Energy Harvesting by Satellites Using Electro Dynamic Tethers

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***Abstract*— Satellites operating remotely in a hostile environment require significant power resources to function. However orbital speeds are high and near earth orbits pass through plasma belts and through the earth's magnetic field. Electrodynamic tethers offer scope of taking advantage of these condition with direct harvesting via electrodynamic tethering being the most promising, despite the difficulties encountered in early experimentation.**

***Keywords*–EDT, harvesting in space, satellite tethering, plasma, orbital shifting**

I. Introduction

Satellites have been using what were called booms to provide gravitational stabilization in orbit and for isolating detectors. For instance, the Australian scientific Satellite FedSat, a microsatellite with primary dimensions circa 60cmx60cm had a boom of several meters, which significantly complemented the use of gravity wheels, What has become recognized – and patented –is that such a tether attached to a satellite travelling at significant velocity in an orbit roughly equatorial will cut through at almost 90 degrees the flux lines of the earth's magnetic field, and also be traversing through electrified plasma:

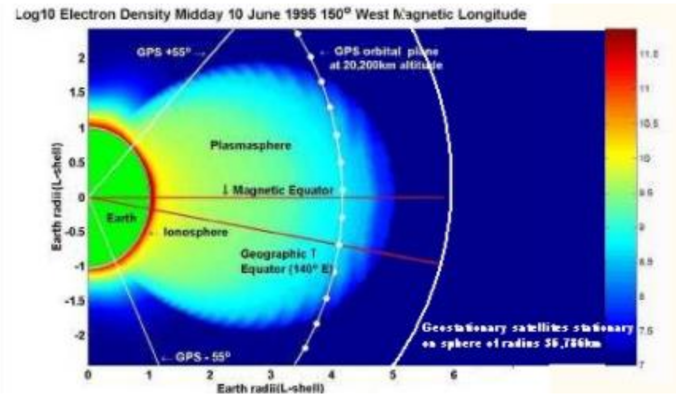

Fig 1. Satellite orbits about earth with electron density demarcating the ionosphere and plasmasphere.. GPS satellite orbits (60 degree to the orbital plane) also marked as well as the orbit of a polar satellite of geostationary period..

Early satellites carried traditional batteries, NiCd and Lithium, adequate for short lifetimes. This was augmented by solar cells. For satellites embarking to the further planets a range of batteries based on radioactivity has been used. The ever increasing processing of miniaturization has made possible the current generation of nanosatellites, with dimensions of the order of 10 to 35 cm. Such satellites can be simply launched, with large payloads (many satellites) possible for each launch. However the area available for solar cells to be mounted has significantly decreased, which is only partly compensated for by the reduction of power requirements of sensor and computational components. Thus there is a growing interest in schemes for harvesting energy by satellites through there active lifetime. It is also becoming obvious that there must be sufficient reserves of power for satellites to purposefully self-destruct at end of defined mission – so as to alleviate the growing problem of space junk. But the most exciting aspect of tethering is by sourcing energy locally satellites in quite low LEO orbits may be shifted further from Earth while only requiring an initial relatively inexpensive launch to a lower orbit.

II Physics in Orbit

A Low Earth Orbit or LEO satellite orbits the Earth 200 - 2000 km altitude with a speed in the range 7.8 – 6.9 km/sec for a (near) circular orbit. Plasma densities are indicated in Fig 1. The earth's magnetic field about the earth is in the range 25 to 65 micro teslas. But due to the solar wind of charged particles the field at satellite height can be as much 100 times what would be anticipated by a simple bar-magnet model. It is important to note that there is an extreme difference between the day and night side of the earth due to the solar wind:

Fig 2. Schematic diagram of impact of solar wind on earth's magnetic field.

III (EDT) ELECTRODYNAMICAL TETHERING

EMFs in conductors due to motion in a magnetic field are a staple topic in Electrical Engineering courses. But how to apply to a tether – which is inherently one dimensional ? In his 2006 Patent, C.L. Johnson, an employee of NASA proposed to couple the ends of an EDT in space to the surrounding plasma. By this means the circuit is completed and a powering current can be drawn.

Fig 3. NASA artists image of satellite with tether. [3]

Note that the less massive object at the end of a satellite's tether is on a lower orbit.

The induced current on an EDT acts as a brake on the satellite: reversing current direction using energy derived from solar cells or storage provides a boost to the satellite.

III PHYSICS OF ELECTRODYNAMIC TETHER

In 1831 Michael Faraday demonstrated magnetic induction when he showed that when a smaller conductive coil was moved within a larger coil carrying current a current was induced within the moving coil.

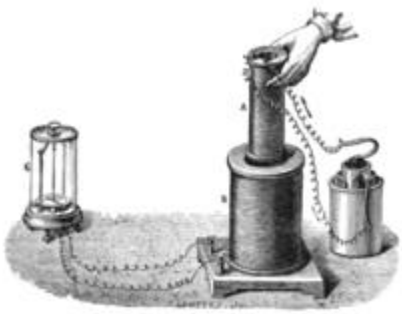

Fig 4 One of Faraday's 1831 experiments. Moving the smaller coil induced a current in the larger coil detected by the galvanometer.

Subsequently James Clerk Maxwell developed electromagnetic theory as a mathematical theory within which one talks of the flux within a level conductive coil as the integral over the enclosed region **A** of the vertical component of the magnetic field **B** as the total flux Φ. Mathematically the total flux traversing an enclosed loop is given as

$\Phi = \int \mathbf{B}.d\mathbf{A}$ and the induced **EMF is** $(d/dt)\Phi$

It is precisely Faraday's observation that is exploited by EDT = electrodynamic tethers.

The earth's magnetic field is akin to that of a bar magnet, whose South Pole is located at the North (magnetic) pole

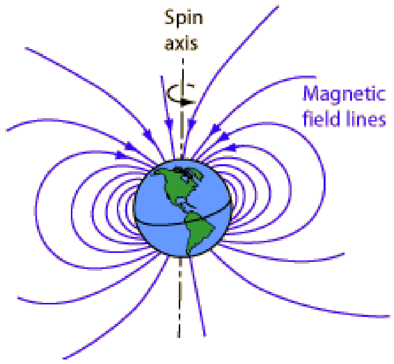

Fig 5 Schematic magnetic field of the earth.

Satellites are normally launched in the direction of the spin of the earth, as this gives a modest boost. We consider a satellite so launched, in an orbit at small angle to the equator. In this case the satellite motion is essentially perpendicular to the flux lines of the earth's magnetic field.

Tethers are conductive cables, protected in various ways from the corrosive effects of the higher oxygen levels in the region of low earth orbit (LEO) satellites. A tether is a one-dimensional object, but by coupling the satellite itself, and the tip of the tether to the local plasma, a conductive circuit is brought into existence. No need to determine the exact shape for the virtual circuit, it determining the flux change as the tether moves over unit time (one sec) one realises that it is given (primarily at least) by the area swept out by the tether.in unit time. That is the flux change in unit time is **LvB**, where B is the average field, L is tether length, and v is orbital velocity. This is indicated in the following sketch

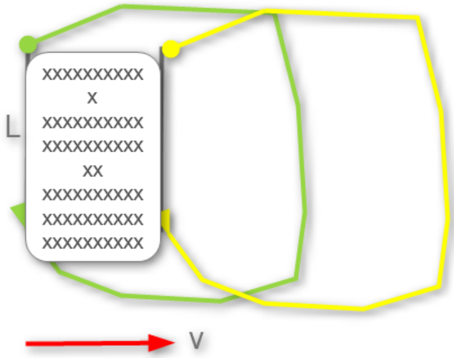

Fig 6. Showing how tether primarily determines the inductive current.in a loop - the effective area swept . In this diagram drawn viewing from above the South Pole the satellite goes from Left to Right with velocity **V** and field lines (**B**) denoted by **x** are into the page (northwards) The two coloured loops indicate the"phantom" and somewhat diffuse conductive link through orbital pasma.

Students of Electromagnetic theory are familiar with Lenz's Law, which states that the induced current is such as to oppose the *inducing* motion. In other words, there is an inherent **braking** effect. The energy available to the functioning of the satellite from the EDT reduces the satellites potential energy, lowering its orbit. But conversely, if satellite battery power is available to ***reverse current*** flow in the tether, then the tether drag will serve to boost the satellite to a higher orbit. One can view the reversible role of the tether as comparable to the action of reversible water turbines, that can draw water from a reservoir generating electric power, or pump water up to the same reservoir.

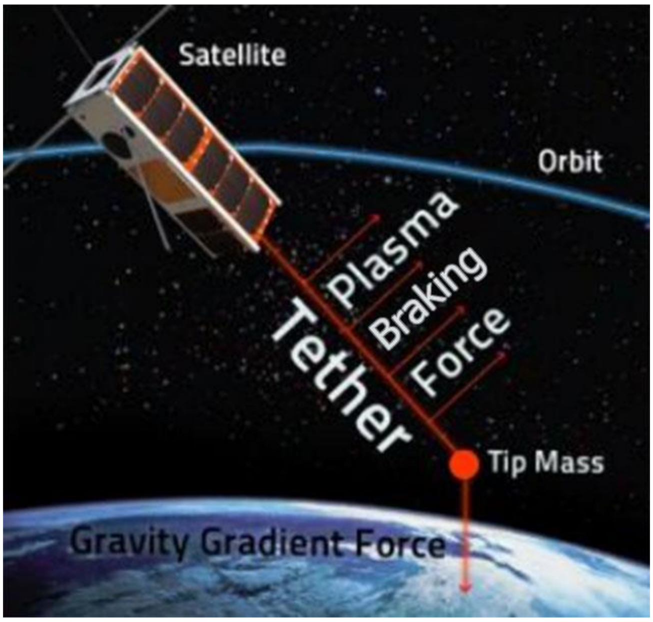

Fig 7. Nano satellite of the current CubeSat design with attached tether connecting the CubeSat to a smaller tip.

CONCLUSION

Nineteenth century physics, developed by Faraday and Maxwell, established and explains how for a static conductive loop, changes in the magnetic field B through the loop lead to an induced Voltage difference. Space technology has given us a deeper understanding of the earth's magnetic field, and knowledge of the prevalence of plasma at LEO orbit levels, and the recognition that for low earth orbits the field strength is of a magnitude capable of exploitation. EDT tethers allow LEO satellites to harvest orbital energy enabling a novel strategy for controlling orbital elevation, both upwards and downwards. The LEO environment is quite hostile to EDT tethers, and there has been some spectacular failures, but at least for relatively short life satellites EDT tethering seems to be a most promising technology.

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About the author Dr Harvey A Cohen

Dr Cohen completed two years of electrical engineering at Sydney University before transferring to the Science Faculty. He then completed a PhD in computational methods in quantum electrodynamics. Following a post-doc at the University of Adelaide he became a lecturer originally in Mathematics and later in Computer Science at La Trobe University. His experiences of teaching undergraduate mechanics lead to "loud-thinking" student efforts in qualitative physics, which research lead him to an initial appointment within the Artificial Intelligence Laboratory, at MIT, Cambridge Mass, and later on a visiting professorship at MIT. A user of the very earliest microcomputers, he conducted an educational robotics project OZNAKI for 8 years, then developed an early Talking Communicator for severely disabled non-speech children. Over time his AI interests turned to vision, and he researched texture recognition, number-plate recognition, image restoration. He was a listed researcher on the establishment of the CRC for Satellite Systems in 1997. He is a Life Member of the IEEE.