

Overview of Space Tether Applications: State-of-the-art Knowledge and Tools

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Past Space Tether Experiments [1]

- Space tether experiments go back to 1966, when the NASA **Gemini 11 and 12** manned spacecraft were linked to their Agena upper stage to investigate the mechanics of linking spacecraft with tethers.
- Between 1989 and 1995 a multitude of Canadian and Japanese sounding rockets successfully deployed electrodynamic tethers (958 m for **Oedipus-A**, 1170 m for **Oedipus-C**) on sounding rockets, making observations of various plasma phenomena.
- In 1992, NASA flew a space shuttle mission that attempted to deploy the Italian Space Agency's **Tethered Satellite System** (TSS). The **TSS-1** was a 550 kg spacecraft that was to be wound out on a 20 km long conductive tether. Unfortunately, the satellite deployment stopped at ~ 260 m due to a malfunction in the reeling mechanism.

Past Space Tether Experiments [2]

The **first fully successful orbital flight test of a long tether system** was **SEDS-1**, which tested the **Small Expendable Deployer System** in 1993.

In SEDS-1, a 25 kg minisatellite was deployed down towards the Earth from a Delta II rocket stage on a 20 km long nonconductive tether. Therefore, the tether was cut at the deployer and the end mass payload, with a 20 km tether kite tail, re-entered the atmosphere at a location that was very accurately predicted before the flight.

The SEDS deployer had been developed at NASA's Marshall Space Flight Center while the end mass payload at NASA's Langley Research Center.

In 1993, the **Plasma Motor Generator (PMG)** experiment used the SEDS technology to deploy a 500 m long conductive tether from a Delta second stage with the primary goal of testing power generation and thrust by means of an electrodynamic tether system.

PMG was a successful mission that proved, for a short duration, the ability to generate power or thrust through interaction with the surrounding plasma field

Past Space Tether Experiments [3]

In 1994, the **SEDS-2** experiment was performed with the same gear as SEDS-1, deploying a 20 km long nonconductive tether for a longer and more ambitious mission. After a smooth deployment, the tether was left attached to the Delta to determine long-term tether stability and micrometeoroid risks.

The tether was about the thickness of ordinary string. It was expected to survive for twelve days, but it **suffered a cut 3.7 days after deployment.** The Delta II second stage and the remaining 7.2 km of attached tether stayed in orbit for over a month before re-entering the earth atmosphere.

SEDS-2 was observed by the optical telescope at Kwajalein.

In 1996, NASA reflw the TSS hardware on the Space Shuttle Orbiter. The **TSS-1R** mission was terminated before due time when an electrical arc severed the tether just before the end of deployment, at 19.7 km. Nevertheless,

the mission confirmed the large EMF potentials possible at orbital speeds: the tether electromotive force and current reached values in excess of 3500 volts and 1 amp, respectively.

Past Space Tether Experiments [4]

In 1996, the US Naval Research Laboratory (NRL) and the National Reconnaissance Office (NRO) flew the **Tether Physics & Survivability (TiPS)** experiment

to characterize the dynamics and survivability of a tethered system in space.

TiPS tested a new nonconductive tether design based on a hollow braid made of “Spectra” fiber. The system consisted of two end bodies connected by a 4 km tether, with a diameter of ~2.5 mm. Each of the subsatellites had laser retroreflectors for laser tracking. The initial orbit was circular, at an altitude of 1022 km and inclination of 63.4°.

Over the life of the TiPS experiment, an international network of 27 Satellite Laser Ranging (SLR) sites, the Altair radar at the Kwajalein Missile Range (KMR) in the Marshall Islands, and several ground based telescopes contributed to the dynamics knowledge. The survivability aspect of the mission was confirmed by the orbital tracking provided by the US Space Command (USSPACECOM).

The NASA-standard orbit model **GEODYN** was the primary tool used to determine the orbital and librational parameters from ground based range data supplied by laser and radar.

This system proved that tethers can be made to be survivable

Failed Space Tether Experiments

In 1998, the **Advanced Tether Experiment (ATEX)** was launched into orbit aboard the National Reconnaissance Office (NRO) sponsored Space Test Experiment (STEX). ATEX was intended to demonstrate deployment and survivability of a new tether scheme as well as controlled libration maneuvers.

Unfortunately, the experiment was a complete **failure**: after deployment of only 22 m of tether, STEX ejected the ATEX package to protect itself.

The **Young Engineers' Satellite (YES)** had been designed to deploy a 35 km tether in the GTO orbit to demonstrate the dynamics and tethered momentum transfer. YES was launched on the Ariane 502 the 30th of October 1997. Unfortunately, the launch window requirements were changed resulting in the tether posing a high collision and debris risk. As a consequence, YES was not deployed.

YES had been financed by ESA, the Dutch government and Delta-Utec

Delta-Utec (Netherlands) is currently investigating the feasibility of developing a tether that will completely degrade by ultra-violet when the nominal mission has been executed:

DUtether Project

Upcoming Space Tether Experiment

A follow up of the SEDS experiments, designed **Propulsive SEDS (ProSEDS)** is slated for launch within the next year (the current planned date is March 29, 2003). The ProSEDS mission will deploy 5 km of bare wire plus 10 km of Spectra tether from a Delta II upper stage to achieve ~ 0.4 N of drag thrust, deorbiting the stage.

The ProSEDS experiment is managed by **Marshall's Advanced Space Transportation Program**.

NASA's industry and academia team for the ProSEDS experiment includes:

Tether Applications of Chula Vista, Calif.; ***Tether Unlimited*** of Seattle; ***Electric Propulsion Laboratory*** of Monument, Colo.; ***The Michigan Technic Corp.*** of Holland, Mich.; ***Triniton Systems Inc.*** of Chelmsford, Mass.; ***Smithsonian Astrophysical Observatory*** of Cambridge, Mass.; ***Alpha Technologies*** of Huntsville; ***Colorado State University*** in Fort Collins; ***University of Michigan*** in Ann Arbor.

Planned Space Tether Experiments [1]

The Michigan Technic Corporation is working with NASA on ProSEDS, and is also working towards a follow-up experiment named “**Space Transfer with Electrodynamic Propulsion (STEP)**”. STEP will apparently be flown in conjunction with another tether experiment, the **Atmospheric-Ionospheric Research Small Expendable Deployer Satellite (AIRSEDS)**.

The **ASTOR/STEP-AIRSEDS** mission *is to be delivered to space via ejection from the shuttle orbiter*. The mission will demonstrate the use of electrodynamic tethers (ED) in boosting, deboosting, and conducting plane changes of a satellite without the use of chemical propellants.

- ProSEDS will only investigate using a tether to drop an orbit, STEP would also demonstrate orbital reboost.

The ASTOR/STEP-AIRSEDS mission was originally developed at Marshall in 1999 under a Small Business Innovation Research (SBIR) grant. **Due to a change in primary emphasis at NASA Marshall from ED tethers to momentum exchange tethers, this mission was migrated to the DoD this year.**

Planned Space Tether Experiments [2]

At the Kyushu University (KU), Japan, the development of the **Double Tethered Experimental Satellite (D-TES)** is in progress. It will be launched as a H-IIA piggy-back satellite and its main objective will be to deploy a 20 km tether and get data of the tether dynamics. An important feature of the system is that the tether consists of parallel elements knotted at certain distance to reduce the risk to be cut by a collision with space debris.

In 1998, at the University Space Systems Symposium (USSS) – a joint Japanese/US student conference – the **QUEST (Kyushu – US Experimental Satellite Tether)** mission was conceived. The QUEST mission will be launched as a secondary payload aboard the Japanese H-IIA launch vehicle. The primary mission objective is to successfully deploy a 2 km tether (made of Kevlar) and study the control and dynamics associated with the deployment. After the operational mission, the tether will be cut to examine orbit transfer.

Since November 2001 another experiment, named **QTEX**, has been investigated at KU. It will be launched as a piggy-back satellite in which the daughter is joined with the mother and the tether deployment system is contained in the mother. The tether length will be 2 km and the motion of the tethered satellite system (TSS) will be observed for at least 4 months to study the TSS dynamics

Proposed ED Tether Systems for Satellite De-orbiting

Tether Unlimited Inc. (TUI) American company is developing a system called the **Terminator Tether™** to provide a low-cost, lightweight and reliable method of removing objects from low earth orbits (LEO). This will be a small device that uses electrodynamic tether drag to deorbit a spacecraft.

Alenia Spazio and the University of Rome “La Sapienza”, in Italy, are investigating an electrodynamic tether system, named **EDOARD (Electrodynamic De-Orbiting And Re-entry Device)**, for satellites and upper stages end-of-life de-orbiting.

Space Tether Links [1]

Various startup companies are now developing tether technologies and performing experiments

Tethers Unlimited Inc. (TUI) is an American research and development company specialized in advanced space technologies and scientific computing solutions. TUI was founded in 1994 by Dr. Robert P. Hoyt and Dr. Robert L. Forward to develop products based upon space tether technologies including:

- The **Terminator Tether™** satellite disposal device
- A failsafe, multi-line tether structure for micrometeorite/orbital debris survival called the **Hoytether™**
- The Microsatellite Propellantless Electrodynamic Tether (**μPET™**) Propulsion System
- Tether transport systems (momentum exchange tether techniques and electrodynamic tether propulsion)

TUI has developed **TetherSim™**, that is a highly capable numerical simulator of space tether systems

<http://www.tethers.com/>

Space Tether Links [2]

The Michigan Technic Corporation (TMTC) is the largest US small business involved in space tether development. The TMTC mission is to provide dependable tether technologies for a wide range of applications including satellite reboost and orbital debris reduction. Its **STEP-AIRSEDS** mission will flight-qualify the first systems for future commercial applications of ED space tethers for orbital debris mitigation, satellite reboost/deboost and ISS reboost.

The TMTC **SDT/TOSS** tool represent the state-of-the-art in tether mission analysis and is currently in use on the STEP-AIRSEDS mission.

<http://www.airseeds.com/aerospace.html>

Tether Applications is an American company focused on the identification, development and use of near-term applications of tethers in aerospace environments. It was formed in 1989 by Joseph A. Carroll who, in 1983, developed the concept of a small expandable deployment system (**SEDS**).

<http://www.tetherapplications.com/>

Space Tether Links [3]

Delta-Utec Space Research & Consultancy is a Hollander company actively involved in researches and projects on

- Tether experiments in space: **YES, YES2, MARS-g, CAPREE, TSE, Tethered Satellites in the Earth Atmosphere**
- DUtether project to develop a tether that will completely degrade by ultra-violet at the end-of-mission
- Conductive tethers
 - Delta-Utec has developed **ETBSim**, a new fast tether simulator for electrodynamic tethers
 - Delta-Utec, in co-operation with **IFSI/CNR** in Rome, performed plasma chamber tests to study the behavior of conductive tethers
- Tethers and debris mitigation in response to an AIAA invitation, Delta-Utec performed a comprehensive study on the current state-of-the-art of tether concepts for debris mitigation

<http://www.delta-utec.com/>

Space Tether Links [4]

Smithsonian Astrophysical Observatory (SAO) (Cambridge, MA): since the early 70's, fundamental contributions to space-borne tethered systems have been given by members of the special project group of the SAO.

E.C. Lorenzini, R.D. Estes, M.L. Cosmo, G.E. Gullahorn and Y. Alpert have proposed several of the tethers-in-space system that have been analyzed or flown by NASA during the last two decades. Some members were also actively involved in six tethered orbital flights (TSS-1, SEDS-I, PMG, SEDS-II, TSS-1R, TiPS) and prepared the **Handbook of Tethers in Space** (3rd edition, Dec. 1997) for the NASA Marshall Space Flight Center.

Thanks to a great experience acquired through two decades of studies and involvement in tethered system flights, the SAO special project group has become a leader in tethered systems such as **bare tethers for in-space propulsion** which will be first tested with the flight of **ProSEDS**.

<http://cfa-www.harvard.edu/~spgroup/>

Space Tether Links [5]

Research Group on Dynamics & Control of Tether Systems (Australia) conducts research and development in the dynamics and control of tether applications in space, in the atmosphere and underwater. The strategic objective of the group is to investigate new applications for tethers that promise significant long-term economic benefits.

<http://www.aero.rmit.edu.au/wackettCentre/DCTS/>

ProSEDS experiment at NASA MSFC

<http://astp.msfc.nasa.gov/proseds/>

TiPS Mission

<http://hyperspace.nrl.navy.mil/tips/>

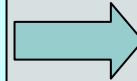
Space Tether Simulation Tools [1]

TetherSim™

Numerical simulation tool for electrodynamic space tether systems
developed by Tether Unlimited Inc.

to enable accurate analyses of the performance and behavior of the Terminator Tether™ device.

Includes models for:



- Tether dynamics
- Orbital mechanics
- Geomagnetic field (IGRF model)
- Ionospheric density (IRI model)
- Atmospheric neutral density (MSISE-90 model)
- Electrodynamic physics
- Solar illumination
- Solar pressure
- Satellite dynamics
- Satellite power

TetherSim™ was also used to determine the rate at which a Terminator Tether™ system can deorbit a spacecraft from various LEO orbits

Contact Point:

Rob Hoyt (hoyt@tether.com)

Space Tether Simulation Tools [2]

ETBSim

ETBSim is an advanced tether simulator based on BeadSim (J.A. Carrol of Tether Applications), a fast multi-bead simulator for dynamics of tethers.

ETBSim has been developed by Delta-Utec to include deployer hardware noise, stochastically generated environmental disturbances, control algorithms, deployment optimization as well as a **conductive tether package**.

The conductive package consists of:

- Composite tethers (flat or round conductive/bare/mechanical)
- Electron/ion collection
- Thermal effects
- IGRF/T-96 magnetospheric model
- IRI ionospheric model
- Solar pressure
- J_2
- Sun and Moon gravity effects

The ETBSim electrodynamic part has been quantitatively verified with the results of Vannaroni et al. (IFSI/CNR) and qualitatively with advanced simulations carried out for ProSEDS

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Space Tether Simulation Tools [3]

Spacecraft Dynamic Tool/Tethered Object Simulation Sub-System (SDT/TOSS)

The SDT and TOSS tools have been integrated by the **Michigan Technic Corporation** to provide a validated, high-fidelity simulation of integrated spacecraft and tethers.

TOSS was developed to support NASA's TSS Orbiter Mission. It was used by MSFC in designing the ProSEDS electrodynamic reentry project and by the Naval Research Laboratory in the design and operations of the TiPS mission.

The **SDT/TOSS** simulator supports **tether dynamics, tether deployment methodologies, thermal models and electrodynamics models**. It represent the state-of-the-art in tether mission analysis and is used on the STEP-AIRSEDS mission by TMTC and NASA MSFC.

For information regarding The Michigan Technic Corporation software products contact: sales@airseds.com

Space Tether Simulation Tools [4]

Lifetime OF Tethers in space (LOFT)

LOFT is a tool to predict the lifetime in orbit of intact or severed tethers

- It can simulate long-term dynamics of tethered satellites using different methods depending on the tether mission
- It includes all the principal orbit perturbations
- It does not consider electrodynamic tethers
- It includes the possibility of calculating collision probabilities and the risk of tether of being cut

LOFT has been developed by **Astrium UK** (software, debris model) in cooperation with the Center of Studies and Activities for Space (**CISAS**) of the **University of Padova** (tether model and dynamics, orbital dynamics) under and ESA Contract. It will probably become available this year.

At CISAS, impact tests were carried out to provide input parameters to the LOFT debris model

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Space Tether Simulation Tools [5]

Tether Simulator Tetsim

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Tetsim is a tool to simulate the dynamics of tethers in space

Its development has been started up by Ean Crellin (**ESA**) and Robin Biesbroek (**JAQAR Space Engineering**, The Netherlands).

This tool is under development. The present version does not include ED tethers. It has not been designed to compute tether lifetimes or collision risk.

Tethered system

- All masses are pointmasses
- The tether consists of numerous beads: small masses connected by massless, straight and inelastic bars

Tether simulator features

- Three-dimensional model
- Massive, bendable, non-deployable tether
- Earth oblateness perturbation
- Influence of sun and moon gravitation
- Solar pressure perturbation
- Animation

Tool to Assess the Tether Risk

Tether Risk Assessment Program (TRAP)

The **Tether Risk Assessment Program** is a new model currently under development at the University of Southampton (UK). TRAP is a short-term model that specifically studies the interaction between space tethers and a debris cloud produced by an on-orbit fragmentation event. The model is composed of three main functions:

The tether dynamics model was validated using Tetsim, the PCD method using the Space Debris Simulation (SDS) suite, which was also developed at the Un. of Southampton

- Breakup Function to model the fragmentation event
- Tether Function to model the tether dynamics. Two types of motion are simulated:
 1. The orbital motion of the centre of mass of the tether about the earth
 2. The librational motion of the end bodies (and beads) relative to the centre of mass
- Analysis Function to compute the collision and sever risks associated with a space tether. The method adopted is that of probabilistic continuum dynamics (PCD)

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Past and Ongoing Studies to Assess the Collision Risk of Tethers with the Space Environment [1]

NASA/JSC

- A **Micrometeoroid and Orbital Debris Impact Study** was performed by NASA Johnson Space Center (JSC) in support of the International Space Station Alpha (ISSA) Tether Power Augmentation Study lead by Marshall Space Flight Center (April 1996). This study had three main objectives:
 1. To assess the potential for the tether being cut while being used to generate power
 2. To estimate the type of orbits which tether fragments would have assumed if the tether was severed, the lifetimes of these orbits, and the risk to other users of space
 3. To assess the risk to ISSA from recontact with tether fragments after the tether was cut.
- Specific studies have been performed on the vulnerability of tethers to orbital debris and meteoroid impacts, using ORDEM96/ORDEM2000 and meteoroid models.
- The **collision risk to the ISS from the ProSEDS tether** has been investigated as well. As a consequence of this study, the warning box of the ISS will have to be expanded whenever the tethered satellite will be evaluated for possible conjunctions.

Past and Ongoing Studies to Assess the Collision Risk of Tethers with the Space Environment [2]

Extensive analyses of collision probability of tethers with space debris and spacecraft have been performed by

- Tether Unlimited Inc. using **TetherSim**
- Delta-Utec using **ETBSim**

Various studies have been accomplished at the Aerospace Corporation

- To determine the probability of collision with resident space objects and untrackable debris for the tether component of the tethered Satellite System (TSS) after it broke away from the shuttle orbiter, in February 1996.
- To calculate the collision probability between a satellite and a space tether.
- To analyze different calculation techniques (analytical and statistical approaches) to determine collision probabilities

Past and Ongoing Studies to Assess the Collision Risk of Tethers with the Space Environment [3]

- A research programme to study the collision risk presented by de-orbiting tethers to the operational satellites and other tethers has been planned by QinetiQ (UK) using the **IDES** model, along with specific assumptions on the collision cross-section.
- Studies to calculate the sever probability of single and double tether systems colliding with orbital debris have been carried out at the Kyushu University, Japan.
- A version for tethers of the Space Debris Impact Risk Analysis Tool (**SDIRAT**) has been developed and used at ISTI/CNR (former CNUCE), in Italy, to evaluate the orbital debris impact rate on gravity gradient stabilized cylindrical tethers. This tool has also been applied to compute the expected operational lifetime of the EDOARD tethered system.

Lessons Learned

Tether technology has advanced significantly since its dawn over 30 years ago

- The success of the **SEDS** system proves that tethers are ready to move from experiments to applications
- The **TSS-1R** mission confirmed that large EMF potentials can be obtained at orbital speeds
- The **TiPS** mission proved that tethers can be made to be survivable
- Some basic theories on space tethers, especially with regards to power generation and passive propulsion, have been confirmed by the past tether experiments
- The Plasma Motor Generator in 1993 and the Tethered Satellite Systems in 1992 and 1996 deployed long conductive tethers from orbiting spacecraft and generated kilowatts of power. **ProSEDS** will take the technology one step further, to produce thrust and de-orbit a payload.

Tether systems have strong potential for providing low-cost propulsion capabilities for a number of applications

However, the past experiments have also highlighted the difficulty in deploying extremely long tethers, while safety concerns have sometime led to a complete failure of the mission.

A number of space tether simulators have been developed in the past, other are currently under development, but various problems are still to be solved.