TETHER DESIGN FOR SPACE DEBRIS TOWING

R. Benvenuto, M. Lavagna

Department of Aerospace Science and Technology (DAER), Politecnico di Milano - Italia

Towing Tethers

Mission Overview

Tethers' exploitation for space debris mitigation/remediation

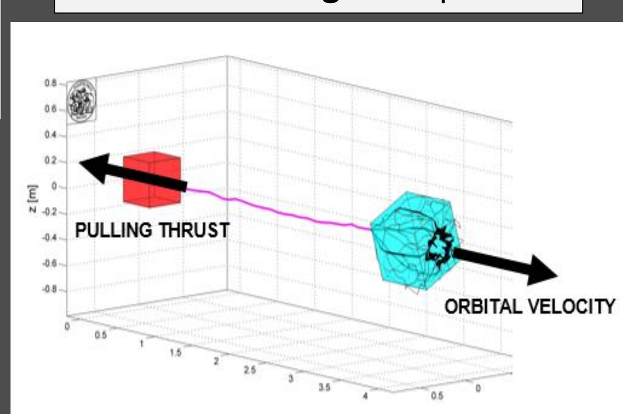
- TETHER: long thin cable – mechanical connection – not withstanding compressive loads
- MITIGATION: tethered devices installed on-board (drag augmentation, EDTs)
- REMEDIATION: elastic connection established in-orbit by means of different capture strategies: nets, harpoons, tentacles, grasper, etc.

Debris Tethered-Disposal Options

TOWING TETHERS:
- Non-conductive
- Exploiting chaser thrusters to de/re-orbit system

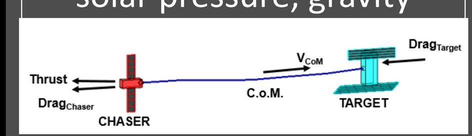
ELECTRO-DYNAMICS TETHERS:
- Conductive
- Exploiting Lorentz Force through interaction with magnetic field and ionosphere

Capture net and towing tether de-orbiting concept



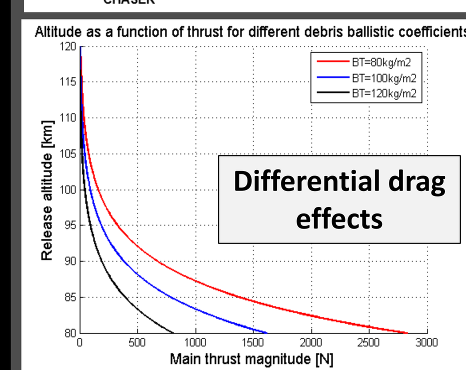
Towing Tethers' Dynamics and Control Simulations

MODEL
- 6 DOF end-bodies with flexible appendages
- Discretized viscoelastic model for flexible tether
- Perturbations: air drag, solar pressure, gravity

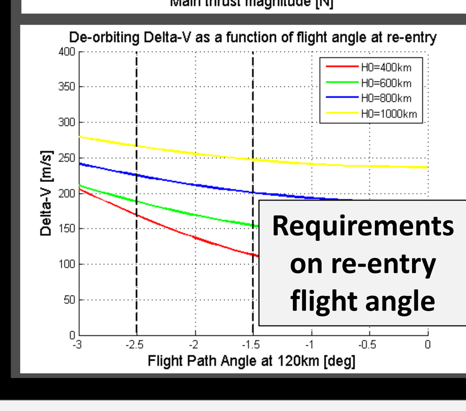


Operations sequence for high-thrust controlled re-entry
- Stabilization/Pre-tensioning
- Dragging
- Post-burn control
- Tether cut and CAM (if needed)

GNC
- Closed-loop GNC with feedback on tether tension and relative distance
- RCS (PWM) for relative maneuvering
- No control on tether length (fixed-length



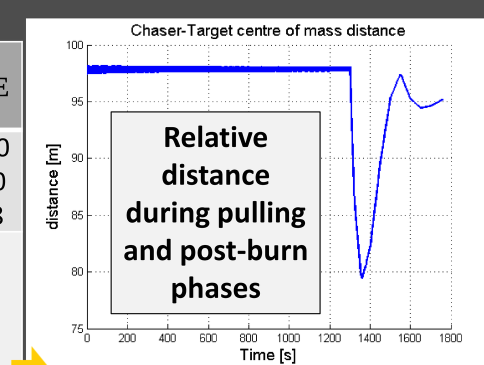
Differential drag effects



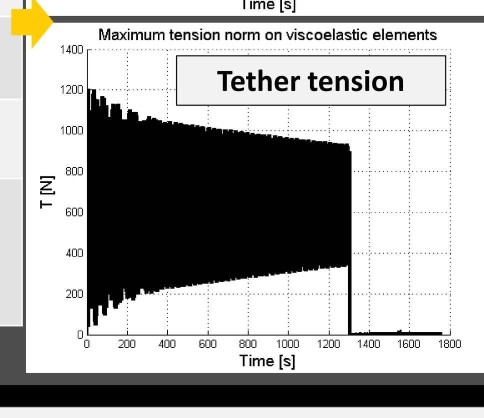
Requirements on re-entry flight angle

STIFF TETHER CASE

Mass [kg]	Chaser = 1300 Target = 5000 Tether = 0.58
Initial orbit altitude [km]	600
Thrust [N]	Main = 800 RCS = 25
ΔV [m/s]	160
Flight angle at 120km [deg]	-1.6



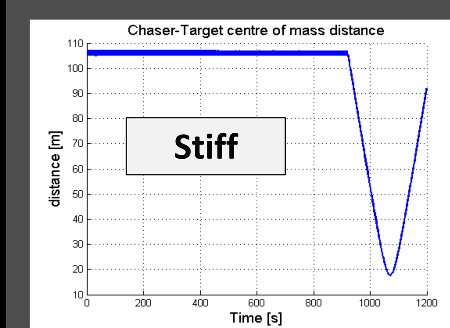
Relative distance during pulling and post-burn phases

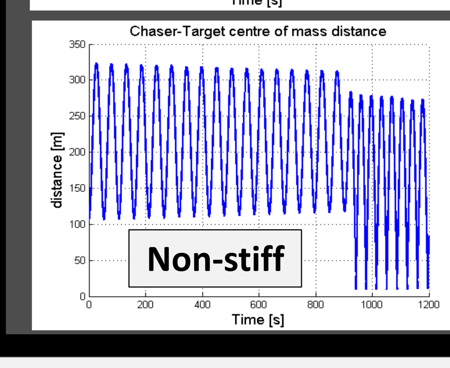


Tether tension

Fundamental influence of **tether elasticity** on dynamics behavior

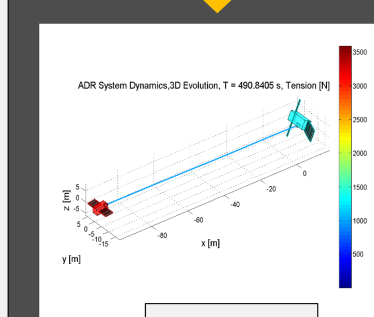
CASE	Stiffness [N/m]	Damping [Ns/m]	PROS	CONS
Stiff	1.57e3	0.3	• Stronger control authority on stack pose	• Pre-tensioning needed • Harder post-burn control
Non-stiff	1.57e1		• Easier post-burn control • Limited whiplash effect	• Greater tail-wagging effect (strongly dependent on connections)





Relative distance during pulling and post-burn phases (non-controlled post-burn)

Tail-wagging = target angular momentum build-up, may lead to entanglement



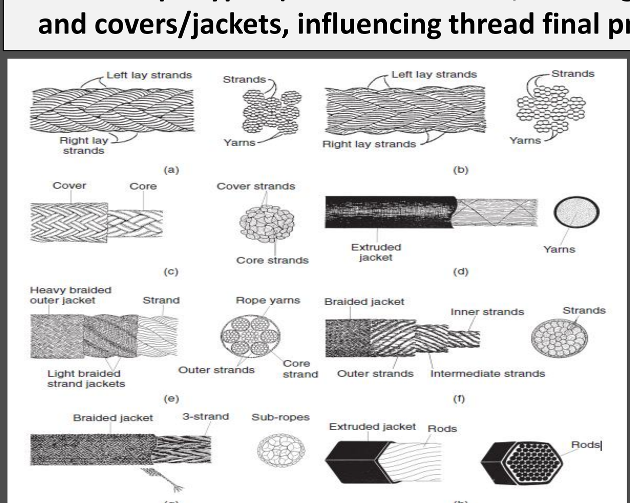
Non-stiff

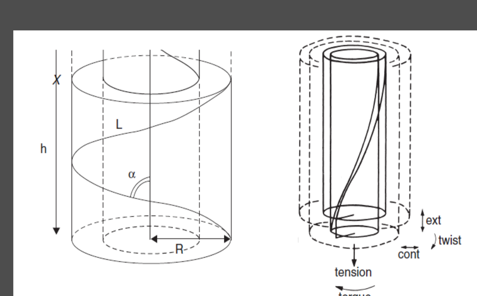
Tether Design

Design Drivers and Requirements

- **Dynamics/Thermal simulations allow to set mechanical/thermal design drivers**
- **Synthetic fibers as Aramid/HPME identified as candidate materials**
  - high tensile strength, high breaking tenacity
  - high impact strength
  - low density (lightweight)
  - fatigue resistance, creep and shrinkage resistance
  - dimensional stability
  - heat resistance
  - chemical resistance
- **Other material requirements:**
  - Stiffness (dynamic behavior): to be correctly tuned depending on expected dynamic behavior and control bandwidth
  - Foldable, spoolable
  - Stress relaxation

Modern rope types (different strand #, braiding technique and covers/jackets, influencing thread final properties)





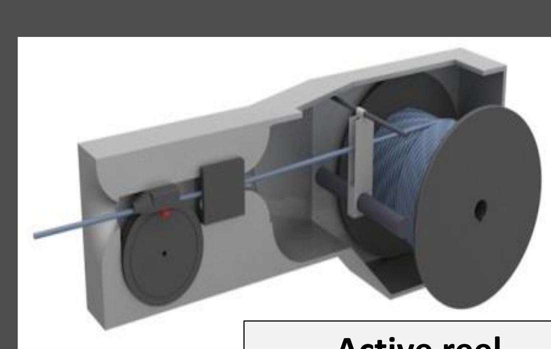
Twisted yarn geometry: directly related to braid retention of strength

Mechanical Properties of Candidate Materials

Material	Breaking strength [GPa]	Young's modulus [GPa]	Density [Kg/m³]	Melting/decomposing temperature [°C]	Function
Dyneema	3.7	116	970	150	Mechanical
Kevlar	3.6	130	1440	500	
Technora	3.4	73	1390	500	
Sylramic (Silicon carbide fibre)	2.6	350	3000	Over 1400	Thermal insulation
Nextel (alumina fibre)	2	190	3050	1800	

Tether support system

Functions:
- Storing, releasing, holding
- Winding/unwinding
- Depend on control strategies



Active reel mechanical design

ACTIVE REEL
- If variable length tether control
- Critical system, more complex
- Actively controlled

PASSIVE SPOOL
- If fixed length tether control
- Simpler system, more reliable
- Passive releasing system
- Decoupled from chaser dynamics to limit interactions

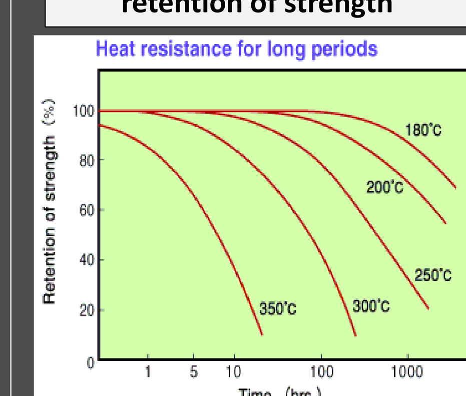
Thermal Analysis

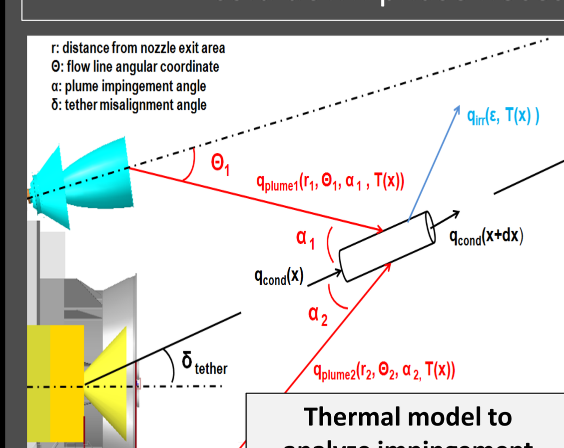
GAS PLUME IMPINGEMENT ON THE TETHER:

- Thrusters' exhaust plume impingement during disposal burns (limited time)
- Aramid fibers high retention of strength at high temperatures (depending on burning time)
- Thermal analysis have demonstrated that insulation is necessary for the first 5 to 10 meters of the tether
- Chemical resistance to plume impingement is also a requirement

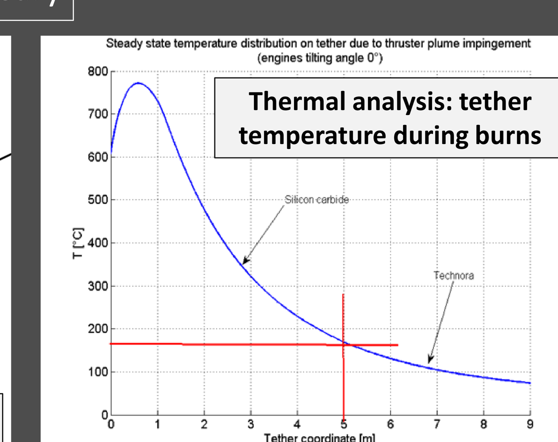
Insulation's options:
- **First part of the tether in Sylramic**
  - Good mechanical properties at high temperatures
  - Heavier solution
  - Link Aramid/Sylramic TBD
- **Nextel insulation sheath**
  - Lightweight solution
  - Limited burning time – cold down phase necessary

Technora heat resistance: retention of strength





Thermal model to analyze impingement



Thermal analysis: tether temperature during burns

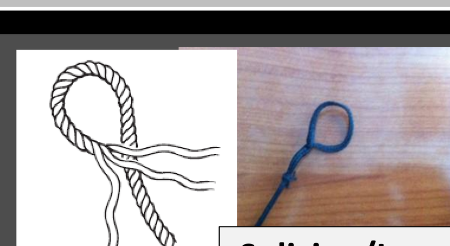
Tether Testing

Material Mechanical and Dynamical Tests

Fiber mechanical properties are weakened by:
- Braiding, weaving, twining
- Knotting, looping, splicing

Material testing:
- to characterize real parameters for design technological solutions
- to reduce the number of uncertain parameters in flexible dynamics model validation process

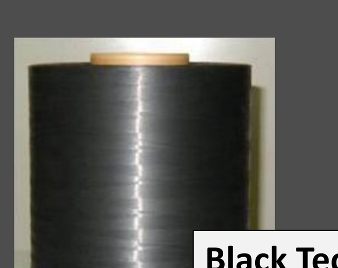
Material test campaign on 547 tex Technora braids and knotted braids:
- Tensile tests
- Dynamical-mechanical testing



Splicing/Looping

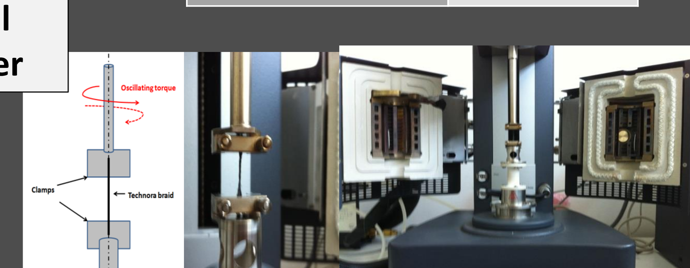
Technora braids damping characteristics

Axial damping ratio [-]	0.106
Torsional damping ratio [-]	0.079
Bending ratio [-]	0.014



Black Technora

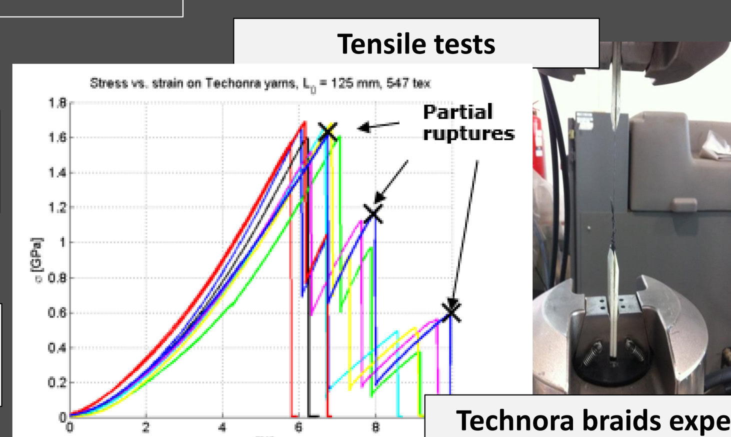
Torsional rehometer



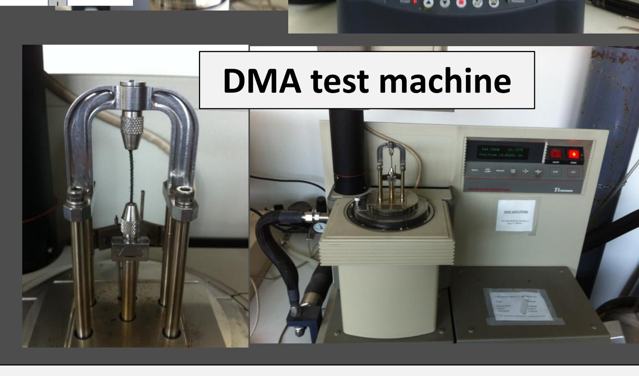
Technora braids mechanical characteristics

Braid Young's modulus [GPa]	25	34% of nominal fiber
Braid Shear Modulus [GPa]	0.118	
Braid Breaking Stress [GPa]	1.6	47% of nominal fiber
Knot Breaking Stress [GPa]	0.5	

Tensile tests



DMA test machine



Technora braids experimental results obtained within the ESA-sponsored ESA- PATENDER Study, in consortium with GMV Spain, Prodintec,Spain

Conclusions and Roadmap

Benefits of Tethers for Active Debris Removal:
- Safety distance
- Lightweight payload
- Centre of mass alignment with thrust axis not a constraint

Criticalities:
- System flexibility effects on the connected system (tether oscillations, entanglement and breakage)
- Whiplash effect (pre-tensioning)
- Post-burn bounce-back
- Atmospheric re-entry – differential drag
- Tail-wagging – tumbling target
- Gas plume impingement on tether

Closed loop GNC & thermal control have proved to be necessary and effective

Design and testing:
- Detailed design and testing of support system/connections/insulation
- Tests to Validate dynamics models
- Tests to characterize real parameters and verify functional requirements
- Performances quantification, requirements verification in relevant environment

Proposed qualification roadmap:
- Friction-less table or underwater scaled dynamics + DMA → **TRL 4/5**
- Microgravity testing + thermo-vacuum → **TRL 5/6**
- Sub-orbital flight or I.O.D. → **TRL 7**

Subset of related references

- R. Benvenuto, S. Salvi and M. Lavagna, "*Dynamics Analysis and GNC design of flexible systems for space debris active removal*". Acta Astronautica, 2015.
- R. Benvenuto and M. Lavagna, "*Towing tethers to control debris removal dynamics*", 65th International Astronautical Congress, IAC-14-C1.6.09, Toronto, Canada, 2014.
- R. Benvenuto, M. Lavagna, A. Cingoli, C. Yabar and M. Casasco, "*MUST: multibody dynamics simulation tool to support the GNC design for active debris removal with flexible elements*", 9th International ESA Conference on Guidance, Navigation & Control Systems, Porto, Portugal, 2014.
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- H. P. Menard, "*Dynamic Mechanical Analysis – A practical introduction*". 2nd Edition, CRC Press, Taylor & Francis Group, 2008.
- H. A. McKenna, J.W.S. Hearle and N. O'Hear, "*Handbook of fibers rope technology*". The Textile Institute, Woodhead Publishing Limited, Cambridge, England, 2004.