Experiment of Tethered Nanosatellite Flying with Electrodynamic Tether

Title: **Experiment of Tethered Nanosatellite Flying with Electrodynamic Tether**
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1. The Need

Low-cost, high efficiency and multi-purpose propellantless propulsion in space is a highly desirable technology. The electrodynamic tethered nanosatellite system, in which two nanosatellites are connected by a long, flexible, electrically conductive tether, becomes specifically appealing because it uses passive electromagnetic interactions with the Earth's magnetic field to generate power or provide propulsion to the satellite. By this way, the electrodynamic tether (EDT) is able to provide low-cost orbit modification (de-orbit and boost), electrical power generation, and spacecraft formation flying without the use of propellant as required by conventional satellites. The following table summarizes the current status of EDT technology development.

Element	Discussion	Status
Stable Deployment of Tether	Operation of an EDT system requires deployment of the tether in a dynamically stable configuration.	Demonstrated by PMG, TSS 1&1R, SEDS, TiPS missions
Tether Retrieval	Necessary to mitigate collision risks or to permit satellite operations precluded by the presence of a deployed tether.	Successful retrieval demonstrated by TSS-1
Power Generation	Useful power generation requires delivery of power to a load while accommodating the large changes in tether voltage that occur due to magnetic field variation over each orbit.	Basic physics demonstrated by PMG, TSS-1R; **Useful power generation not demonstrated.**
Long-term Dynamic Stabilization of EDT	Variations in electrodynamic forces can result in instability of swinging librations and higher order oscillations of the tether.	**Not yet demonstrated.**
Bare Tether Anode Current Collection	A long bare tether may provide a highly-efficient, zero-consumable means of collecting electrons from the ionosphere.	**Not yet demonstrated.**
Arc-Resistant or Arc-Tolerant Tether	M/OD impacts will inevitably cause damage to insulation on deployed electrodynamic tethers.	**Not yet demonstrated.**
High Voltage Power System	Propulsive EDT may experience significant voltages (100's - 1000's Volts) at relatively high currents (0.1's - 10's Amps).	**Not yet demonstrated.**
M/OD & AO-Survivable Conducting Tether	Tethers on orbit will be subjected to impacts by micrometeorites and orbital debris, and many tether materials such as insulation will suffer degradation and erosion by atomic oxygen.	**Not yet demonstrated.**
Tracking and Prediction	A tethered satellite will appear to ground observers to move in a 'non-Keplerian' orbit, even without electrodynamic thrusting. Current Space Command systems are not prepared to properly track and predict the orbital motion of tethered systems.	**Not yet demonstrated.**

Despite the accomplishment of the tethered systems experiments, the space tethers missions have stopped after 1990's and left us with a number of untested theoretical predictions due to budget limitation. Recently, there has been a renewed interest on the tethered system. Specifically, attentions have been focused on the EDT because of its potential in propellantless decreasing or increasing the momentum of the tether system in space, providing an affordable technology for deorbiting the satellites to address the problem of space debris, which is a potential collision risk as more and more man-made objects cluttering the sky and expected to double every few years as large objects weaken and split apart. Among those, many of the task can be examined with a new EDT experiment using low-cost nanosatellite platform.

In addition, there is a growing interest in the ground radar community in the metrology of HF radars to understand how a coherent backscatter radar works in the Super Dual Auroral Radar Network (SuperDARN) - an international radar network for studying the Earth's upper atmosphere, ionosphere and connection into space system. This requires a good interpretation of convective motion of the F-region ionosphere at high latitudes. To date, there has been little quantitative use of backscatter signal amplitudes.

The induced current in EDT radiates waves due to the Cerenkov Effect in which electric charge is moving through the ionospheric magnetoplasma at a speed that matches the phase speed of some electromagnetic wave mode. By detecting the induced radiation waves using ground radar, one can calibrate the cross section of coherent backscatter and thus be able to investigate the shape and/or distribution of the field-aligned irregularities. Thence, the tethered nanosatellite formation flying provides a desperately needed, effective and low-cost testing bed for long range ground radar systems (SuperDARN).

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2. Mission Objectives

The mission objectives are separated into two parallel areas, the engineering and scientific objectives.

2.1

2.2 The Engineering Objectives:

The engineering objectives are to test the key EDT theory and technologies that have not yet been demonstrated in space. They are:

(i) deployment and stabilization of an EDT of 500 meter long together with a slave nanosatellite from a master nanosatellite using gravity-gradient force,

(ii) current collected by a bared EDT and the resulting Lorentz force to validate the EDT model, and

(iii) de-orbit of the nanosatellite formation from 700km low Earth orbit to 300km in a few months using the EDT technology.

All of the engineering objectives will be the first of its kind in nanosatellite history. The success of the engineering objectives will be measured by on-board sensors as well as ground observation. Attempts to detect the tethered nanosatellite formation flying on the ground could be undertaken using Canadian magnetometers for the Alfven waves and VLF and HF receivers for the higher bands.

2.3

2.4 The Scientific Objectives:

The scientific objectives are to

(i) understanding how a coherent backscatter (CBS) radar in the high-frequency SuperDARN system works to improve the interpretation of convective motion of the F-region ionosphere at high latitudes, and

(ii) detecting the radiation by a conducting tether for the development of plasma electromagnetic theory.

These scientific objectives can be achieved by measuring the tether-originating waves on the ground using existing equipment.

3. Concept of Operations

The proposed EDT experiment will be conducted using low-cost nanosatellite technology. The concept of EDT for current generation has been tested in previous space missions to demonstrate the theoretical possibility to power generation, de-orbit or adjust the orbit of a spacecraft using the Lorentz force generated by an EDT. Practical demonstration of the technology is still left untested. In addition, there is a growing interest in the ground radar community in the metrology of HF radars.

The EDT nanosatellite formation flying consists of two nanosatellites and one EDT. The master and slave nanosatellites will be linked by a long EDT after separation. The two nanosatellites will be jointed together to launch. After ejected into space from launch vehicle, the two nanosatellites will orbit together until they reach the stable status and the then the slave nanosatellite will be separated from the master using the inter-satellite separate mechanism. As the slave nanosatellite has been separated from the mater with a predefined delta V, the EDT is released from the slave. Once the slave is separated from the master by a certain distance, it will rely on the gravity-gradient force to deploy the rest of the tether. The whole system, including the nanosatellites and the EDT, will be stabilized by the gravity-gradient force. A camera will be mounted on the master will record the deployment process of the tethered nanosatellites and its dynamic behaviour after the tether is fully deployed, while the tether tension will be measured at the master too to determine the Lorenz force generated. In addition, the current generated by the bare EDT will be measured at the slave and relayed to the master to communicate to ground station. The information is critical for the validation of the dynamic theory of EDT, especially the long term stability of tethered nanosatellite formation flying using EDT technology. It will be the first of its kind in nanosatellite history.

As the conducting tether crosses through the Earth's magnetic field, a positive voltage will be generated along the EDT length relative to the ambient ionospheric plasma. The electrons in the ionosphere will be collected by the bare tether and begin flowing down the tether to the slave nanosatellite, where the electron emitter will expel them back into the ionosphere to complete the current loop. This current in the tether will interact with the Earth's magnetic field to generate a Lorentz force on EDT opposite to the direction of its orbital motion. Through its mechanical connection to the master and slave nanosatellites, the EDT will thus lower their orbit without propellant and power. It will be the first of its kind in demonstrating de-orbiting of spacecraft propellantless in space history, not just for nanosatellite.

The technical risk associated with the proposed experiment will be relatively low. Once successful, we will carry on the second phase of the experiment to actually raise the orbit of nanosatellites by reversing the current direction in the EDT with power generated by solar cells so that the Lorentz force on the EDT will be aligned with the direction of its orbital motion. This propellantless adjustment of the nanosatellite's orbit will enable the nanosatellite to carry out more complex mission tasks in the future. Furthermore, it will prove the concept of space elevator using EDT to transport the space assets from one orbit to another in the future.

Once the EDT has been successfully deployed, it will reradiate, or scatter, radio waves in a range of polar angles, including the direction anti-parallel to the incident wave direction. To a first approximation for thin wires, the scattering is independent of azimuth. Thus, a reflected signal can be returned to the radar transmitter site. The amplitude of the reflection can be found from classic electromagnetic (EM) theory, assuming that the SuperDARN carrier frequency is a few megahertz above the local plasma frequency. The comparison of the magnitude of this artificial reflection with the spontaneous backscatter from the same neighborhood furnishes a measurement of the radar cross section of the backscatter.

Currently, SuperDARN radars probe the ionosphere with horizontally polarized wave electric fields. The decomposition of this linear polarization by the magneto-ionic ionosphere into O- and X- polarization assures that waves incident upon the wire will have a polarization component appropriate for reflection.

Over-the-horizon (OTH) radars are designed to find targets many degrees of latitude away, i.e., to have outgoing and returning waves reflected obliquely by the ionospheric F region. Backscatter by the irregular high-latitude F region is thus a distraction, but it must be physically understood in order to improve measures taken to improve the signal/noise ratio. The basic scientific interest is hence the same as for the SuperDARN research.

The mission scenario wherein the EDT initially orbits at 600-800 km altitude fits well with the HF reflection objective. One would use the echo-detection from the highest altitudes as a training activity for acquiring the reflection. The best backscatter characterization data would probably be acquired when the tether deorbited to 300 km where the ionosphere is the densest and backscatter from density irregularities is strongest.

4. Key Performance Parameters

The mission has ***four*** key performance parameters that will be evaluated during the mission's execution.

4.1 Successful deployment of tether to be effected in a stable manner

The first objective of the mission, and concurrent to all future mission objectives, is the successful deployment of the 500 meter EDT from the nanosatellite. The mission takes advantage of the low mass of the satellites involved and is thereby capable of reducing the length of the tether necessary to provide significant power and thrust. This limits risks during deployment as well as operation. The success of this objective can be verified by the onboard camera as well as the ground radars.

4.2.1 Collection of electron using bare tether is to be proven for the first time.

The collection of electron using a bare tether will be proved by measuring the current generation in EDT. Previous successful missions employed insulated EDT and the electron collection and emission were performed by the plasma contactors at both ends of EDT. Although thought to be feasible, useful power generation has never been proven with the use of a bare tether.

4.2.2 Ejection of electron using MEMS electron emitter.

Concurrent to the previous parameter, the ejection of electron is necessary in order to generate current/power. The previous demonstrated successfully plasma contactors consuming fuel in order to emit electrons back to plasma. However, these plasma contactors do not fit for nanosatellite mission. The mission proposes a novel MEMS electron emitter that does not consume any fuel to provide efficient electron emission suitable for nanosatellite. This will be another first for the presented mission.

4.3 Successful detection of Radiation Wave from Ground based radar observation

The passage of an EDT will induce radiation waves in space. This mission will provide an unprecedented opportunity to observe the phenomenon employing ground based radar for radio scientists.

5.4 Demonstration of EDT for orbit management of nanosatellites

The final parameter is the useful employment of EDT for the orbit management of satellites. As a final mission objective, the satellite’s orbit will be modified significantly by using the interaction of the EDT and the magnetic field of the Earth. This will present a low-cost, low-mass, propellantless way to de-orbit satellites at the end of their useful life. If successful, one can further reverse the current direction in EDT by the battery on satellite and the conduct the orbit boost experiment.

5. Space Segment Description

The orbit of the EDT nanosatellite formation flying is assumed to be a sun-synchronous orbit with an altitude between 600 and 800km. The EDT nanosatellite formation flying consists of two nanosatellites and one EDT. The master and slave nanosatellites weigh 3kg and 2kg, respectively, and will be linked by a 500 meter long EDT after separation. The nanosatellite will be manufactured by the Space Flight Laboratory (SFL) at University of Toronto Institute for Aerospace Studies (UTIAS) based on its CanX-2 nanosatellite design in order to reduce development risk, time, and cost. The CanX-2 nanosatellite has been successfully launched on April 28, 2008 and is still working properly in space now. The master nanosatellite will be a rectangular prism of dimensions 10 x 10 x 34 cm. The master nanosatellite will contain the power, on-board computer, communication, attitude determination and control, nano-propulsion, inter-satellite separate mechanism and a camera. The detailed technical specification of the master nanosatellite can be found from the UTIAS' website: www.utias-sfl.net/nanosatellites/CanX2/system.html.

The slave will be a cube of 10 x 10 x 10 cm, including a 500 meter long EDT and tether deployment mechanism, a MEMS electron emitter, a current measurement unit, and a short ranged radio communication system with the master nanosatellite. The EDT system and electron emitter will be developed by York University. The EDT will be made of braided aluminum bare wire with a diameter of 1 mm. The total mass of the EDT will be 0.8kg. The expendable self-deployer of EDT will be a derivative of the successful flight-proven Small Expendable Deployer System (SEDS), which will fit inside the slave nanosatellite. To emit electrons into plasma, a field effect electron emitter will be developed and tested. This is the only technology proposed in this mission that has not been tested in space, which requires space qualification test. The slave nanosatellite won't have its battery and solar cells. It will use part of the current generated by the EDT to power the current meter and radio communication system. This will be another first technology demonstration.

The two nanosatellites will be jointed together to launch. After ejected into space from launch vehicle, the two nanosatellites will orbit together until they reach the stable status and the then the slave nanosatellite will be separated from the master using the inter-satellite separate mechanism developed for CanX-4&5 by SFL at UTIAS

6. Orbit/Constellation Description

As outlined above, the desired orbit of nanosatellite is a sun-synchronous orbit with an altitude between 600 and 800km. This orbit is selected in order to provide an excellent scenario for ground observation using Canadian ground radars such as SuperDARN.

The EDT nanosatellite formation flying will provide an unprecedented ability to change orbits of nanosatellite formation for difference mission tasks without using any fuel. This will be accomplished by employing the Lorentz force generated by the EDT to adjust the orbital height. In addition, the success of propellantless orbit adjustment would enable variable baseline for interferometric observations by varying the tether length at different orbits.

7. Implementation Plan

It is estimated that the development/fabrication period will be 2 years. The estimated cost for whole mission would be around $3 million US dollars with the cost breakdown as: (a) the cost for the master nanosatellite with full three-axis attitude control - $2 million, (b) the slave nanosatellite with EDT, its deploying mechanism and electron emitter - $0.5 million, and (c) launching cost - $0.5 mission.

The development of EDT system and the slave nanosatellite will be conducted in the Centre for Research in Earth & Space Science (CRESS) at York University. CRESS is comprised of laboratories that provide specific capabilities to carry out the work, such as, Clean Room (class 10000), clean Work Room, Design, and Assembly/Test. The experimental facilities include vibration table and Temperature vacuum chamber. It is well known for its activities in developing and fabricating space instruments. The most recent mission is its contribution of LiDAR and weather station to the Phoenix Mission to Mars. Dr. Zhu is the director of space engineering program at York University. He will be the mission leader and responsible for the development of EDT and the slave nanosatellite. He will work with Dr. Laframboise at York University to design and develop the field effect electron emitter. Dr. Misra at McGill University will study the long term stability of EDT and provide the design parameter to Dr. Zhu.

In addition, Dr. Zhu will work closely with (i) Dr. Ng of Canadian Space Agency to develop the mission parameters and international collaboration, (ii) Dr. Zee, the director of SFL at UTIAS, to develop the master system and overall system, (iii) Dr. James of Communications Research Centre Canada who will lead the radio scientists to achieve the scientific objectives.

The development of the master nanosatellite will be conducted in the Space Flight Laboratory (SFL) at UTIAS, which is a unique university lab in Canada and an international leader in nanosatellite and microsatellite development. It has a tracked record in developing, fabricating, and launching nanosatellites. Currently, it has launched four nanosatellites into space and over the past 8 years. In addition, the EDT and the slave nanosatellite will be sent to SFL for the final testing and integration with the master nanosatellite.

As mentioned before, Dr. James will lead the radio scientists (Drs. Hussey and Riddolls) to achieve the scientific objectives by using existing Canadian ground radar networks. There is no requirement for equipment investment to carry out scientific observation, as they will be done using existing ground facilities.

7.1 Funding Scheme

The risk and cost of the proposed experimental mission will be relatively low compared with (a) the risks associated with other space missions, (b) the significant engineering and scientific benefits out of the mission, and (c) the training of highly qualified personnel at universities. If the proposal is accepted and a firm commitment to launch is provided, the team will request funding from Canadian Space Agency Grant & Contribution program for the technology developments relating the EDT and its deployment system as well as the fabrication/testing of the tethered nano-satellites. Detailed information on Grant & Contribution program can be found on http://www.asc-csa.gc.ca/eng/resources/gc/default.asp.

8. Contact Person and Team Organization

8.1 Contact Person:

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8.2 Team Organization:

As shown above, we have formed a strong team of various universities and government agencies with complementary expertise:

Name	Affiliation	Responsibility
Z. Zhu	York University, Canada	Mission Leader, EDT System & Slave Nanosatellite
J. Laframboise	York University, Canada	Space Particle Charging/Emission, Electron emitter
A. Ng	Canadian Space Agency	Nanosatellite and International Collaboration
R. Zee	SFL-UTIAS, Canada	Design of Nanosatellite and System Integration
G. James	Communications Research Centre Canada	Radio Wave Radiation and Detection
G. Hussey	University of Saskatchewan, Canada	HF Backscatter Theory
R. Riddolls	Defence Research and Development Canada	Operations of SuperDARN
A. Misra	McGill University, Canada	Electrodynamic Tether Stability