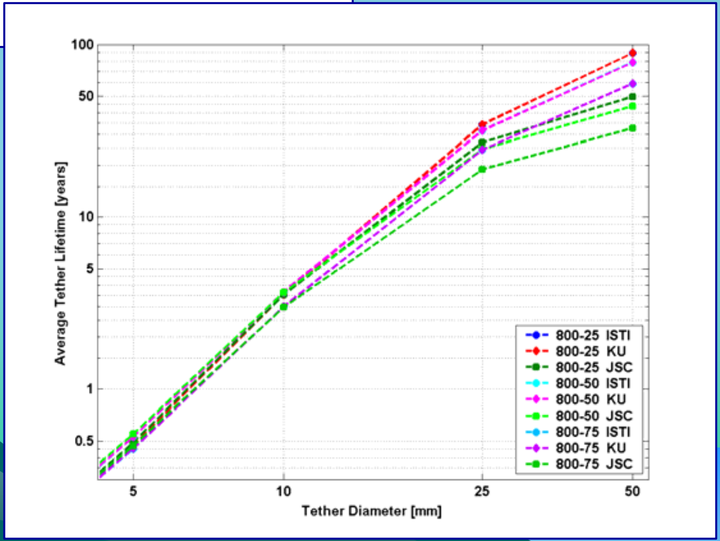




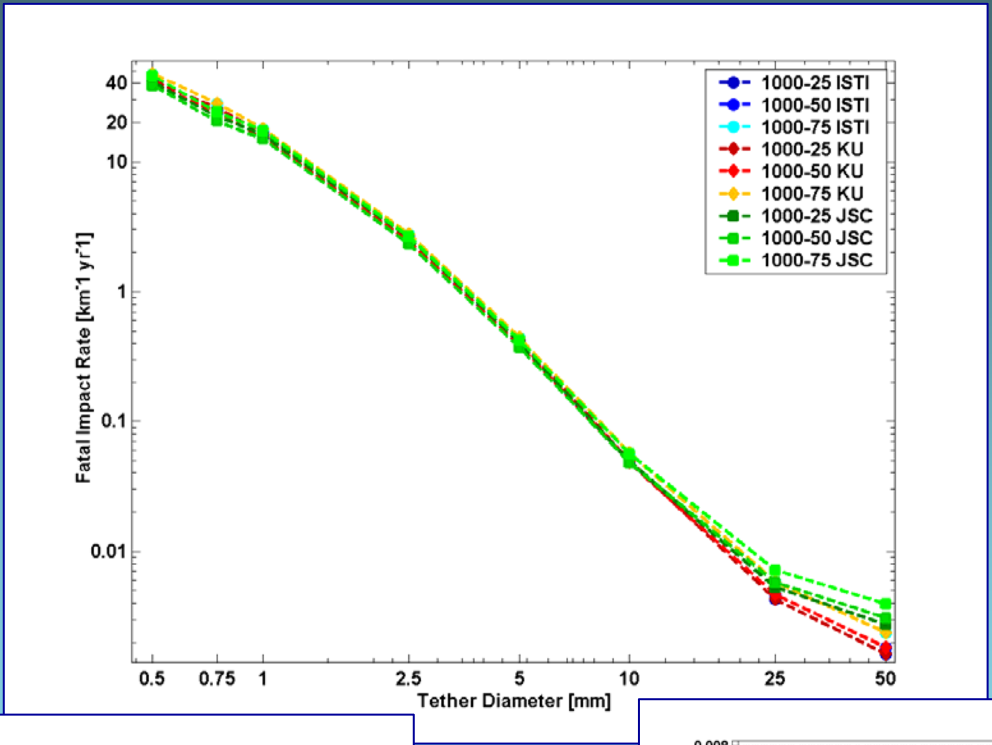
Results of the First IADC AI 19.1 Test
Average Tether Lifetimes of a 7.5 km Tether

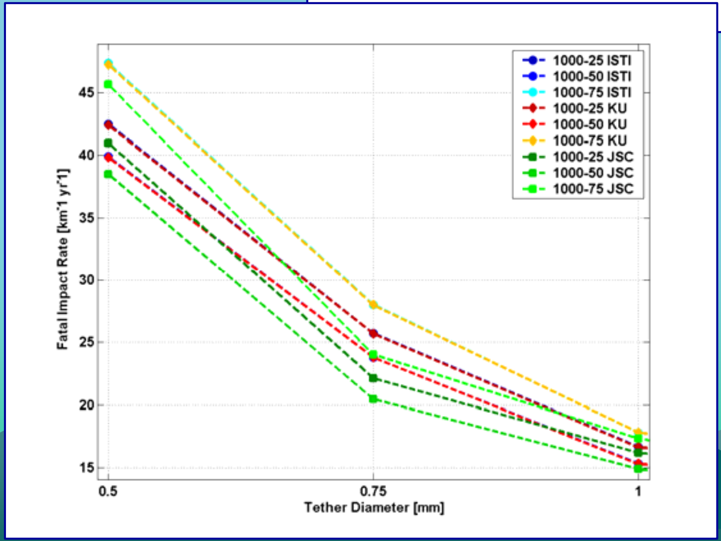


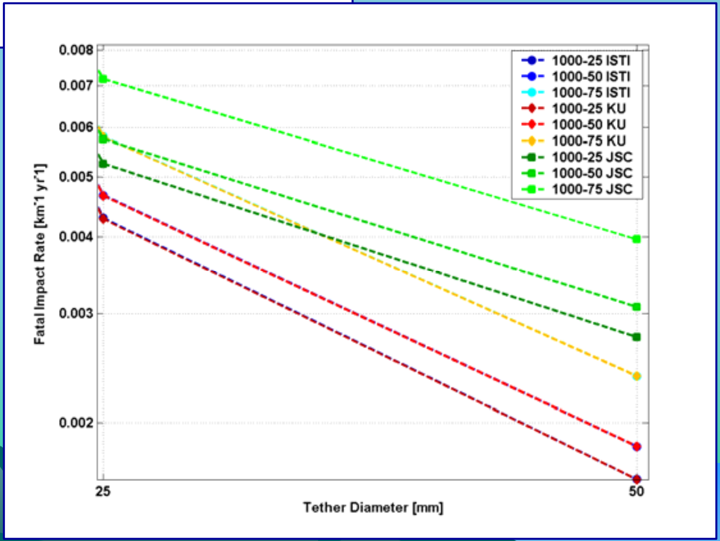




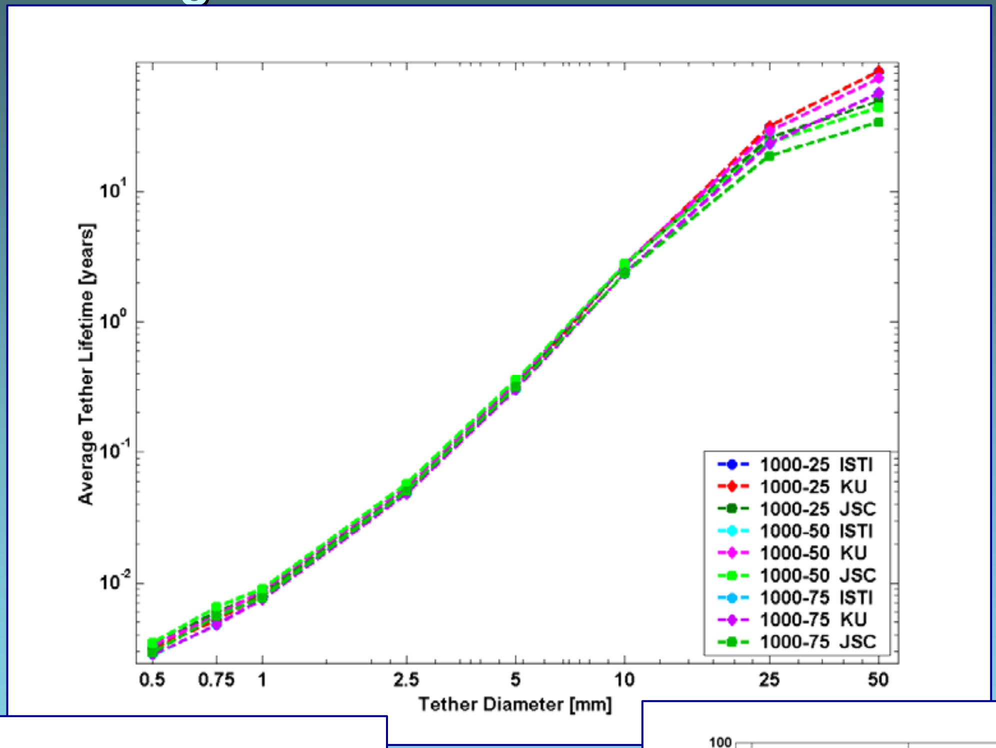
Results of the First IADC AI 19.1 Test
Fatal Impact Rates

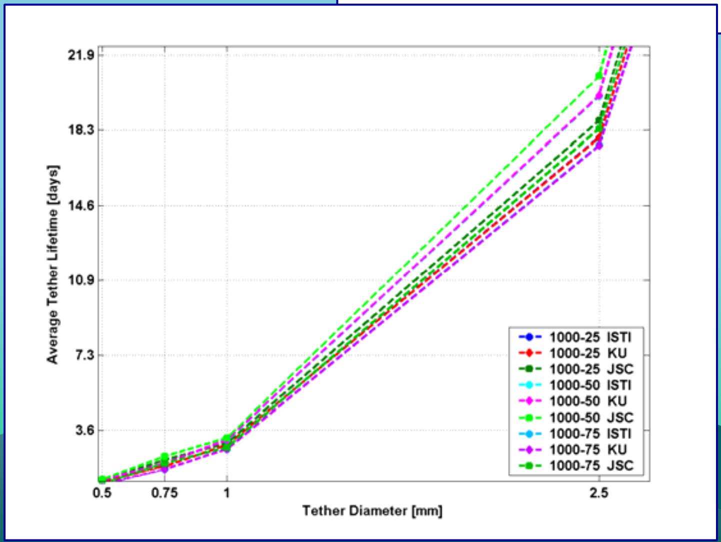


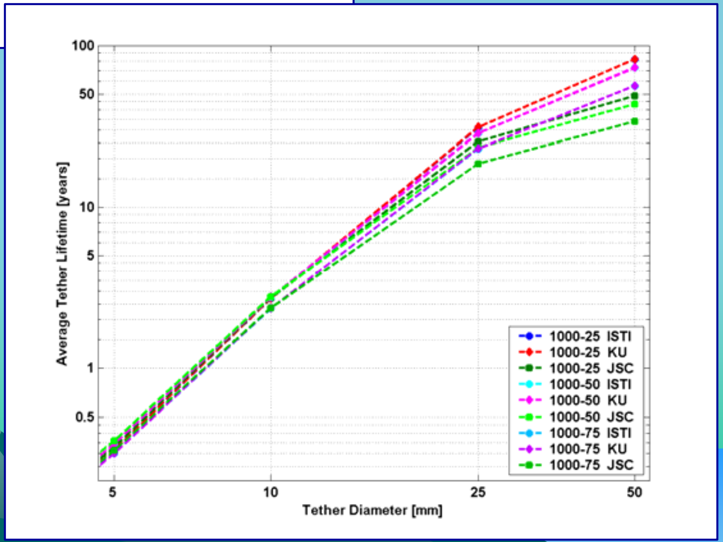




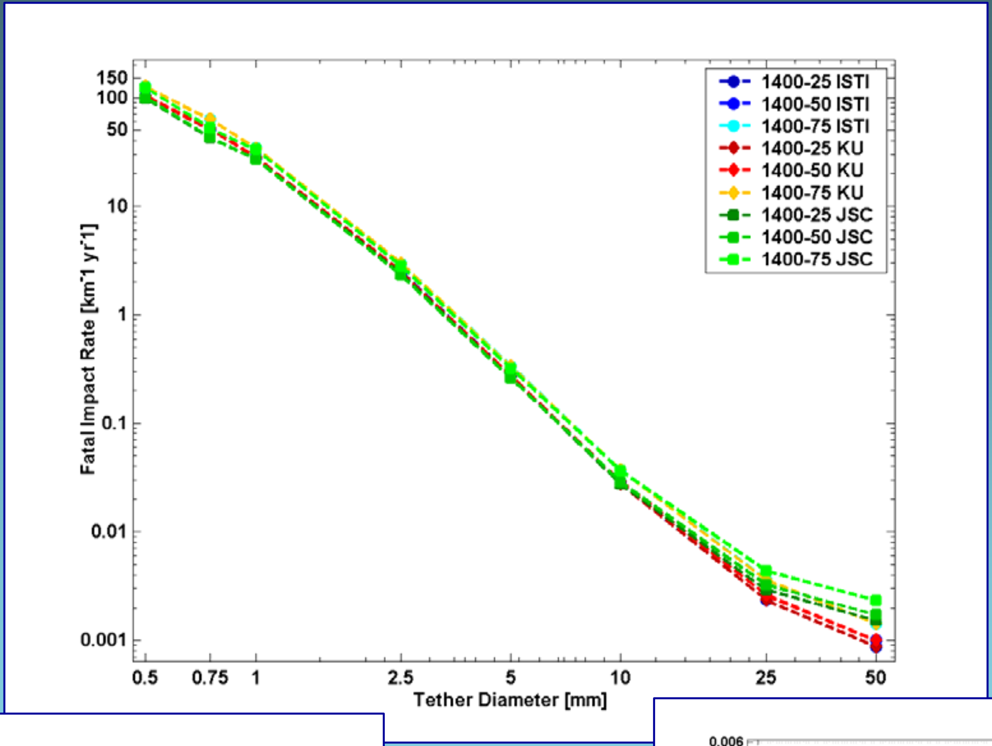
Results of the First IADC AI 19.1 Test
Average Tether Lifetimes of a 7.5 km Tether

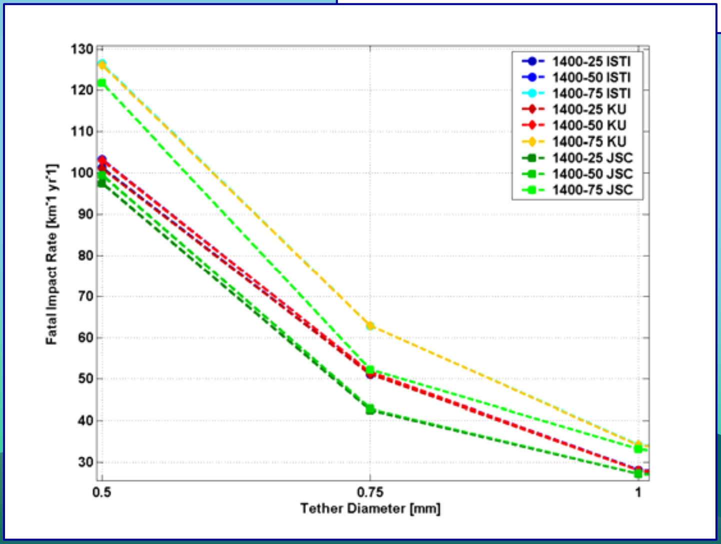


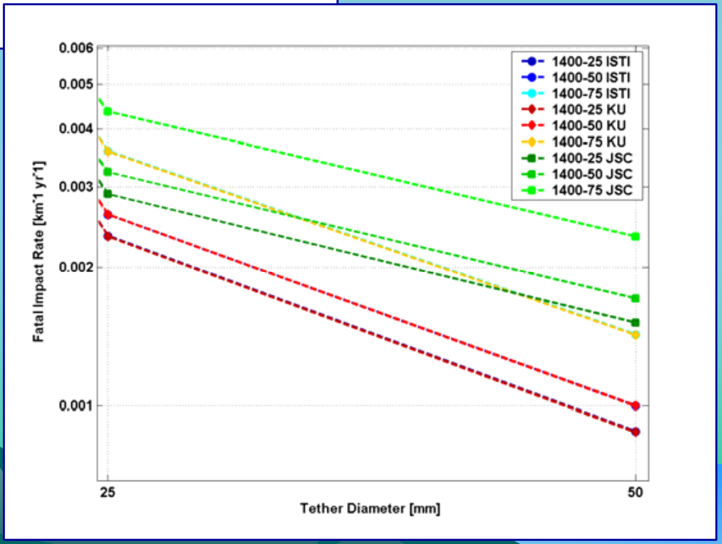




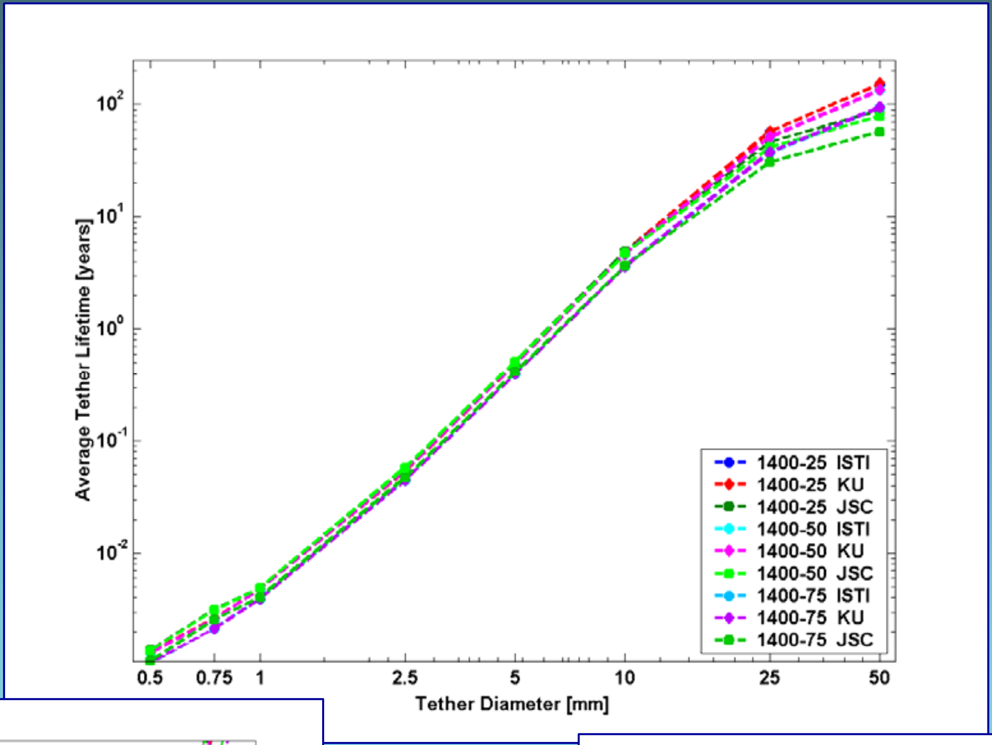
Results of the First IADC AI 19.1 Test
Fatal Impact Rates

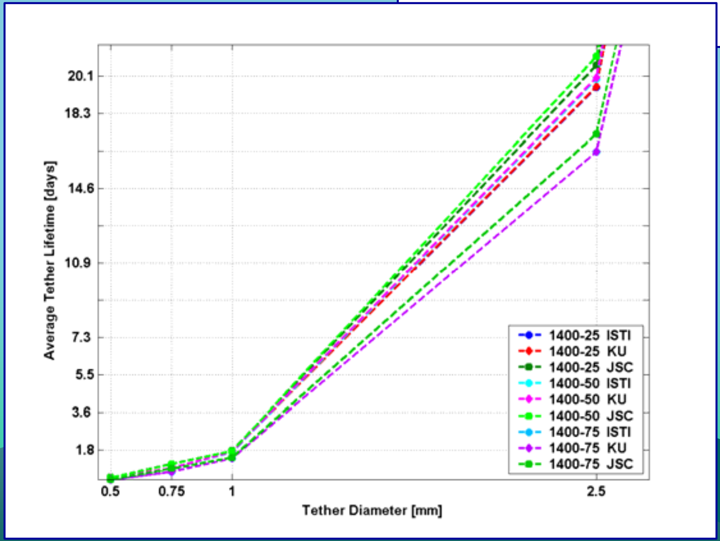


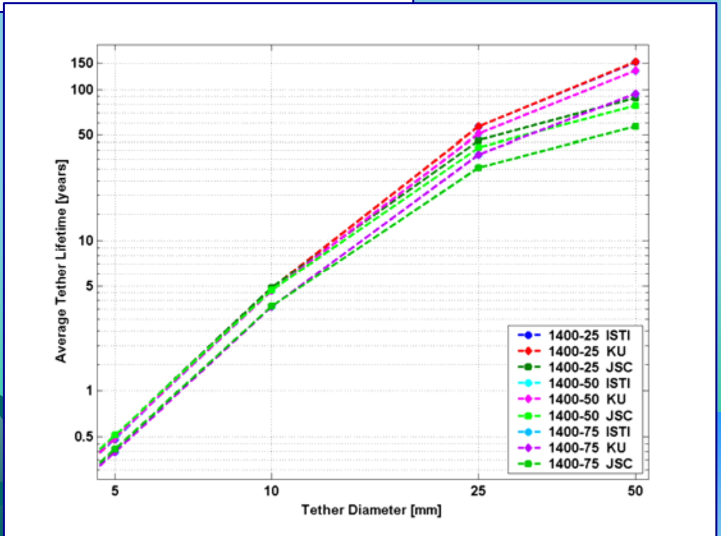




Results of the First IADC AI 19.1 Test
Average Tether Lifetimes of a 7.5 km Tether







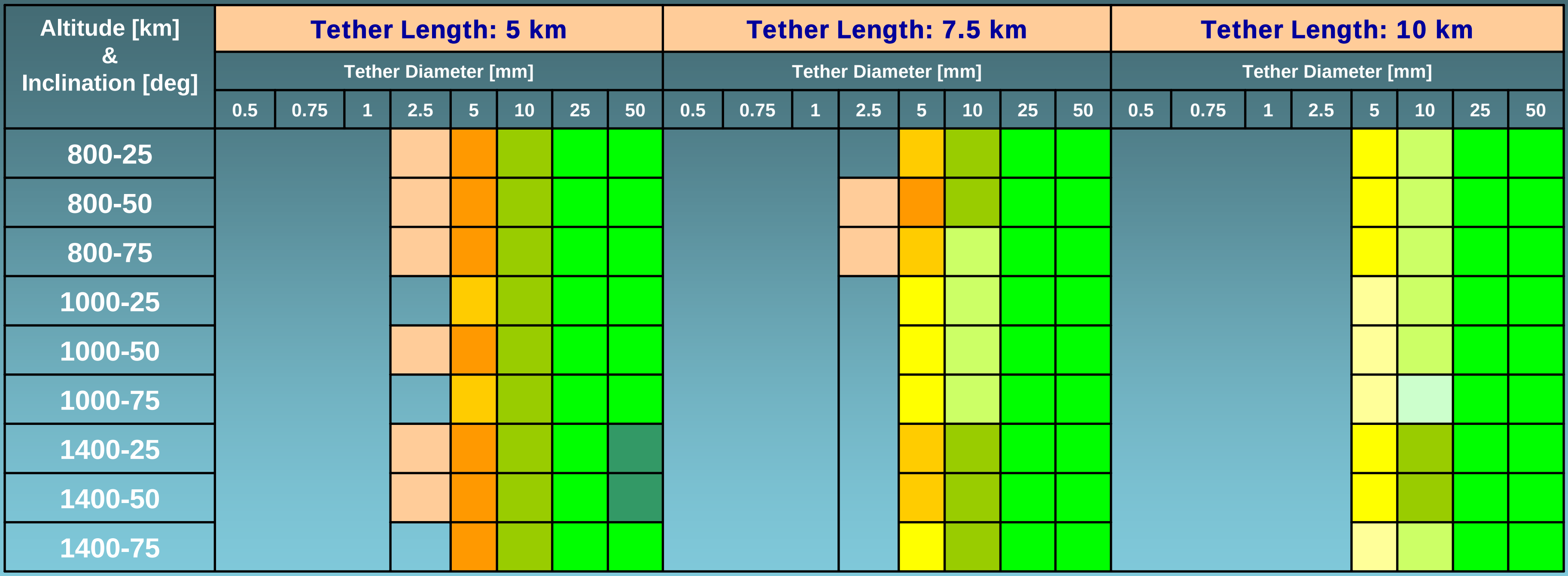
General Conclusions of the First IADC AI 19.1 Test

A good agreement was found among the ISTI, JSC and KU results, leading to the following general conclusions

- **Single line tethers with diameter smaller than 1 mm may survive intact for less than 10 days for all orbital configurations and tether lengths assumed in the study**
- **Increasing the tether diameter to 2.5 mm may result in an average lifetime in between one and two months for a 5 km tether at 800 km, reducing to less than one month at 1000 and 1400 km**
- **A 5 mm single line tether may survive intact for less than 1 year in all orbital and tether scenarios hypothesized**
- **Above 1 cm, the impact with space debris could not be longer a threat for a number of potential missions using tethers. At 1 cm, a 5 km tether may survive intact for a long while, ranging from a minimum of nearly 3 years, at 1000 km and inclination of 75˚, to a maximum of about 7 years at 1400 km and inclination of 25˚**
- **Much more massive tethers with diameters of 2.5 cm and 5 cm may operate for relatively long times, ranging from a few decades to more than a century, depending on the orbital scenario and tether length**
- **In conclusion, provided the tether vulnerability conjecture and the space debris flux model are reasonable, a single line tether with a diameter of 2.5 cm, or larger, may certainly survive the space debris environment for a moderately long time to assure the feasibility of a number of missions. The same is also applicable to a 1 cm tether if the required time for the mission is within a few years**

Using the ORDEM2000+Grün debris flux model maybe results in the most conservative estimate of the tether survivability

General Conclusions of the First IADC AI 19.1 Test



Maximum Average lifetime of at least:

- 30 days
- 70 days
- 100 days
- 150 days
- half an year
- one year
- two years
- three years
- ten years
- one century

IADC AI 19.1 – Test 2
Survivability Analysis

The techniques and tools developed at ISTI, JSC and KU were applied to realistic de-orbiting scenarios based on the concept of the Terminator Tether, from Tether Unlimited Inc.

Detailed computations and through comparisons were carried out for simulated de-orbiting missions of a 1500 kg spacecraft, with initial altitudes of 800 km, 1000 km and 1400 km and orbital inclinations of 0˚, 25˚, 50˚ and 75˚

To increase the probability that the tether will survive the meteoroids and orbital debris environment for the mission duration, a double line tether design was analysed in addition to the single wire solution

Tethers with a length of 7.5 km were considered, adopting conducting wires with diameters of 0.5 mm and 1 mm

With regards to the double line solution, three configurations, where the length of each tether segment was 5, 10 and 100 meters, were simulated

Two specific tether vulnerability conjectures were considered, that of limiting the minimum fatal debris diameter to 1/4 and 1/3 of the tether diameter

IADC AI 19.1 – Test 2
Classification of the Analysed Cases

FOR EACH DE-ORBITING MISSION SCENARIO, SIXTEEN CASES WERE ANALYSED TO IDENTIFY A SUITABLE TETHER DESIGN ABLE TO GUARANTEE, PROVIDED THE HYPOTHESES ASSUMED ARE CORRECT, THE FEASIBILITY OF THE MISSION

7.5 km Single Line Tether			
No.	D_T [mm]	d_C [mm]	D_{TC} [mm]
Tether Vulnerability Conjecture No. 1			
1	0.5	0.125	0.35
2	1.0	0.250	0.70
Tether Vulnerability Conjecture No. 2			
3	0.5	0.167	0.35
4	1.0	0.333	0.70

single line tethers

double line tethers

7.5 km Double Line Tether					
No	D_T [mm]	d_C [mm]	D_{TC} [mm]	L_S [m]	NL
Tether Vulnerability Conjecture No. 1					
5	0.5	0.125	0.35	100	75
6	0.5	0.125	0.35	10	750
7	0.5	0.125	0.35	5	1500
8	1	0.250	0.70	100	75
9	1	0.250	0.70	10	750
10	1	0.250	0.70	5	1500
Tether Vulnerability Conjecture No. 2					
11	0.5	0.167	0.35	100	75
12	0.5	0.167	0.35	10	750
13	0.5	0.167	0.35	5	1500
14	1	0.333	0.70	100	75
15	1	0.333	0.70	10	750
16	1	0.333	0.70	5	1500

IADC AI 19.1 – Test 2
De-orbit Times

THE DE-ORBIT TIMES ASSUMED WERE THOSE COMPUTED BY HOYT & FORWARD FOR A 7.5 km ELECTRODYNAMIC TETHER, WITH MASS 1% OF THE HOST SPACECRAFT, TO DECREASE THE ALTITUDE OF A 1500 kg SPACECRAFT TO 250 km

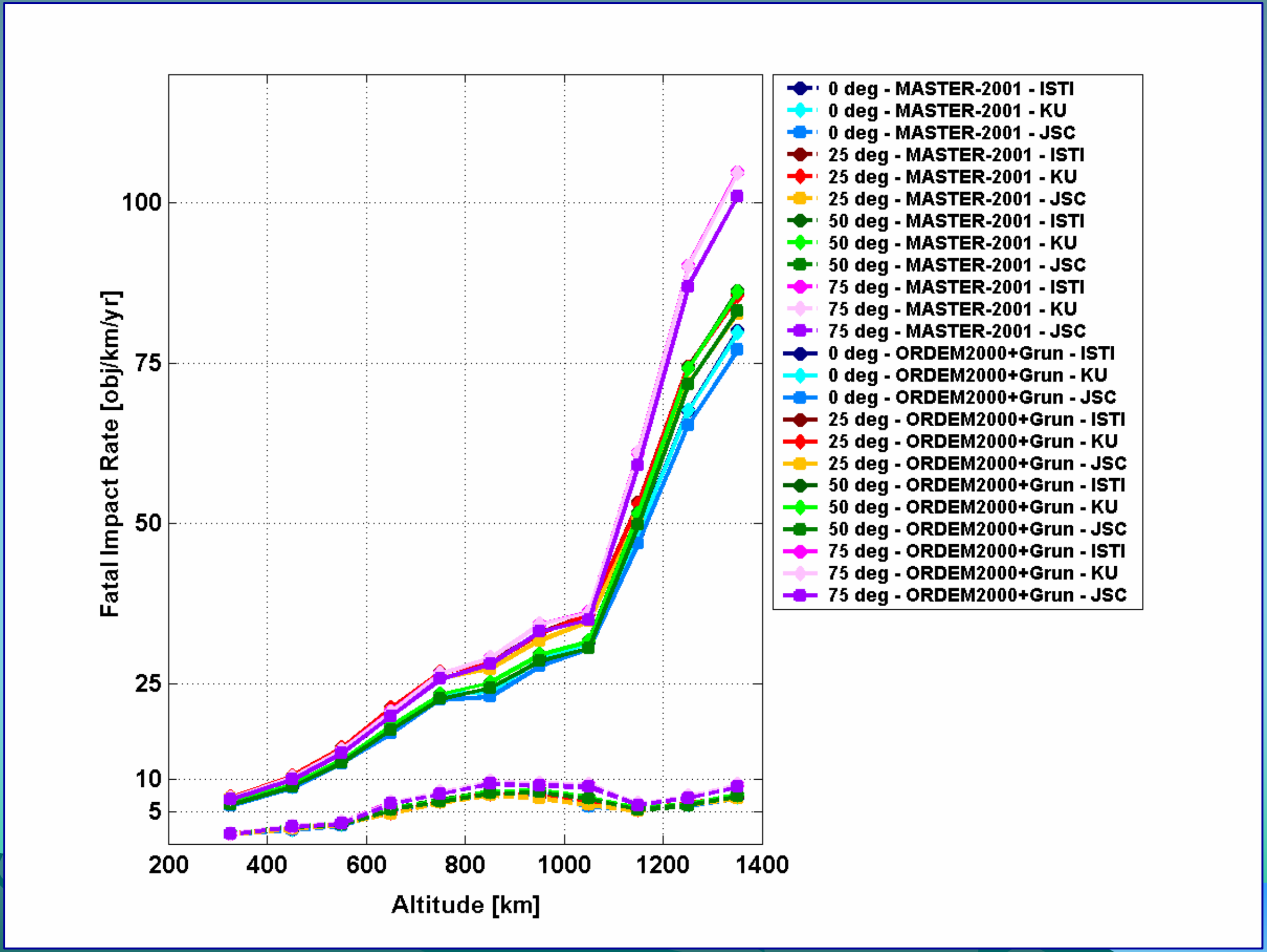
The maximum efficiency is possible for equatorial orbits

Initial Altitude [km]	Orbit Inclination			
	0°	25°	50°	75°
	DE-ORBIT TIME [days]			
1400	170	220	325	EDT not efficient
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

At high inclinations, electrodynamic drag, if any, is significantly less effective

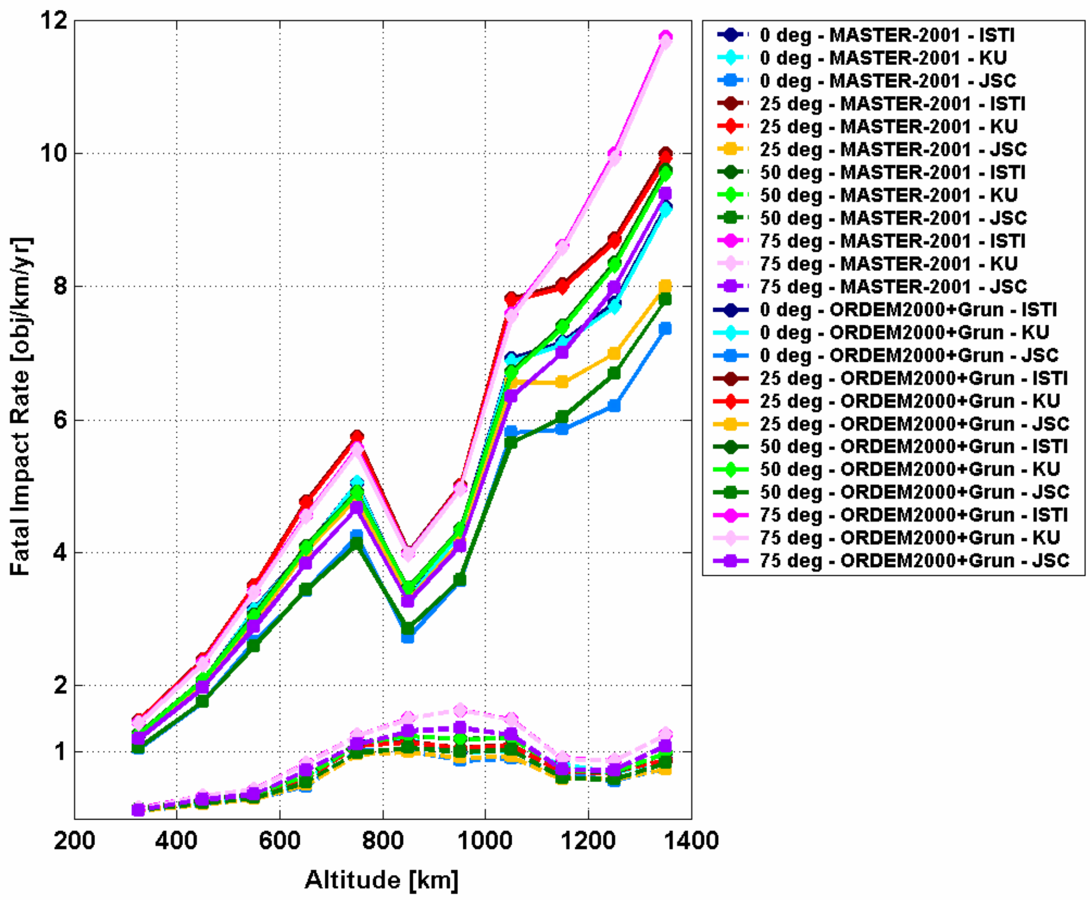
Results of the Second IADC AI 19.1 Test
Fatal Impact Rate

Comparison of ISTI, JSC and KU fatal impact rates for a 0.5 mm tether if the first vulnerability conjecture and MASTER-2001 or ORDEM2000+Grün are applied.



Results of the Second IADC AI 19.1 Test
Fatal Impact Rate

Comparison of ISTI, JSC and KU fatal impact rates for a 1 mm tether if the second vulnerability conjecture and MASTER-2001 or ORDEM2000+Grün are applied



Results of the Second IADC AI 19.1 Test Survival Probability of a Single Line Tether

Survival probability of a 7.5 km single line tether

Space debris flux model: MASTER-2001

SURVIVAL PROBABILITY [%] OF A SINGLE LINE TETHER
SPACE DEBRIS FLUX MODEL: MASTER-2001

De-orbit Altitude [km]	Orbital Inclination											
	0°			25°			50°			75°		
	ISTI	JSC	KU	ISTI	JSC	KU	ISTI	JSC	KU	ISTI	JSC	KU
CASE 1 $D_T = 0.5$ mm; $d_C = 1/4\ D_T = 0.125$ mm												
1400	0	0	0	0	0	0	0	0	0	-	-	-
1000	0	0.1	0	0	0	0	0	0	0	0	0	0
800	1.7	3.2	1.7	1.2	2.3	1.1	0.1	0.3	0	0	0	0
CASE 2 $D_T = 1$ mm; $d_C = 1/4\ D_T = 0.250$ mm												
1400	0.4	0.6	0.4	0.1	0.2	0	0	0	0	-	-	-
1000	12.0	13.8	12.0	5.9	7.4	5.9	0.9	1.5	0.9	0	0	0
800	39.1	41.1	39.2	35.0	36.9	35.0	17.7	19.9	17.8	0.4	1.0	0.4
CASE 3 $D_T = 0.5$ mm; $d_C = 1/3\ D_T = 0.167$ mm												
1400	0	0	0	0	0	0	0	0	0	-	-	-
1000	1.3	3.3	1.2	0.4	1.4	0.3	0	0.1	0	0	0	0
800	12.6	19.8	12.7	11.0	17.5	11.0	2.7	6.4	2.7	0	0.1	0
CASE 4 $D_T = 1$ mm; $d_C = 1/3\ D_T = 0.333$ mm												
1400	5.5	8.9	5.5	2.5	4.7	2.4	0.3	0.8	0.2	-	-	-
1000	32.6	38.3	32.7	22.0	27.8	22.1	8.1	12.5	8.1	0	0.1	0
800	56.9	61.5	57.0	54.3	59.4	54.3	36.8	43.1	36.9	4.4	7.9	4.4

Results of the Second IADC AI 19.1 Test
Survival Probability of a Single Line Tether

Survival probability of a 7.5 km single line tether

Space debris flux model: ORDEM2000+Grün

SURVIVAL PROBABILITY [%] OF A SINGLE LINE TETHER SPACE DEBRIS FLUX MODEL: ORDEM2000+GRUN												
De-orbit Altitude [km]	Orbital Inclination											
	0°			25°			50°			75°		
	ISTI	JSC	KU	ISTI	JSC	KU	ISTI	JSC	KU	ISTI	JSC	KU
CASE 1 D_T = 0.5 mm; d_C = 1/4 D_T = 0.125 mm												
1400	0	0	0	0	0	0	0	0	0	-	-	-
1000	0	0	0	0	0	0	0	0	0	0	0	0
800	0	0	0	0	0	0	0	0	0	0	0	0
CASE 2 D_T = 1 mm; d_C = 1/4 D_T = 0.250 mm												
1400	0	0	0	0	0	0	0	0	0	-	-	-
1000	0	0	0	0	0	0	0	0	0	0	0	0
800	0.2	0.7	0.2	0	0.2	0	0	0	0	0	0	0
CASE 3 D_T = 0.5 mm; d_C = 1/3 D_T = 0.167 mm												
1400	0	0	0	0	0	0	0	0	0	-	-	-
1000	0	0	0	0	0	0	0	0	0	0	0	0
800	0	0.2	0	0	0	0	0	0	0	0	0	0
CASE 4 D_T = 1 mm; d_C = 1/3 D_T = 0.333 mm												
1400	0	0	0	0	0	0	0	0	0	-	-	-
1000	0.5	1.8	0.5	0	0.3	0	0	0.1	0	0	0	0
800	4.1	8.2	4.1	1.6	3.9	1.5	0.4	1.6	0.4	0	0	0

Results of the Second IADC AI 19.1 Test
Survival Probability of a Single Line Tether

Very similar conclusions were obtained by ISTI, JSC and KU for all the single line tether solutions proposed in the study plan. The analyses carried out confirmed that the survivability concern is fully justified for a single line tether

The results obtained by ISTI, JSC and KU confirm that the single line electrodynamic tethers prescribed for this study (Length = 7.5 km, Diameters = 0.5 mm and 1 mm) cannot be safely used for de-orbiting from the altitudes and inclinations considered

Results of the Second IADC AI 19.1 Test
Survival Probability of a Double Line Tether

In order to increase the probability that the tether will survive the meteoroids and orbital debris environment for the mission duration, detailed analyses were carried out for the double line tether configurations proposed

- **The ISTI and JSC results are very similar for both the MASTER-2001 and ORDEM2000+Grün environments**
- **The KU outcomes show a much lower survival probability in general, which is justified by the different mathematical approach used to estimate the overall survival probability during the mission**

As a rule in this work, only when the survival probability is simultaneously ≥ 95% for ISTI, KU and JSC, is the idealized de-orbiting mission considered to be successful

SURVIVAL PROBABILITY [%] OF A DOUBLE LINE MULTI-LOOP TETHER
SPACE DEBRIS FLUX MODEL: ORDEM2000+GRÜN

De-orbit Altitude [km]	0°			25°			50°			75°		
	ISTI	JSC	KU	ISTI	JSC	KU	ISTI	JSC	KU	ISTI	JSC	KU
CASE 5 – 75 loops												
1400	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-
1000	12.4	14.5	0.0	0.5	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
800	42.5	45.2	9.9	28.5	31.1	2.1	9.5	11.3	0.1	0.0	0.0	0.0
CASE 6 – 750 loops												
1400	0.4	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-
1000	79.8	81.0	36.3	54.6	56.9	8.3	36.5	39.2	1.3	0.0	0.0	0.0
800	91.2	91.8	76.3	87.3	88.1	62.6	76.9	78.3	43.2	8.8	10.4	0.1
CASE 7 – 1500 loops												
1400	6.3	7.7	0.0	0.6	0.9	0.0	0.0	0.0	0.0	-	-	-
1000	89.3	89.9	59.7	73.7	75.3	27.8	60.1	62.3	10.6	0.4	0.6	0.0
800	95.5	95.8	87.3	93.4	93.9	78.9	87.6	88.4	65.3	29.0	31.6	2.3

SURVIVAL PROBABILITY [%] OF A DOUBLE LINE MULTI-LOOP TETHER
SPACE DEBRIS FLUX MODEL: MASTER-2001

De-orbit Altitude [km]	0°			25°			50°			75°		
	ISTI	JSC	KU	ISTI	JSC	KU	ISTI	JSC	KU	ISTI	JSC	KU
CASE 5 – 75 loops												
1400	46.7	49.5	0.9	29.3	32.2	0.1	5.7	7.1	0.0	-	-	-
1000	82.5	83.7	44.4	71.2	73.1	26.3	42.2	45.0	3.7	0.0	0.0	0.0
800	92.8	93.3	81.3	92.6	93.1	78.0	80.8	82.0	53.0	12.8	15.0	0.6
CASE 6 – 750 loops												
1400	92.4	92.9	55.8	87.9	88.8	38.7	73.6	75.2	10.0	-	-	-
1000	98.0	98.2	91.5	96.5	96.8	86.1	91.3	91.9	67.4	36.6	39.4	1.8
800	99.2	99.3	97.9	99.2	99.3	97.4	97.8	98.0	93.3	79.7	80.9	52.2
CASE 7 – 1500 loops												
1400	96.1	96.4	74.4	93.8	94.2	61.6	85.7	86.7	30.6	-	-	-
1000	99.0	99.1	95.6	98.2	98.4	92.7	95.5	95.9	81.9	60.2	62.4	12.6
800	99.6	99.6	98.9	99.6	99.6	98.7	98.9	99.0	96.6	89.2	89.9	71.9

Survival probability of a 7.5 km double strand multi-loop tether

$D_T = 0.5$ mm

$d_C = 1/4\, D_T = 0.125$ mm

SURVIVAL PROBABILITY [%] OF A DOUBLE LINE MULTI-LOOP TETHER
SPACE DEBRIS FLUX MODEL: ORDEM2000+GRÜN

De-orbit Altitude [km]	0°			25°			50°			75°		
	ISTI	JSC	KU	ISTI	JSC	KU	ISTI	JSC	KU	ISTI	JSC	KU
CASE 14 – 75 loops												
1400	39.3	53.8	0.9	17.3	31.3	0.0	4.2	12.3	0.0	-	-	-
1000	92.9	95.0	71.6	84.4	89.0	46.8	76.2	82.9	28.7	6.6	15.4	0.0
800	95.7	97.0	87.9	93.8	95.6	80.5	88.8	91.9	68.5	33.8	46.6	4.7
CASE 15 – 750 loops												
1400	90.7	93.7	55.9	82.9	88.4	31.3	70.8	79.7	12.2	-	-	-
1000	99.3	99.5	96.5	98.3	98.8	92.0	97.2	98.1	86.9	74.3	81.6	25.2
800	99.5	99.7	98.7	99.3	99.5	97.7	98.8	99.1	96.0	89.0	92.2	69.5
CASE 16 – 1500 loops												
1400	95.2	96.8	74.5	91.0	94.0	55.3	84.1	89.2	33.9	-	-	-
1000	99.6	99.7	98.2	99.1	99.4	95.9	98.6	99.0	93.2	86.2	90.3	49.4
800	99.8	99.8	99.3	99.7	99.7	98.9	99.4	99.6	98.0	94.3	96.0	83.2

SURVIVAL PROBABILITY [%] OF A DOUBLE LINE MULTI-LOOP TETHER
SPACE DEBRIS FLUX MODEL: MASTER-2001

De-orbit Altitude [km]	0°			25°			50°			75°		
	ISTI	JSC	KU	ISTI	JSC	KU	ISTI	JSC	KU	ISTI	JSC	KU
CASE 14 – 75 loops												
1400	98.5	98.9	89.9	97.6	98.3	84.1	94.1	95.7	64.5	-	-	-
1000	99.6	99.7	98.4	99.2	99.5	97.1	98.0	98.5	92.2	77.4	82.8	39.9
800	99.8	99.9	99.6	99.8	99.9	99.5	99.5	99.6	98.7	95.4	96.4	88.3
CASE 15 – 750 loops												
1400	99.8	99.9	98.9	99.8	99.8	98.2	99.4	99.6	95.4	-	-	-
1000	100	100	99.8	99.9	99.9	99.7	99.8	99.9	99.2	97.4	98.1	90.4
800	100	100	100	100	100	100	99.9	100	99.9	99.5	99.6	98.7
CASE 16 – 1500 loops												
1400	99.9	99.9	99.4	99.9	99.9	99.1	99.7	99.8	97.7	-	-	-
1000	100	100	99.9	100	100	99.8	99.9	99.9	99.6	98.7	99.0	95.0
800	100	100	100	100	100	100	100	100	99.9	99.8	99.8	99.4

Survival probability of a 7.5 km double strand multi-loop tether

D_T = 1 mm

$d_C = 1/3\ D_T$ = 0.333 mm

Results of the Second IADC AI 19.1 Test

Survival Probability of a Double Line Tether

Summary of the Results

Tether diameter = 0.5 mm

De-orbiting Mission feasibility if SP ≥ 95% according to ISTI, KU and JSC

ORDEM2000+Grün

$d_c = 1/4\ D_T$

Never

Possible

$d_c = 1/3\ D_T$

$NL = 1500$

from 800 km in equatorial orbit

MASTER-2001

$d_c = 1/4\ D_T$

$NL = 750$

from 800 km up to 25°

$NL = 1500$

from 1000 km in equatorial orbit

from 800 km up to 50°

$d_c = 1/3\ D_T$

$NL = 750$

from 1000 km up to 25°

from 800 km up to 50°

$NL = 1500$

from 1000 km up to 25°

from 800 km up to 50°

Results of the Second IADC AI 19.1 Test
Survival Probability of a Double Line Tether
Summary of the Results

Tether diameter = 1 mm

De-orbiting Mission feasibility if SP ≥ 95% according to ISTI, KU and JSC

ORDEM2000+Grün

$d_c = 1/4\ D_T$

NL = 750
from 800 km in equatorial orbit

NL = 1500
from 800 km up to 25°

$d_c = 1/3\ D_T$

NL = 750
from 1000 km in equatorial orbit
from 800 km up to 50°

NL = 1500
from 1000 km up to 25°
from 800 km up to 50°

MASTER-2001

$d_c = 1/4\ D_T$

NL = 75
from 800 km up to 50°

NL = 750
from 1400 km in equatorial orbit
from 1000 km up to 50°
from 800 km up to 75°

NL = 1500
from 1400 km up to 25°
from 1000 km up to 50°
from 800 km up to 75°

MASTER-2001

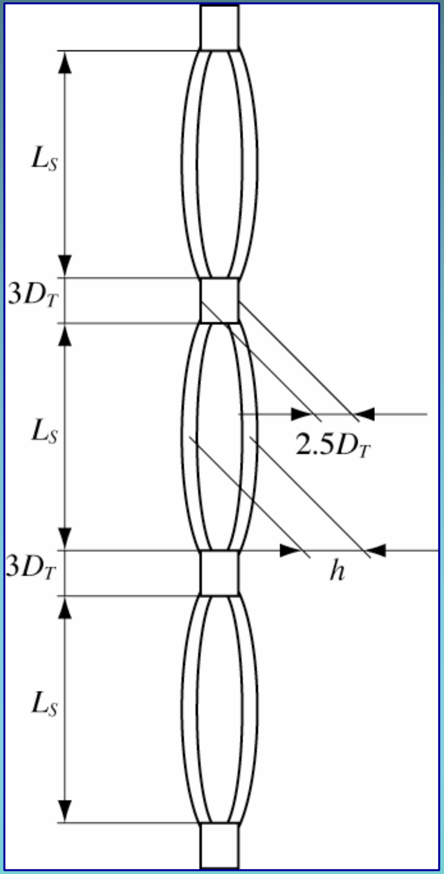
$d_c = 1/3\ D_T$

NL = 75
from 1000 km up to 25°
from 800 km up to 50°

NL = 750
from 1400 km up to 50°
from 1000 km up to 50°
from 800 km up to 75°

NL = 1500
from 1400 km up to 50°
from 1000 km up to 75°
from 800 km up to 75°

Results of the Second IADC AI 19.1 Test
Variation of the survival probability with the distance between the two strands in a loop



According to the AI 19.1 requirements, ISTI and JSC developed and adopted mathematical approaches in which the distance between the two strands in a loop was supposed to be large enough to allow to consider each strand separately. But such distance was not explicitly expressed in the ISTI and JSC methods

KU elaborated a more complex and general method where, being the distance between strands a variable of the problem, it could be consequently modified

An additional test was then proposed to assess the variation of the overall survival probability with the distance *h*. This test was carried out at the Kyushu University

Results of the Second IADC AI 19.1 Test

Variation of the survival probability with the distance between the two strands in a loop

Overall survival probability [%] as a function of h/D_T			
h/D_T	De-orbiting from 1000 km, 25°	De-orbiting from 800 km, 25°	De-orbiting from 800 km, 50°
1.000	2.4	14.4	7.5
1.259	4.9	20.6	12.1
1.585	12.0	33.0	22.7
1.995	20.2	43.6	32.9
2.512	28.9	52.6	42.3
3.162	37.9	60.6	51.0
3.981	46.6	67.6	59.1
5.012	54.9	73.7	66.2
6.310	62.4	78.8	72.4
7.943	69.1	83.1	77.7
10.000	74.8	86.7	82.2
12.589	79.7	89.7	86.0
15.849	83.9	92.1	89.0
19.953	87.3	94.0	91.6
25.119	90.1	95.6	93.6
31.623	92.4	96.9	95.3
39.811	94.3	97.9	96.6
50.119	95.8	98.7	97.7
63.096	95.9	98.8	97.9
79.433	95.9	98.8	97.9
100.000	95.9	98.8	97.9

Variation of the survival probability of a 7.5 km double strand multi loop tether with the ratio h/D_T

$D_T = 1$ mm

$d_C = 1/3\ D_T = 0.333$ mm

$NL = 1500$

Space debris flux model: ORDEM2000+Grün

An upper limit of h/D_T exists above which the results do not change any more. In the specific case analysed, this limit corresponds to $h/D_T \sim 50$ and, being $D_T = 1$ mm, to a distance between strands of about 5 cm

Thus, at least for the analysed case, a distance between wires of nearly 5 cm is sufficient to fulfil the AI 19.1 requirements.

Study Summary and Recommendations

By using electrodynamic drag to greatly increase the orbital decay rate, an electrodynamic space tether can remove spent or dysfunctional spacecraft from low Earth orbit rapidly and safely

But tethers in space present unusual problems when viewed from the space debris perspective

To assess the space debris related concerns, a new task (Action Item 19.1) on the "Potential Benefits and Risks of using Electrodynamic Tethers for End-of-life De-orbit of LEO Spacecraft" was defined by the Inter-Agency Space Debris Coordination Committee (IADC), in March 2001

Two tests were proposed

1. **to compute the fatal impact rate of meteoroids and orbital debris on space tethers in circular orbit, at different altitudes and inclinations, as a function of the tether diameter**
2. **to assess the survival probability of an electrodynamic tether system during typical de-orbiting missions**

IADC members of three agencies (ASI, JAXA and NASA) volunteered to participate in the study and different computational approaches were specifically developed in the framework of this IADC task

In both tests

- **very simple tether orbital configurations and designs were assumed. Tethers were supposed to be in circular orbit and aligned along the gravity gradient**
- **specific tethers vulnerability conjectures were considered, that of limiting the minimum fatal debris diameter to 1/ 4 and 1/3 of the tether diameter**

Study Summary and Recommendations

First IADC AI 19.1 Test

The lifetimes of conventional single line tethers may be limited, by damage due to meteoroids and orbital debris impacts, to times much shorter than the mission duration

Provided the tether vulnerability conjecture and the space debris flux model adopted are reasonable, a single line tether with a diameter of 2.5 cm, or larger, may certainly survive the space debris environment for a moderately long time to assure the feasibility of a number of missions. The same is also applicable to a 1 cm tether if the required time for the mission is within a few years

Single line tethers lifetimes can be improved by increasing the tether diameter. However, this might incur a prohibitive mass penalty as well as additional operational problems for many missions

resorting to different and creative designs is necessary to reduce the tether vulnerability to space debris

Second IADC AI 19.1 Test

According to ISTI, JSC and KU

- The survival probability grows considerably for a double line design with a sufficiently high number of knots and loops
- The survival probability increases in the double loop configurations with number of loops and minimum fatal debris diameter
- Survival is also more likely from lower initial altitudes and inclinations

Moreover

- All results are strongly dependent on the orbital debris/meteoroids model adopted, with much higher survival probabilities obtained overall from the lower MASTER-2001 fluxes
- According to the Kyushu University results, the survival probability decreases with the distance between the two cables in each single loop

Study Summary and Recommendations

Electrodynamic tethers have strong potential to become effective mitigation measures, but various problems are still to be solved before this technique can be practically adopted. From the space debris perspective, resorting to creative tether designs is necessary to increase the tethers survivability, but:

- **Considerable differences are still existing in the flux of small particles predicted by the environment models, e.g. MASTER-2001 and ORDEM2000. Thus, additional efforts should be done to possibly define a common standard model**
- **New hypervelocity impact experiments, using tethers of different material and design, should be necessary to identify appropriate ballistic equations**

The mathematical approaches developed for this study can be applied to any available environmental model and tether vulnerability condition, thus allowing more precise evaluations as the accuracy of the environment and tether models improves

These methods can only be applied to tethers which are in circular orbit and are aligned along the gravity gradient

In highly eccentric orbits, major challenges should be introduced

Content of the Draft Report of AI 19.1

A draft of the report for AI 19.1 was prepared including

1. Objectives of the IADC AI 19.1
2. Introduction
3. Overview of space tether applications, with a short history of missions using space tethers
4. Electrodynamic drag concept and electrodynamic tethers (EDT) proposed to de-orbit spacecraft (TT & EDOARD)
5. Potential benefits of using EDT, i.e. save the mass, reduce the de-orbit times, increase the effectiveness in terms of Area-Time-Product
6. Potential risks of using EDT, i.e. space debris related concerns
   - Proposals to reduce the tether vulnerability
   - The impact of tethers on the space environment
7. Study plan for the IADC AI 19.1 of 30 November 2003
8. Main study assumptions
   - Space debris flux models
   - Tether orbital configuration and design
   - Tether vulnerability to space debris impacts
9. Mathematical approaches
   - The ISTI/CNR approach
   - The Kyushu University method
   - The NASA/JSC method
10. Results of the first AI 19.1 test
    - Fatal impact rates
    - Average tether lifetimes
11. Results of the second AI 19.1 test
    - Fatal impact rates
    - Survival probability
12. Summary of the study and recommendations