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How Can Satellites Draw Energy From The Earth's Magnetic Field?

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Abstract:
Satellites are an essential part of the modern world of information and technology. A large part of our data transfer relies on these satellites. With the world moving towards space travel, any improvements to satellites positioning and longevity could be key. In addition, the last minute movements that the tether, a part of the satellite that will be explained later in the paper, can be used to manoeuvre the satellite out of the way of meteors and other satellites, thus protecting them from damage. The space debris travels at very high speeds of approximately 25,000 km/h. These debris can break satellites, or even fragment into many pieces that can be directed towards the Earth. Additionally, since the first breakthroughs with magnetorquers around 1998, there has not been much improvement to them overall. While this is partly due to the fact that the additional cost alone does not match the additional utility from an economic standpoint, this does not mean that there is no scope for additional research in this area. Additionally, the first tethers were going to be launched onto a NASA satellite in 2003, but the mission was not completed, meaning that they too have not had any significant focus since the last two decades.
The purpose of this paper is to detail existing technology that can be manipulated or modified to be used in satellites to adjust their orientation, elevation, orbit. Additionally, it will go over the technology to launch them into space while using little to no propellant. Along with technology, this includes things like design and material changes, as well as physical additions, both internal and external. The focus will be on the functioning of the technology, as well as its practicality.

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I. Previous works include:

The paper “Charge and magnetic field interaction with satellites” by David. B. Beard talks about how satellites interact with the Earth's magnetic field. It also gives figures on the altitude, size and strength of magnetic fields.

The paper "Development of Electrodynamic Tethers for Propellantless Propulsion in Low-Earth Orbit" by Derek Cheyne, Mitchell Miller, and others talks about a CubeSat experiment where a satellite was launched into orbit using only the Earth’s magnetic field. This experiment was extremely important in proving the propellant fuel free launches. It also gives information on CubeSat sizes and information on the tethers. The paper “Lessons Learned from the Development and Flight of the First Miniature Tethered Electrodynamics Experiment” by George Li, Liam Spence, and others helps explain the experiment and what actually happened in the mission. The paper “Developing the Miniature Tether Electrodynamics Experiment” by Bret Bronner and Duc Trung provides a great visual representation of the tether circuit and functioning. It provides information about the technical side of the experiment detailed in the previously mentioned paper.

It is important to understand why weight is a key factor when launching satellites while maintaining protection for the satellite, and how the magnetorquer will affect that. An example is the amount of care that has been taken to choose materials for the satellite. In the article- ‘What Materials Keep Satellites Safe in Space?’ On RealClearScience, the various material choices for satellites are listed and their reason for use is also explained. Not only the material, but other factors also have to be considered for the protection of the satellite. The article- ‘Earth's Magnetosphere: Protecting Our Planet from Harmful Space Energy – Climate Change- NASA.gov’- goes over the Earth’s strong magnetic field, and helps explain its dangers. The article- ‘The invisible buffer zone with space - atmospheres, magnetospheres and the solar wind- ase.tufts.edu’ also goes over this.

This paper mentions the specific orbit certain satellites orbit in. These are important in gauging the speed of the satellites, their distance from the Earth’s surface, and the magnetic field strength corresponding to those factors as well. The article- ‘Popular Orbits 101 - Aerospace Security- Aerospace.csis.org’ goes over these orbits. The extent of the magnetic field with respect to the ISS is detailed in- ‘Does The Earth's Magnetic Field Go Past The ISS?- Forbes.com’. The orbit most CubeSats orbit in is the Lower Earth Orbit, and the article-

'"Lower Earth Orbit"- The European space agency- 2/03/2020'-details this orbit.

For a basic understanding of the Earth's magnetic field, 'Geomagnetism Frequently Asked Questions. NGDC.gov' provides answers to commonly asked questions. This is especially helpful for those unfamiliar with the area, but ranges to complex questions as well.

While this paper goes over the tether as a potential source of propulsion, and the magnetorquer as a potential source of electricity, it is important to understand currently- 'What Powers a Spacecraft? | NASA Space Place'

This paper mentions CubeSats quite regularly, and they are well explained in the following article- 'CubeSats Overview | NASA'. The alternative to fuel propulsion using the tether system is a relatively new concept, and a recent experiment using the tether system is detailed in- 'Tiny satellite uses Earth's magnetic field to generate thrust- freethink.com'

This article goes over satellite dimensions- 'How big is that satellite? A primer on satellite categories | Viasat'

II. The functioning of the systems:

While it is accepted that magnetic fields themselves do not do work directly, they can do work indirectly. If a current carrying loop were to move and cause a change in magnetic flux, the loop would generate a magnetic field that would in turn do work on the charges or currents. In this way, magnetic fields cause the movement of electrons and hence do work by moving them. This is explained by Faraday's Law of Induction. This law explains how a current carrying wire experiences a force in a magnetic field.

Earth's magnetic field has a strength ranging from 30-60 microteslas on the surface, and about **[Kenneth.R.Lang-Tufts.edu]**. This means that there is still a usable magnetic field present where satellites would orbit. These satellites usually weigh well over 1000 kg, some of the larger ones weighing roughly 6500 kg. A 'U' is a standard unit, or in other words measurements of 10x10x10cm **[Sarah Loff-NASA],[Alex Miller-Viasat]**. CubeSats have measurements in U's. These satellites are usually made only up to 12U, meaning they are always very lightweight. One complete revolution of the Earth in the Lower Earth Orbit, has a radius of about 1000 km, and it takes roughly 90-120 minutes to complete a single orbit. Using the formula F=ma, and substituting force, we get acceleration as 9.24 m/s^2. Most satellites are used to send and receive data either from different parts of the Earth or outer space. This magnitude of acceleration is important to note when understanding why data transfer is so difficult with these particular satellites. These problems, however, can be sorted by putting the satellites into geosynchronous orbit. This is when the satellite orbits at exactly the same speed as Earth and hence always stays above a given location **[M.Nichols-Aerospace]**.

This is a potential future change since currently CubeSats have not been launched into geosynchronous Earth orbit.

III. Magnetorquer:

The magnetorquer of the satellite focuses on using the relative position of the Earth's magnetic field to stabilise and orient satellites, and even control satellite altitude. They are made out of a single coil, which is the main magnetorquer, which then connects to a circuit. This coil is what allows the system to move and reposition the satellite. When the system detects a change in magnetic field or any magnetic force using the attached magnets, it passes a current through the coil to create a magnetic reverse force that causes the satellite to pivot about its centre of gravity. This system is in use in current satellites, however, the purpose of this paper is to bring focus to the magnetorquer, detail some improvements that could be made to it, and explain its pairing with the tether.

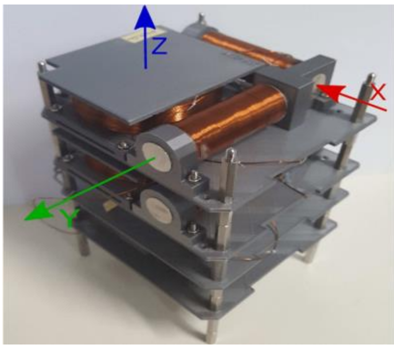


Figure 1, by Simone Battistini obtained through researchgate. This figure details what a magnetorquer looks like, showing the various coils and layers of coils. The three arrows denote the orthogonal directions about which the satellite rotates. The arrows also highlight which coil controls movement in which direction.

Paired with the magnetorquer, magnetic materials are attached outside the satellite. These magnetic materials get magnetised differently depending on the direction in which the magnetic field is pointing. This allows the satellite to understand its relative position to the Earth. In turn, it can use the three coils to move in any direction. The way they work is that one coil has an increased current passing through it, and as a result of Lorentz force the satellite moves in that direction. The circuit then makes use of combinations of these three coils to turn, lower or raise, and even move the satellite.

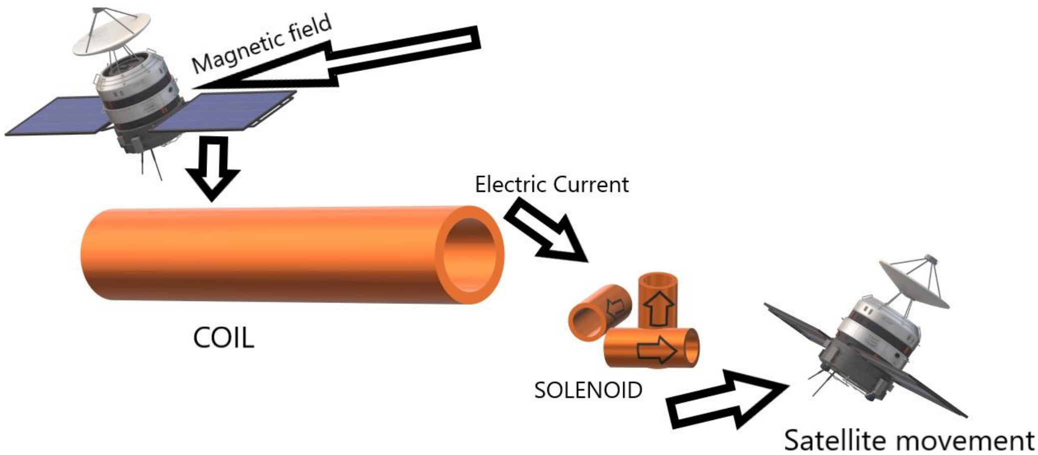


Figure 2. This diagram shows how the large coil with a loop of current passes electricity into the three solenoids that in turn make changes to the orientation of the satellite by interacting with the Earth's magnetic field. Based on the combination of movements along the three axes, the satellite rotates or moves up and down.

The effectiveness of the magnetorquer is dependent on the strength of the magnetic field, meaning it will be less effective in higher orbits. If this condition is not present, the satellite will turn far more slowly. If the field is non-uniform it will function based on the strength of the field it is currently in.

Strictly theoretically speaking, the magnetorquer could be used on satellites of all sizes. However, with things like the ISS, the coil would have to be too large and heavy (up to 1200 kg) for the benefits of the Magnetorquer to be practical **[Alex Miller-Viasat]**. The fact that there is variation in magnetic flux across different parts of the orbit mean that the magnetorquer may not work very reliably with larger satellites due to their large masses. This high mass would not be moved significantly or quickly, since the magnitude of force would remain the same for CubeSats and larger satellites if an identical magnetorquer was used. Large satellites are still contained in lower orbits and while the magnetorquer alone might not be sufficient, it could be considered if paired with an additional tether system detailed further in the paper, that was scaled up for the size of the satellite. Thus, when in regions with a lower magnetic flux the magnitude of force would be too small to move the large satellites mass. However, for CubeSats, the magnetorquer works well along with the tether system, since it avoids all fuel propellant required to get the satellites in orbit and in position.

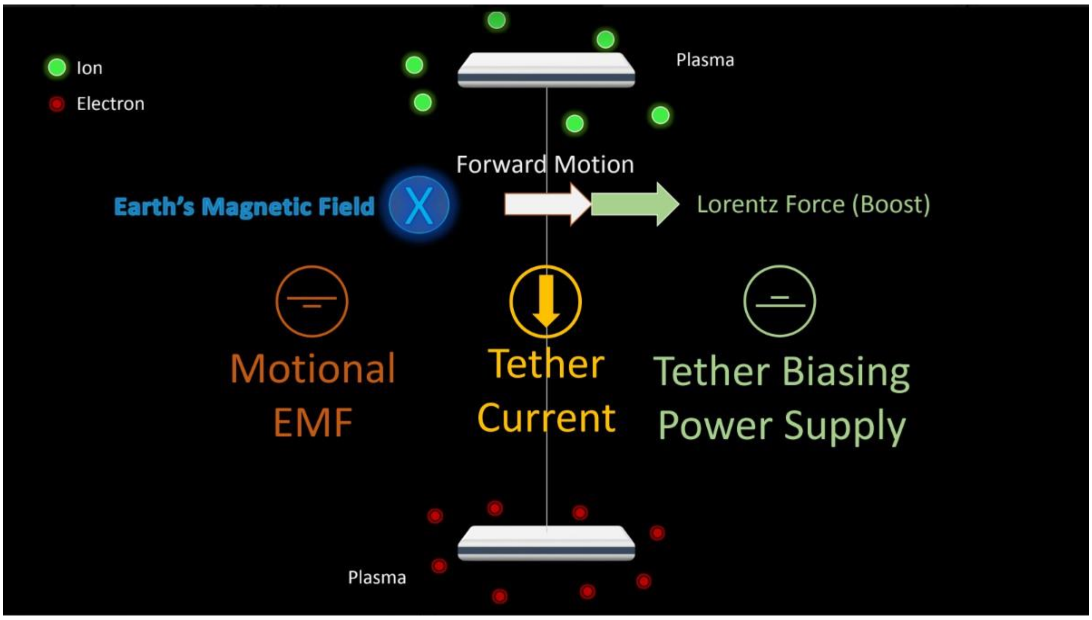
IV. Tether:

Tethers, or Electrodynamic Tethers, can be attached to CubeSats to provide propulsion into orbit without using any consumable fuel propellant. This means that they would be able to reach lower orbit using only the Earth's magnetic field **[Cheyne and Miller]**. The way this works is that the coil in the magnetorquer carries a current, and experiences a force from the Earth's magnetic field. The placement of the coil allows it to be pushed into orbit. The force generated accounts for the atmosphere's drag as well. They also provide the ability to change the inclination or orientation of the CubeSats, as well as their altitude. This is the function that could allow the satellite to avoid space debris collisions.

Additional benefits of these tethers include the fact that the tether can function as an antenna as well and can send and receive signals. However, since the satellites move at such high speeds the transmission cannot happen effectively, and limited data can be immediately transferred. This is because they are in the lower Earth orbit, not the geosynchronous orbit. What this means is that they do not remain directly above a region of the Earth for very long, and would not revolve in sync with the Earth, and thus would not remain directly above the region with which they were transferring data.

The Lorentz force, from the Earth's magnetic field, acts on the current carrying tether to move the satellite forward or backward. There are ions at one end of the tether and electrons at the other. The electrons are contained within a hot cathode. The circuit has two modes, Passive Current Mode and Active Current Mode

[Bronner and Trung]. In passive current mode there is no electron emission, the potential difference is low, and the only movement is of ions due to the small amount of current(around 1μA). However, in Active Current Mode, the cathode emits electrons, which raises the potential difference between the two ends. As a result, the current in the tether also increases. In this mode the ion flow is cancelled out. As a result of the flow of electrons the current generated creates the tether's own electric field. This is what interacts with the Earth's magnetic field and allows the satellite to move. Based on the direction of flow of current the direction of movement of the tether changes. The up and down movement is controlled by the electricity produced by the solar panels satellites contain anyways. This is what allows the main functioning of the circuit.



From paper 4 (Bronner and Trung). This shows the two sections of the tether, one containing electrons and one containing ions. The tether current denoted in yellow shows the direction of current. When the arrow points in the opposite direction, that is, the electrons are flowing, the satellites experience Lorentz force in the opposite direction and move respectively.

V. Summary:

The materials themselves are not very expensive since they would be required in small quantities for CubeSats. Kevlar, the main material of the tether, is not too heavy and the total additional weight of the tether would be around 0.5-1 kg, since the larger space tethers weigh 5-6 kg on average satellites **[Bronner and Trung]**. The next part is the magnetorquer, however this is already present on satellites. The change to be made to the magnetorquer would be the introduction of a larger copper coil. One of the attached magnets should be suspended in such a way that as it feels a force from the Earth's magnetic field it moves within the coil. This in turn will generate a current sizable enough to be used by the satellite.

Since the magnets are contained within the satellite, a layer of conductive material such as iron, copper, or aluminium, roughly 100μm thick to ensure it does not add too much weight. This could be added around the magnetorquer to ensure the magnetic field lines terminate, and don't pass through and interfere with other satellites or other systems within the same satellite. This would also add protection to the magnetorquer. These costs altogether also would not be very large, since sheets of these metals are easily available. **[M.Nichols-Aerospace]**

While further working along these lines, the magnetorquer could be wired to a battery which would store energy instead of using it to move the satellite. In this way there would be direct energy production in the form of electricity while the satellites orbit Earth. This would mean while the satellite does not need to be adjusted, all the energy generated can be stored and used. This also means the solar panels could be reduced in size. Solar panels are large and add significantly to the drag of the satellites as well as the weight, so this would reduce both of these and allow for the required propulsion energy to be lower.

These two systems in combination are not present in any long term satellites, and the tether especially could be largely beneficial in reducing fuel consumption in a world which is turning electric due to rising fuel prices. Additionally, it would be beneficial to the environment since minimal fuel would be burned. However, new launching systems, launching pads, and recovery systems for these systems will have to be developed.

Currently they are used only in CubeSats, if at all, and these satellites are allowed to enter the atmosphere and burn up since their minimal data is transferred while in orbit. This obviously would not work for large satellites, and is something that would have to be considered.

These modifications to satellites are not only possible, but practical as well. When looking at the fact that a lot more energy can be generated, stored as well as saved. This, in totality, would definitely account for any additional mass, slight changes in shape or density would also be accounted for by the fact that less propellant would be required despite the increased mass. The technology and materials required for these modifications are all existing and in use in other devices as well. Battery storage has been in use for a long time. The satellites also already have space within them for small, high energy batteries. Tethers are external and require minimal circuitry within the satellite since they can just be connected to the battery or directly to the magnetorquer.

VI. Answer to the research question:

To answer the question "***How can satellites draw energy from the Earth's magnetic field?***", I would say there are two ways. One is using a magnetorquer that was modified to produce a current by drawing some energy from the solar panels, and some from the coil that was passing through a magnetic field as the satellite was orbiting the planet. While the current generated may not suffice to power the entire satellite, it could allow for the satellites 7–10-year lifespan to be increased, thus reducing space waste. The second way is the Tether. Unlike the magnetorquer, the tether would directly use the Earth's magnetic field to move and increase or decrease its inclination. This, combined with the fact that it can propel the CubeSat into space makes it incredibly useful. If adopted to store energy from when movements are not required, it could prove extremely useful in directly generating extra energy for satellites. In short, satellites can use magnetorquers and tethers along with batteries to generate and store energy using only the Earth's magnetic field as a source.