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THE EFFECTS OF SPACE WEATHER ON EARTH-ORBITING SATELLITES

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Shana Figueroa

Shana S. Figueroa

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Approved:

Professor Grover A. Swartzlander, Major Advisor

Abstract

Intensified activity in the near-Earth space environment caused by the eleven-year solar cycle, such as geomagnetic storms, high-energy particles, and trapped radiation, causes serious problems for orbiting artificial satellites. These satellites serve vital functions in our highly technological society. This IQP explores aspects of the space environment and their effects on satellite operations. The societal importance of satellites is examined, as well as specific cases of satellite failures due to space weather. Solutions to problems affecting satellites due to space weather are also discussed.

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Executive Statement

Space weather is the phenomena that occurs when magnetic and particle disturbances occur in the area between the Earth and the Sun due to solar activity, such as coronal mass ejections and solar flares. Since the Space Age began in 1957, the space environment has become increasingly important because of the effects that it has on satellites and their functions in space. When increased solar activity occurs, the outward flux of solar particles and magnetic fields from the sun (called the solar wind) is increased. The velocity of particles in the solar wind also increases. Due to the increased solar activity, spacecraft operations can be disrupted by contact with energetic particles. Satellites experience greater atmospheric drag produced by a denser space environment. These disruptions have caused millions of dollars of damage each year. In addition, communication systems, terrestrial power grids, and scientific research suffer significant losses when a satellite anomaly due to the space environment occurs. Given the importance and cost of satellite missions in space, it is of increasing necessity that space weather and its effects on satellites be fully understood.

When considering the different effects space weather has on satellites in orbit around the Earth, it is important to recognize the spacecraft's mission and, consequently, where it is in orbit in order to accomplish its mission. There are several general types of satellites used today, and specific orbits that each one needs to travel in. Possible orbits are separated into four categories: low earth orbit (LEO), medium earth orbit (MEO), polar orbit, and geosynchronous or geostationary orbit (GEO) [1]. There are five different types of satellites that orbit the Earth according to their mission objectives: weather satellites, communication satellites, navigation satellites, remote sensing satellites, and scientific research satellites. The orbit a satellite assumes is the most distinguishing factor in what kinds of satellite anomalies due to space weather it is susceptible to. In LEO, the main concern for a satellite's well being are the affects of drag, while in MEO surface charging is of primary concern. In GEO bulk charging and single event phenomena caused by high-energy particles create the most damaging problems for a spacecraft. Knowing the mission of a specific satellite determines what orbit it will assume in space, and, consequently, what considerations should be made to ensure that the spacecraft is adequately prepared for the rigors of the space environment.

Like the Earth's own atmosphere, space is also subject to changes in its environment due to natural phenomena, changes that are know collectively as space weather. The space environment that a satellite must endure includes geomagnetic storms, impacts from high-energy galactic cosmic rays, and exposure to varying amounts of radiation, all connected to the Sun's solar cycle. Solar activity, such as coronal mass ejections and flares, vary in frequency according to an 11-year cycle, called the solar cycle. These cycles are defined by regular variations in solar activity, demarked by the solar maxima and solar minima. As the sun rotates around its poles, the magnetic field lines within the corona become warped, twisting and tangling with each other, and in the process storing vast amounts of energy [17]. When the field lines suddenly realign themselves, they release their stored energy in the form of solar flares and coronal mass ejections. Another phenomenon caused by the solar cycle is known as a geomagnetic storm. Geomagnetic storms occur when the solar wind's kinetic energy is converted into magnetic energy that is stored in the Earth's magnetotail and is periodically dissipated [18]. These storms produce energized plasma (5 to 50 keV) that can extend into geosynchronous (high) orbit and cause such problems as spacecraft charging and increased drag. Galactic Cosmic Rays are particles that arrive within the vicinity of the Earth from outside the solar system. Interaction of spacecraft with galactic particles can cause an assortment of satellite anomalies, including bulk charging and single-event phenomena. Charged particles (electron, protons, and heavy nuclei) from the Sun and the solar wind become trapped in the Earth's magnetosphere due to the planet's magnetic field, known as radiation. Large enough doses of radiation can cause electrical and mechanical components in spacecraft to degrade, known as radiation damage. Semiconductors, semiconducting devices, and dielectrics are most effected by radiation damage.

Space weather has created problems for technological systems on Earth as well as on satellites in space, even before space weather was known to exist. Unfortunately for satellite companies, while technological systems on Earth have the advantage of the atmosphere that filters out most harmful particles that arrive within the Earth's vicinity from space, satellites are directly exposed to the space environment with no protection other than that which they are given when they are designed, which is quickly becoming less and less. In the mid 1980's, a satellite revolution took place that embraced the new paradigm of lower costing, higher risk satellites, known as smallsats [35]. The advantage of the smallsat is its low cost, enabling companies that would otherwise be unable to afford a satellite the opportunity to enter into the spacecraft market. The disadvantages of the smallsat are the restrictions on its payload size, its shorter lifetime, and the lack of redundancy which makes the smallsat more susceptible to single-point failures.

Up to 1,000 new satellites, valued at $30 billion, will be launched into orbit between 1997 and 2007, most of which will be launched into LEO because of the available space there [32]. In 1998, $800 million to $1 billion in insurance premiums was available to satellite companies. Between 1994 and 1999, it is estimated that over $500 million in insurance claims were disbursed due to on-orbit spacecraft failures [29]. Many satellite companies will not admit that their satellite failed due to space weather anomalies in order to collect on the insurance

money, even though there might be strong evidence pointing to the space environment as the cause of the failure. Satellite failures can also destroy a company, ruining its reputation, cutting off its funding, and removing the company's competitive edge [37]. Some spacecraft failures that have been proven to have been caused by anomalies induced by space weather or highly suggest space weather as the cause include Skylab, Solar Maximum Mission, QuickBird 1, EarlyBird1, Solidaridad 1, Galaxy IV, Anik E1 and E2, Telstar 401, Intelsat 511, Equator-S, and GOES-8 and –10. Some steps that can be taken to avoid weather-induced problems include minimizing the potential for spacecraft anomalies by incorporating precautions into the design before launch, better testing of satellite components during the design phase, and defensive orbital maintenance when it is known that a solar particle event is coming. By implementing design precautions and being aware of the condition of the space environment that the satellite occupies, a satellite company can protect its investment before debilitating problems occur.

While the time when increased solar activity will occur can be predicted using the F10.7 index, the solar activity from day to day is unpredictable. Many satellite companies will not admit that the failure of one of their satellites was due to space weather in order to collect the insurance money on it, and to protect their reputations as the makers of a quality product. They will often either publicly state the cause of the satellite failure as having unknown origins or will state that the satellite failed due to some design flaw, rather than admit that their satellite was lost because it was not adequately protected from the space environment. The inability of satellite companies to predict the daily solar weather, plus less adequate protection against the space environment and the unwillingness of many satellite companies to admit to space weather failures, points to a future with an increasing number of satellites failing due to "mysterious" causes that can be traced back to the space environment.

money, even though there might be strong evidence pointing to the space environment as the cause of the failure. Satellite failures can also destroy a company, ruining its reputation, cutting off its funding, and removing the company's competitive edge [37]. Some spacecraft failures that have been proven to have been caused by anomalies induced by space weather or highly suggest space weather as the cause include Skylab, Solar Maximum Mission, QuickBird 1, EarlyBird1, Solidaridad 1, Galaxy IV, Anik E1 and E2, Telstar 401, Intelsat 511, Equator-S, and GOES-8 and –10. Some steps that can be taken to avoid weather-induced problems include minimizing the potential for spacecraft anomalies by incorporating precautions into the design before launch, better testing of satellite components during the design phase, and defensive orbital maintenance when it is known that a solar particle event is coming. Developing a system that would be able to salvage failed satellites from orbit would also be beneficial to satellite companies. By implementing design precautions and being aware of the condition of the space environment that the satellite occupies, a satellite company can protect its investment before debilitating problems occur.

It is possible that no matter how well a spacecraft is protected against space weather, there will still be failures and outages that have origins in the space environment. The solar cycle is still not completely understood by scientists, though its effects are felt every day in the form of radio blackouts and temporary satellite outages. While the time when increased solar activity and its repercussions will occur is known on an average yearly basis according to the F10.7 index, the solar activity from day to day is unpredictable. The inability of satellite companies to predict the solar weather on any given day coupled with less adequate protection provided to the spacecraft against the space environment point to a future with an increasing number of satellites failing due to "mysterious" causes, that can be traced back to the space environment.

Introduction

Space weather is the phenomena that occurs when magnetic and particle disturbances occur in the area between the Earth and the Sun due to solar activity, such as coronal mass ejections and solar flares. Since the Space Age began in 1957, the space environment has become increasingly important because of the effects that it has on satellites and their functions in space. When increased solar activity occurs, the outward flux of solar particles and magnetic fields from the sun (called the solar wind) is increased. The velocity of particles in the solar wind also increases. Due to the increased solar activity, spacecraft operations can be disrupted by contact with energetic particles. Satellites experience greater atmospheric drag produced by a denser space environment. These disruptions have caused millions of dollars of damage each year. In addition, communication systems, terrestrial power grids, and scientific research suffer significant losses when a satellite anomaly due to the space environment occurs. Given the importance and cost of satellite missions in space, it is of increasing necessity that space weather and its effects on satellites be fully understood.

The objectives of this report are to research and understand the effects of space weather on satellites, to examine the importance of satellites on society and how their damage by space weather affects society, and to explore specific cases of satellite failures due to space weather and the associated losses resulting from the failures. Some solutions to the problems that affect satellites due to space weather will also be proposed and explored.

This project may serve as an informational source for companies, organizations, or persons seeking a review of space weather and its impacts on the satellite industry. The report is separated into three sections. The General Satellite Information Section (Section 1) will provide the reader with general information about typical satellites, their functions and their orbits. The Space Weather Phenomena Section (Section 2) will give information about the space environment and satellite anomalies. Finally, the Case Studies Section (Section 3) of the report examines the costs associated with spacecraft and subsequently the cost of their failures. Examples of satellites that have failed owing to space weather are listed, as well as possible solutions to the problems plaguing satellites due to the space environment.

Section 1. General Satellite Information

1.1. Introduction

When considering the different effects space weather has on satellites in orbit around the Earth, it is important to recognize the spacecraft's mission and, consequently, where it is in orbit in order to accomplish its mission. There are several general types of satellites used today, and specific orbits that each one needs to travel in.

1.2. Typical Orbits

Possible orbits are separated into four categories: low earth orbit (LEO), medium earth orbit (MEO), polar orbit, and geosynchronous or geostationary orbit (GEO) [1]. A satellite is in LEO if it orbits 100 – 1,000 km above the Earth's surface. Because LEO orbit is close to the surface of the Earth, the atmosphere is denser than any other orbit and satellites will be affected mainly by drag in LEO. The lifetime of a spacecraft is often based solely on the amount of thruster fuel available to keep the satellite in orbit and perform other space maneuvers. This limiting factor keeps the lifetimes of spacecraft in LEO short due to the constant use of thruster fuel used to battle against atmospheric drag. Medium earth orbit exists at 1,000 – 36,000 km above the surface of the Earth. MEO orbit is not widely used by spacecraft because it does not provide the advantages gained from the other orbits such as a stationary position over the Earth (as in GEO) or a close-up view of the Earth's surface (as in LEO). Polar orbit is in the LEO region that exists approximately 850 km (530 miles) above Earth. The polar orbit is important for satellites that need to pass over the entire Earth's surface in 24 hours, which is often the case for weather and remote sensing satellites [2].

GEO is the highest orbit that a satellite can occupy while still being considered an Earth-orbiting object, and exists at a specific altitude that allows the satellite in GEO to match the earth's rotation and appear to be stationary over a certain spot on the globe [3]. To determine the height necessary to accomplish geostationary orbit, Newton's Law of Gravitation can simply be used:

$$T^2 = \frac{4\pi^2}{G \cdot M} r^3$$

where T is the period of the Earth (24 hours), G is the gravitational constant (6.67 x 10^{-11} $N \cdot m^2/kg^2$), M is the mass of the Earth (6 x 10^{24} kg), and r is the radius of the orbiting object from the center of the Earth [4]. Solving for r and subtracting the radius of the Earth (6380 km), in order for the orbiting satellite to match the Earth's period it must be about 36,000 km (22,338 miles) above the Earth's surface. Every geosynchronous satellite must be 2 degrees apart (about 1,500 km) to prevent their signals from interfering and to prevent possible collisions [5]. Because the satellites must be 2 degrees apart, only 180 satellites can occupy GEO at one time (currently there are actually over 220 satellites in GEO because of their frequency differences). Spacecraft positions in GEO are extremely valuable because of the limitation on their number, and satellite positions over North America are completely sold out.

2.3. Common Spacecraft Types

There are five different types of satellites that orbit the Earth according to their mission objectives: weather satellites, communication satellites, navigation satellites, remote sensing satellites, and scientific research satellites. Figure 1 shows examples of current spacecraft in orbit from each major satellite type.

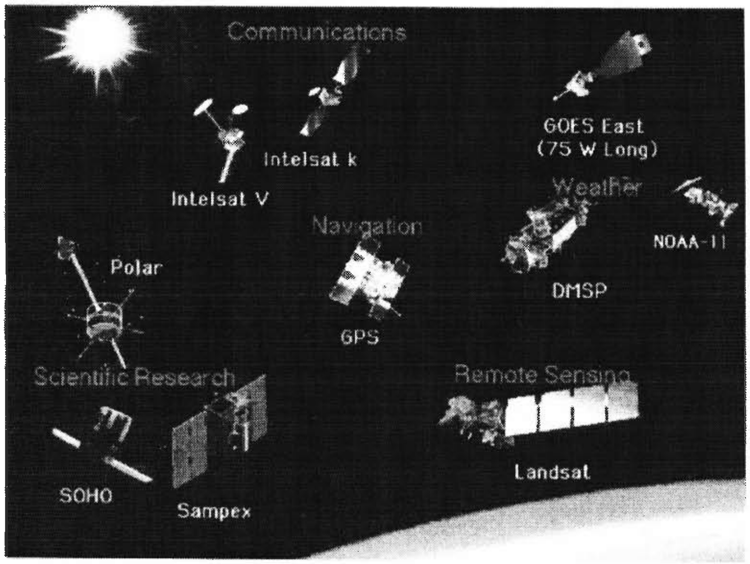


Figure 1. An illustration of different satellite types.

Weather satellites are spacecraft with payloads designed to measure the energy waves that radiate from the Earth's atmosphere [6]. These energy waves can then be interpreted into atmospheric conditions, such as cloudiness, temperature, and moisture levels. Weather satellites can be utilized in a great variety of orbits, such as GEO and polar orbit. At GEO, weather satellites are able to monitor entire hemispheres, enabling them to track large storms and hurricanes. Polar-orbiting weather spacecraft can obtain atmospheric data from the entire surface of the Earth every 24 hours, such as ozone layer integrity, cloud movement, and atmospheric temperature. Satellites in polar orbit can only focus on a certain spot in the atmosphere for a short period of time, but the images are clearer because of the close proximity of the spacecraft. Environmental satellites are a branch of weather satellites that differ in that they provide images of the Earth's surface in LEO that aid in managing natural disasters and ecological catastrophes, such as forest fires and insect infestations [7]. Satellites allow people to observe the weather over the 70% of the Earth's surface that is covered by water, where it is very difficult for observations to be made from the surface. Severe storms can now be spotted and tracked as they move in from the ocean, whereas before satellite technology there was little to no warning of an impending storm [8].

Communication satellites are used to relay information and facilitate communication on a large scale between people and organizations, and are used in a wide variety of telecommunication applications such as wireless telephones, pagers, television, and radio. A communication satellite must always have a direct “line of sight” to its counterpart antenna on Earth in order to relay and receive information for the surface [5]. This necessity requires almost all communication satellites to be in geostationary orbit in order to maintain constant contact with the ground. Today, there are about 150 communication satellites in GEO, far outnumbering any other satellite type in the same orbit [9]. LEO and MEO orbits are being investigated for possible communication satellite use because the GEO orbit is completely filled. Also, lower orbits would require less powerful transmissions and smaller antennas [5]. Several satellite companies are already planning to launch dozens of satellites into LEO within the next few years, including systems of satellites that add up to billions of dollars in worth [10].

Another form of spacecraft known as navigation satellites is used specifically to aid navigation in the sea and air. Navigation satellites are located in LEO and orbit the globe every twelve hours in order to cover as much of the Earth’s surface as possible [11]. Navigation satellites are set up as constellations (series of satellites produced by the same company with the same mission), such as the Global Positioning System (GPS), distributed across the sky in order to provide the positions of objects anywhere on the surface of the Earth. At least four satellites are needed to gain an accurate 3-D position from the Earth’s surface [12].

Remote sensing satellites are satellites that occupy low Earth orbit in order to "take pictures" of the Earth's surface using varying techniques. The remote sensing market is very large because remote sensing satellites can provide a 1 meter resolution of anywhere on the Earth's surface [13]. Some remote sensing techniques include aerial photography, color infrared film (CIF), thermal infrared multispectral scanner (TIMS), and synthetic aperture radar (SAR). Each technique involves detecting energy waves from a particular area of earth and analyzing the data using different methods in order to determine such characteristics of the surface as hidden physical features, the height of the ground, and artificial features like camouflage [14]. Satellites that can be considered remote sensing satellites are environmental satellites, surveillance satellites, and scientific satellites (for archeology, among other things).

Finally, scientific satellites are spacecraft specifically designed to aid in research and exploration in space. Scientific satellites can be in any orbit that is needed to complete its mission, including venturing outside of GEO and into what is called interplanetary orbit. Some typical scientific missions conducted by satellites include observing and collecting data about the sun, making close observations of Earth phenomena, and taking photographs of the cosmos. Most scientific satellites are owned and operated by government-funded organizations, and are not for profit; hence, they are usually not insured for large sums of money [15].

1.4. Summary

The orbit a satellite assumes is the most distinguishing factor in what kinds of satellite anomalies due to space weather it is susceptible to. In LEO, the main concern for a satellite's well being are the affects of drag, while in MEO surface charging is of primary concern. In GEO bulk charging and single event phenomena caused by high-energy particles create the most damaging problems for a spacecraft. Knowing the mission of a specific satellite determines what orbit it will assume in space, and, consequently, what considerations should be made to ensure that the spacecraft is adequately prepared for the rigors of the space environment.

Section 2. Space Weather Phenomena

2.1. Introduction

Like the Earth's own atmosphere, space is also subject to changes in its environment due to natural phenomena, changes that are know collectively as space weather. The space environment that a satellite must endure includes geomagnetic storms, impacts from high-energy galactic cosmic rays, and exposure to varying amounts of radiation, all connected to the Sun's solar cycle. When inserting a satellite into space, it is essential to understand the effects that space weather has on the satellite to ensure that its mission is successfully completed. This section of the report will detail specific space weather events as well as the effects that these events have on unmanned artificial Earth-orbiting satellites.

2.2. The Solar Cycle

Solar activity, such as coronal mass ejections and flares, vary in frequency according to an 11-year cycle, called the solar cycle. These cycles are defined by regular variations in solar activity, demarked by the solar maxima and solar minima. The solar maximum and solar minimum refer to the number of sunspots on the surface of the sun at any given time; a greater number of sunspots denotes a more dynamic magnetic field, i.e. more solar activity.

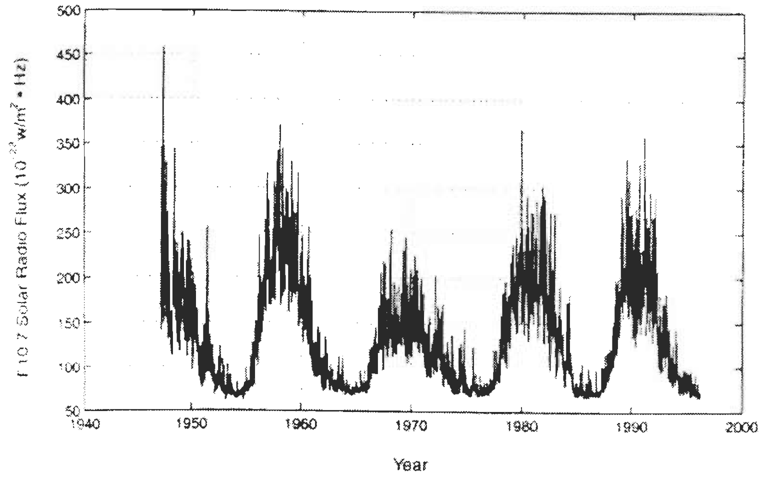


Figure 2. The F10.7 index.

Figure 2 shows the mean daily radio flux of the sun at 10.7 cm wavelength over a period of 50 years, where the peaks are the solar maxima and the valleys are the solar minima. The cycle may vary by about twenty five percent from the mean on a day-to-day basis, making the prediction of solar weather uncertain at a specific point in time. However, the average is well known, and predicting solar weather over an extended period of time is possible [16].

2.2.1. Flares and Coronal Mass Ejections

As the sun rotates around its poles, the magnetic field lines within the corona become warped, twisting and tangling with each other, and in the process storing vast amounts of energy [17]. When the field lines suddenly realign themselves, they release their stored energy in the form of solar flares and coronal mass ejections.

Solar flares are bursts of radiation released from the magnetic field in the sun's corona. As the flares travel toward earth, they bring with them accelerated protons from the sun with energies of 10MeV to 1GeV, enough to interfere with spacecraft in high orbit or to seriously injure, or even kill, astronauts outside the shelter of their spacecraft. On Earth, the flares do not pose a serious threat due to the ionosphere, which absorbs most of the energy from the protons and protects people and electronic systems from harm [18].

Coronal mass ejections, or CMEs, occur when energy released from the sun blows billions of tons of ionized gases, or plasma, from the corona into space. CMEs occur about once a month during solar minimum and twice or more a day during solar maximum, ejecting on average 10^{12} kg of coronal material into space at about 400m/s [19]. The CME develops a shock wave in front of it as it travels through space, where it comes in contact with the solar wind. The solar wind is the constant outward flow of solar particles (ions, protons, and electrons) and magnetic fields from the sun. When the CME comes in contact with the solar wind, it accelerates the particles up to energies greater than 1 million volts. These extremely charged particles can damage the skin of spacecraft as well as cause a variety of spacecraft anomalies.

Besides causing damage to a spacecraft's body, CMEs can also compress the Earth's magnetosphere, which is the uppermost part of the Earth's atmosphere, by several earth radii and increase the density through which any spacecraft traveling in the magnetosphere must endure (Figure 3) [17].

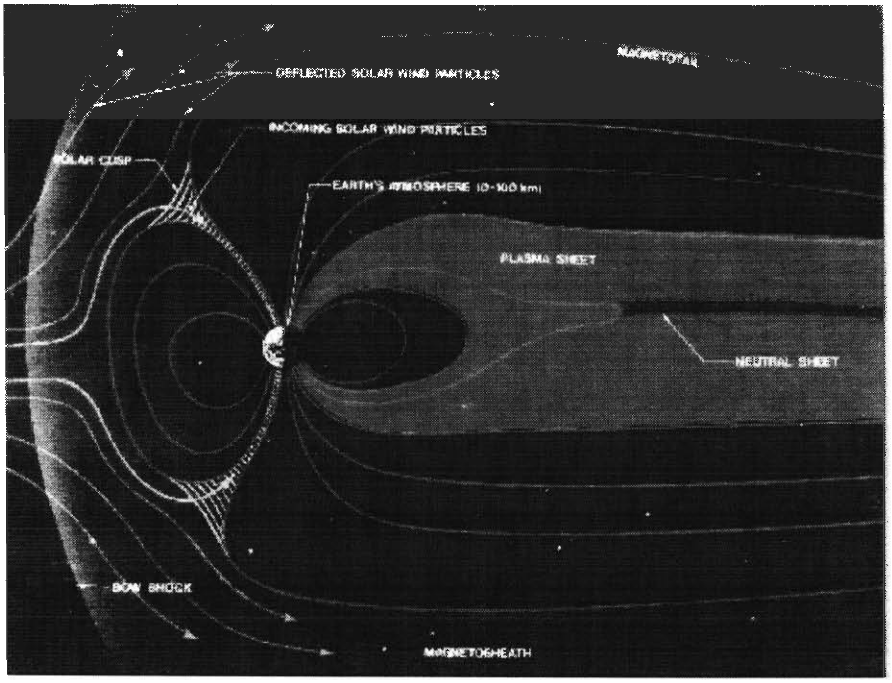


Figure 3. The Earth's magnetosphere.

The increased drag on the spacecraft can cause orbit decay and occasionally reentry before the craft's predicted reentry date.

2.2.2. Geomagnetic Storms

Another phenomenon caused by the solar cycle is known as a geomagnetic storm. Geomagnetic storms occur when the solar wind's kinetic energy is converted into magnetic energy that is stored in the Earth's magnetotail and is periodically dissipated [18]. The magnetotail is the distortion of earth's magnetic field away from earth, parallel to the solar wind.

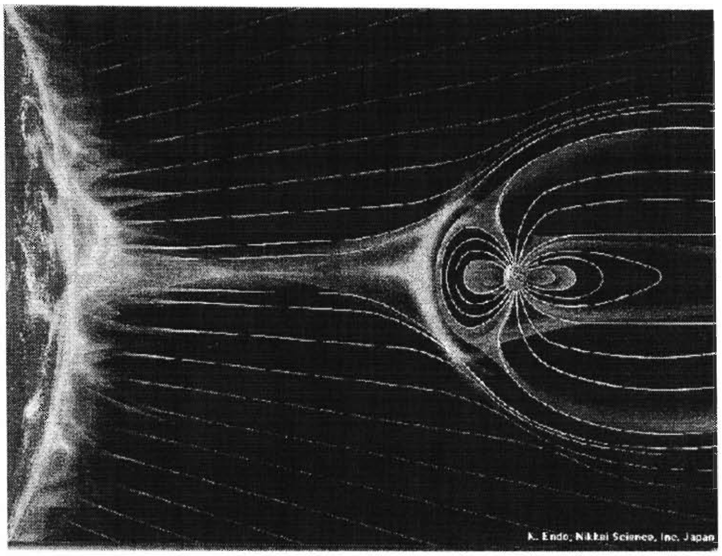


Figure 4. Earth in relation to the solar wind and its magnetotail.

Figure 4 is an illustration of how the sun's magnetic field and the solar wind the sun produces interacts with and compresses the earth's magnetic field, creating the magnetotail. Geomagnetic storms cause a disturbance in earth's magnetic field distinct from regular variations, and range in severity on a scale created by the National Oceanic and Atmospheric Administration (NOAA) from minor (G1) to extreme (G5) (The NOAA space weather scale for geomagnetic storms can be found in Appendix B.). These storms produce energized plasma (5 to 50 keV) that can extend into geosynchronous (high) orbit and cause such problems as spacecraft charging and increased drag.

2.2.3. Galactic Cosmic Rays

Galactic Cosmic Rays are particles that arrive within the vicinity of the Earth from outside the solar system. They are comprised of protons (85%), alpha particles (14%), and heavy nuclei, at energies in the 100MeV range. The flux of galactic particles increases during periods of low solar activity due to less interference from the solar particles that are prevalent during high periods of solar activity [20]. Interaction of spacecraft with galactic particles can cause an assortment of satellite anomalies, including bulk charging and single-event phenomena.

2.2.4. Radiation

Charged particles (electron, protons, and heavy nuclei) from the Sun and the solar wind become trapped in the Earth's magnetosphere due to the planet's magnetic field. The concentration of these charged particles form two toroidally-shaped rings inside the magnetosphere, known as the Van Allen radiation belts. The two Van Allen radiation belts are designated the inner and outer radiation belts and are separated by what is known as a slot region, though the two often overlap each other [21]. The inner radiation belt begins about 400 km from the Earth and extends to 12,000 km, and is composed of mostly energetic solar particles and galactic cosmic rays. The outer radiation belt begins about 12,000 km from Earth and extends to 60,000 km, and is composed of mainly particles from the solar wind and the ionosphere. The ionosphere is a region of the Earth's upper atmosphere that contains free electrons and ions.

Inside the radiation belts, speeding particles can be accelerated to velocities close to the speed of light. When the particles, mostly electrons, achieve a speed comparable to the speed of light, they are known as "killer electrons" because of the damage they are capable of doing to anything they come in contact with, including spacecraft and humans [22]. Energetic particles, including “killer electrons”, transfer momentum when they interact with materials and produce ionization, which creates bulk damage when they disrupt the atomic lattice of the material. Constant exposure to energetic particles causes ionization to build up inside materials, known as radiation. Large enough doses of radiation can cause electrical and mechanical components in spacecraft to degrade, known as radiation damage. Semiconductors, semiconducting devices, and dielectrics are most effected by radiation damage.

2.3. Spacecraft Anomalies

2.3.1. Spacecraft Surface Charging

Electrical potential of a spacecraft or its components is measured relative to the surrounding plasma, where the net current flow should be zero if the spacecraft is to maintain an ideal state of electrostatic equilibrium with its surroundings. Plasmas are ionized gases in the magnetosphere with energies ≥ 100 keV that do not produce significant radiation effects [23]. When a geomagnetic storm occurs, the plasma surrounding the spacecraft (mostly electrons) increases in energy and can charge the surface of the spacecraft to high negative voltages. A certain amount of surface charging during a spacecraft mission is expected and anticipated. However, surface charging that leads to arcing occurs when the electron current from the plasma to the spacecraft is dominated by electrons with relatively low energies of 10 to 20 keV. At these energy levels, the electrical potential exceeds the breakdown field along the surface of the spacecraft or its components and the spacecraft material is unable to effectively dissipate the excess energy. The effects that can lead to surface charging begin to become prevalent at the

Kp=4 to Kp=5 level on the NOAA space weather scale for geomagnetic storms, and become probable at Kp≥6. When surface arcing occurs, the effect is much like a lightening bolt striking the surface of the spacecraft, which causes damage to the surface material and sensitive electronic devises.

2.3.2. Deep Dielectric or Bulk Charging

Dielectric materials are used in many components of a spacecraft, including coaxial cables, circuit boards, and insulating materials. When a high-energy particle, such as a galactic cosmic ray or an accelerated solar particle, comes in contact with a spacecraft, the particle will occasionally penetrate the surface layers of the spacecraft and deposit its charge inside insulating or electrically isolated materials [17]. Similar to surface charging, bulk charging occurs when the electrical potential of the spacecraft exceeds the ability of the material to bleed off the excess voltage, causing arcing to occur. However, in the case of bulk charging, the arcing occurs inside of the spacecraft, burning and damaging the dielectric material and semiconducting devises. Whether or not a discharge resulting from dielectric charging occurs depends on the material, the energy of the particles, and how many high-energy particles strike the material over a period of time [24]. Destructive discharging usually occurs when the influx of electrons at energies equal to or greater than 2 MeV is 1) greater than 3×10^8 per day for three consecutive days, or 2) the influx is greater than 10^9 for a single day [25]. Dielectric charging is one of the most common and destructive ailments of satellites due to space weather, and has been responsible for several well-known satellite failures.

2.3.3. Single Event Phenomena

Single event phenomena (SEP) occur when a single highly charged particle, such as a galactic cosmic ray or a high velocity ion, penetrates directly through a circuit board junction and deposits its charge there. When a highly charged particle moves through a semiconducting devise, it produces electrons and holes that carry current through the devise. For every 3.6 eV of energy that is deposited into the circuit board junction, one electron-hole pair is formed [26]. Semiconducting devises rely heavily upon a precise balance of the available electrons and holes, which controls the amount of current that is able to flow through the devise. By changing the number of available electrons and holes in the devise, the information stored in the computer can be altered and produce phantom commands, or the circuits may be burned out. There are three main kinds of single event phenomena [20]. These include:

- Single Event Upset (SEU): The particle causes the logic state of the devise to change, but can be reset and corrected. This type of event is minor because it can be easily corrected.
- Single Event Latchup (SEL): The particle causes the logic state of the devise to change, but it cannot be reset. This type of event is of moderate concern; the devise must be powered down and turned on again, which can be extremely inconvenient but at least the event is not irreversible.
- Single Event Burnout (SEB): The particle causes the power supply to the devise to short out and fail. This type of event is very bad, given that the devise will either be damaged or destroyed.

2.3.4. Trapped Radiation Effects

The Van Allen Radiation belts consist of galactic cosmic rays, energetic solar particles, and other charged particles such as ions that happen to be floating around in space and become trapped along the Earth's magnetic field lines. When a spacecraft travels through the radiation belts, it is subject to the effects caused by impact with that particle, which can have either short term or long term effects depending on the type of particle and its impact area on the spacecraft. The effects of trapped radiation on a satellite are categorized into three general categories differing by the effect the radiation has on the spacecraft and the duration of the effect [27].

- Total Ionizing Dose (TID): TID is the long-term effect of constant exposure to energetic particles that causes energy accumulation inside the material, which in turn causes ionization. TID can cause such anomalies as voltage discharging and variations in devise parameters.
- Displacement Damage Dose (DDD): DDD is a physical phenomenon that causes cumulative degradation of a spacecraft resulting from the displacement of a material's atomic lattice when it is impacted by a heavy energetic particle, such as a solar or trapped proton or heavy ions. Long-term DDD effects include degradation of a material's performance or alteration of devises' functions.
- Single Event Effects (SEEs): Single event effects are the cumulative effects of single event phenomena. As described earlier, single event phenomena are short-term events that can have either short-term or long-term effects on a spacecraft, depending on the severity of the event.

When a solar event occurs, such as a CME or a powerful solar flare, geomagnetic storms are triggered and more particles are ejected into the radiation belts. A spacecraft traveling through the radiation belts at this time is subject to severe degradation of its surface material, particularly the solar panels. During geomagnetic storms, high velocity ions hit the solar panels and knock electrons out of the crystal array. This degrades the semiconducting material and decreases the lifetime over which the solar cells will be able to produce energy for the spacecraft. For example, a severe geomagnetic storm in March 1990 degraded many of the solar panels of spacecraft in orbit at that time and reduced the operational lifetime of many satellites by down to three years [28].

2.3.5. Spacecraft Drag

Even though a spacecraft is considered to be functioning in outer space, it is often actually still in the vicinity of the Earth's atmosphere and is subject to drag forces. Drag in space usually effects satellites less than 1000 km above the Earth. The density of the space atmosphere a satellite is in can be determined predominately by two space environmental parameters - the F10.7 index and the geomagnetic Ap index (the NOAA space weather scale for geomagnetic storms). A $Kp \geq 6$ (a moderate or higher geomagnetic storm) and a 10.7 cm flux > 250 solar flux units (1 solar flux unit = 10^{-22} $W/m^2 \cdot s$ – the flux of solar particles from the sun) indicates that a measurable increase in drag on satellites will occur at that time [29]. During geomagnetic storms, the GEO atmosphere expands dramatically, compressing the LEO atmosphere and increasing its density by 20% for a mild storm to an increase of easily over 100% during a severe storm. When this occurs, thousands of orbiting objects change trajectory and must be retracked and reidentified. NORAD, which is in charge of tracking objects in orbit around Earth, lost the position of 1400 objects after a severe geomagnetic storm in March 1989 changed their trajectories to lower orbits. It took 2 weeks to relocate all of the objects and their new orbits [29].

Because the F.10.7 index., and space weather in general, varies significantly on a day to day basis, it is impossible to accurately predict the time and location of a satellite reentering the

Earth's atmosphere. The difficulty predicting the atmospheric density inside a satellite's orbit prevents scientists from being able to predict a spacecraft's reentry time with more than 10% accuracy within a 2.4 to 24 hour period, an uncertainty of at least two hours. In that two hour time span, the spacecraft will have circled the globe, making it next to impossible to predict the reentry location of a spacecraft [30]. Luckily for anything in the path of a reentering satellite, most of the spacecraft vaporizes during reentry.

2.3.6. Solar Radio Frequency Interference and Ionospheric Effects

When a satellite transmits a signal to a receiving antenna on Earth in the form of a radio wave, the signal does not navigate a hard vacuum but will encounter various obstacles along its path, such as interfering background noise and the Earth's upper atmosphere. Background noise is any other radio signal that unintentionally interferes with the radio wave being emitted by the satellite [29]. Any object with a temperature above absolute zero is a source of radio energy, and hence a possible source of background noise interference. The sun, at temperatures ranging from 6000 Kelvin to 2 million Kelvin, acts as a huge source of radio noise. When a satellite is within a degree or two of the sun (in relation to the receiving antenna), the signal from the satellite can be disrupted or even completely lost should the sun eject a large radio burst at that time. In normal communications, a signal received by an antenna must be at least 10 decibels (dB) (a factor of ten in power) greater than the background noise in order to be a usable transmission. Even at times of low solar activity, the radio noise from the sun is typically about 20 dB (a factor of 100 in power) above a typical satellite TV transponder. During the solar maximum, when solar activity is the highest, large radio bursts occur more frequently and with greater intensity, increasing the chance that a radio signal emitted by a satellite will be disrupted [31].

A radio signal must also navigate through the ionosphere on its way to the receiving antenna on Earth, which can cause problems with the signal. The ionosphere is composed of an ionized gas (a plasma) that varies in density throughout the upper atmosphere. When a satellite transmits a radio signal through the ionosphere, the signal gets bent as it is refracted through the atmosphere. This refraction can cause radars on Earth to believe an orbiting object in space is in a position that it actually is not, and vice versa for a satellite tracking an object on Earth. During a geomagnetic event, the total electron content (TEC) of the ionosphere increases. The ionosphere becomes densely populated with additional ions and significant bending of the satellite transmission occurs, causing inaccuracy problems in navigation spacecraft such as GPS satellites [31].

2.4. Summary

Space weather was not considered a significant source of satellite anomalies until around Thanksgiving 1982 when the GOES-2 and GOES-4 weather satellites failed for reasons later determined to be related to space weather [17]. Today, it is obvious that the space environment has a significant effect on satellites in space. Where a satellite is in orbit around the Earth and at what time the in the solar cycle the satellite orbits must be considered in the design of a spacecraft in order to decrease the chances of a space weather-induced anomaly resulting in a satellite failure. As will be illustrated in the following chapter, a satellite outage due to the space environment for even a short amount of time can cost millions of dollars and inconvenience millions of people.

Section 3: Case Studies

3.1. Introduction and Costs

Space weather has wreaked havoc on technological systems on Earth as well as on satellites in space, even before space weather was known to exist. Over a century ago when thousands of telegraph wires were in use, electrical current produced by strong geomagnetic storms would sometimes become large enough to power the wires without batteries [32]. In August 1972, a 230 kV transformer in the British Colombia Hydroelectric Authority was destroyed by a current spike caused by a magnetic storm. More recently, on March 13, 1989, a severe geomagnetic storm caused a major power failure of the Hydro-Quebec Power Company that left six million people in Canada without electricity for nine hours. It has been estimated that if a geomagnetic storm only slightly stronger than the storm that hit Quebec in 1989 were to hit the US, the resulting damage would be in the range of $3 to $6 billion. The same day as the Hydro-Quebec Power Company failure, a transformer valued at $36 million melted down at a New Jersey Public Service Company plant [33]. A conservative estimate by the Minnesota Power and Electric Company of the cost of the destruction of transformers due to geomagnetic storms is $100 million [34]. Obviously, the effects of space weather can be felt here on Earth, and they can be major and costly.

Unfortunately for satellite companies, while technological systems on Earth have the advantage of the atmosphere that filters out most harmful particles that arrive within the Earth's vicinity from space, satellites are directly exposed to the space environment with no protection other than that which they are given when they are designed, which is quickly becoming less and less. In the mid 1980's, a satellite revolution took place that embraced the new paradigm of lower costing, higher risk satellites, known as smallsats [35]. Smallsats are satellites weighing 200 kg or less that cost only a few million dollars to build and launch, as opposed to the several hundred million dollar price tag of the average satellite in the past. The smallsat revolution marked a change in the design objectives of the government funded and commercial organizations away from science and advanced technology desires and more toward operating within budget constraints. The advantage of the smallsat is its low cost, enabling companies that would otherwise be unable to afford a satellite the opportunity to enter into the spacecraft market. As the cost of satellites is reduced, the demand for them increases. For example, if the cost of a remote sensing satellite was decreased from $14 million to $4 million, it is estimated that the demand for them would increase by six times [13]. The disadvantages of the smallsat are the restrictions on its payload size, its shorter lifetime, and the lack of redundancy which makes the smallsat more susceptible to single-point failures. Launching one pound of material into space costs from $5,000 to $10,000 [32]. The high cost of launches plus the new satellite philosophy of "smaller, faster, cheaper" prevents newer satellites with valuable high-tech payloads from being equipped with radiation shielding and hardened circuitry, making them more susceptible to space weather anomalies.

Up to 1,000 new satellites, valued at $30 billion, will be launched into orbit between 1997 and 2007, most of which will be launched into LEO because of the available space there [32]. Though smallsats launched into LEO are relatively cheap, communications satellites launched into GEO cost on average $200 to $300 million, a large and expensive investment for any satellite company. In 1992, the commercial remote sensing satellite industry was valued at $190 million, and the aerial remote sensing satellite industry at $2 billion [13]. By 2005, $80 billion a year in voice and data transmissions will be routed through satellites [32]. Because of the high cost of putting any satellite into space and maintaining its orbit, as well as the profit the satellite generates while it functions, spacecraft are typically insured against on-orbit failures depending on the cost and function of the satellite. In 1998, the total number of insured satellites in orbit numbered 186, with a total insured value of $16 billion [36]. The insured value was split between 104 GEO satellites insured for $14 billion and 82 LEO satellites insured for $2 billion. Currently, insurance for satellites is abundant and cheap; the current premium for a $250 million comprehensive coverage of a satellite and its launch is about $25 million. In 1998, $800 million to $1 billion in insurance premiums was available to satellite companies, and large companies like Telesat Canada, Intelsat, and Motorola/Iridium were all getting a piece of the action. The peak insurance value any satellite can have is approximately $420 million. However, recently instead of insuring satellites in LEO, satellite companies are compensating in the shear number of satellites they insert into space to spread out the risk of a failure and its consequences.

As long as the satellite industry is free of any catastrophic events, insurance rates are predicted to continue to fall. One satellite failure is not considered a catastrophic event. Yet when several satellites fail at the same time, as they did in May 1998 after a severe geomagnetic storm, policyholders begin to become concerned that insurance policies might rise in response to the failures. Between 1996 and 1998, satellite insurance companies paid $1.8 billion in satellite failure claims, of which half were due to failures in orbit [32]. Between 1994 and 1999, it is estimated that over $500 million in insurance claims were disbursed due to on-orbit spacecraft failures [29]. The amount of money that insurance companies will pay to satellite companies in the future will steadily rise as the number of satellites in orbit, as well as their failures, increases and the amount of insurance available to a single satellite goes up.

In order for a company to cash in its insurance policy on a satellite that failed in orbit, the failure must be proved to be preventable and controllable, and not a random occurrence or an "Act of God" [34]. Satellites cannot be insured for damage caused by "Acts of God", which space weather anomalies fall into, but can be insured for unforeseen satellite design flaws. For this reason, satellite companies are reluctant to classify a failure as space environment-induced. Also, determining that a satellite failure was indeed caused by space weather is difficult because most satellites that fail in orbit are unrecoverable, and therefore cannot be examined to determine the exact cause of the failure. Only apparent correlations in space and time can be used as evidence that a spacecraft failure was caused by the space environment, and the law requires definite proof of the connection in order to consider a failure an act of God.

Many satellite companies will not admit that their satellite failed due to space weather anomalies in order to collect on the insurance money, even though there might be strong evidence pointing to the space environment as the cause of the failure. Satellite failures can also destroy a company, ruining its reputation, cutting off its funding, and removing the company's competitive edge [37]. Since research and government satellites are non-profit and hence not usually insured, scientists are much more forthcoming with information regarding the radiation effects on their satellites.

The following cases are specific examples of satellite failures that have been proven to be caused by anomalies induced by space weather, or highly suggest space weather as the culprit. The associated cost of each satellite failure is stated as well as the probable cause.

3.2. Case Studies

Skylab – Atmospheric Drag

Skylab was launched into orbit on May 14, 1973 as part of the Apollo program to become the first US space station. Skylab's primary mission was to conduct solar experiments, as well as to observe the long-term effects of space on people and equipment [38]. After Skylab had fulfilled its primary mission, the space station was expected to remain in orbit to assist other space shuttles in the future. Unfortunately, Skylab's orbit had been steadily deteriorating since it had entered space in 1973 and was in need of orbital maintenance to keep it from reentering the Earth's atmosphere. A rescue mission was initiated to attach a booster to the space station in order to thrust it into a stable orbit. However, high sunspot activity between 1978 and 1979 (the solar maximum of solar cycle 21) caused the space station to reenter the Earth's atmosphere on July 11, 1979 over Australia and the Indian Ocean, two years before the rescue mission was scheduled to take place [39].

Solar Maximum Mission – Atmospheric Drag

The Solar Maximum Mission (SMM) satellite was a $240 million research satellite that was launched on February 14, 1980, with its primary mission being to examine the sun in order to gain new insights into solar flares [40]. Nine months after the SMM had been launched, the satellite's Attitude Control System failed when a fuse blew in its steering system, crippling the spacecraft so that it could not point towards the sun. A rescue mission costing $54 million was deployed in April 1984 which consisted of the Challenger space shuttle rendezvousing with SMM and using a mechanical arm to fix the spacecraft. The rescue mission was successful, and the SMM continued to collect data until 1989. The SMM's orbit began to decay after a geomagnetic storm in March 1989, where the satellite dropped about three miles out of its previous orbit and consequently burned up while reentering the Earth's atmosphere in December 1989 [41].

QuickBird 1 – Cause Unknown

QuickBird 1 was a Russian remote sensing satellite launched by Earth Watch Inc. on November 20, 2000. On November 21, 2000, one day after the satellite was launched, the spacecraft failed to circularize its orbit and fell back to earth, where it was destroyed upon reentry [42]. A possible cause of the QuickBird 1 failure might have been that the second stage booster, fired to circularize QuickBird 1's orbit, did not fire for reasons as yet undetermined. However, on November 8, 2000, a very large solar flare erupted from the surface of the Sun, producing a solar storm that measured the fourth highest proton levels since measuring began in 1978. The possibility that solar weather played a part in the unexplained failure of the second stage booster is not unlikely. The cost of QuickBird 1 was estimated to be $60 million, while the launch was insured for $230 million [43].

EarlyBird 1 – Cause Unknown

EarlyBird 1 was an Earth-imaging satellite operated by Earth Watch Inc. that was launched from Siberia into orbit on December 24, 1997, 294 miles above the Earth [44]. The spacecraft was a civilian remote sensing satellite that was to take high-resolution pictures from space for commercial use. The satellite was going to provide the sharpest-ever pictures of the Earth to civilian consumers, such as journalists, allowing anyone to observe even politically sensitive areas on the globe, for the right price [45]. Four days after EarlyBird 1 was launched into space (December 28, 1997), communication was lost with the satellite. The problem was believed to be caused by a power system glitch that caused energy loss to the spacecraft, leaving it virtually dead in the sky. The satellite was not able to be recovered, and Earth Watch Inc. received $29 million from their insurance providers for the loss [46].

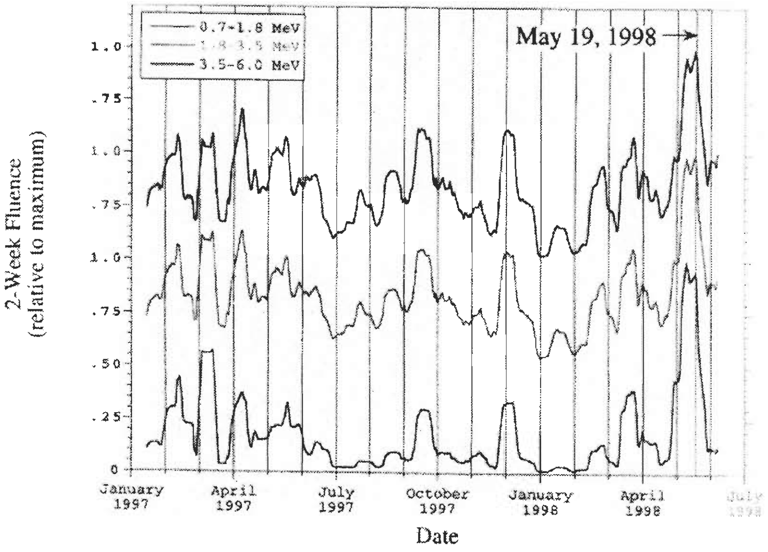
Solidaridad 1 – Bulk Charging

Solidaridad 1 was a Mexican communications satellite owned by the company Satmex that was launched in 1993. On August 29, 2000, Solidaridad 1 stopped operating when the spacecraft control processor, the satellite's main computer, shut down. In April 1999, the primary control processor shut down, leaving the second redundant processor to take over [47]. The failure in August 2000 was particularly damaging because there was no redundant system to compensate. After three days, the satellite's battery supply was exhausted and the spacecraft was considered a total loss. Satmex investigators (as well as the owners of Galaxy IV) officially believe that "tin whiskers", crystalline filaments that grow on the edges of tin-plated relays within the satellite's electronics, were the cause of the Solidaridad 1 failure [47]. However, it is believed by many scientists that the failure of Galaxy IV was not caused by tin whiskers but in fact was the result of bulk charging of the spacecraft. Satmex is the leading Mexican satellite provider, providing television broadcasts, high-speed internet, and digital broadband services to 500 million people in North America. During the Solidaridad 1 failure, Satmex was able to divert 86 percent of all utilized capacity and 95 percent of all users to other satellites by August 30. Solidaridad 1 was insured for $250 million; Satmex ended up receiving $103.1 million in insurance for the loss [48].

Galaxy IV - Bulk Charging

The Galaxy IV was a $250 million communications satellite owned by PanAmSat Corp. that relayed wireless communication throughout North America [49]. Galaxy IV was positioned optimally over the central US and directed 80% of all pager traffic, as well as distributed television broadcasts and critical Doppler radar weather information used by aviation, emergency managers, and agriculture and farming organizations [50]. The satellite was launched on June 24, 1993 and critically failed on May 19, 1998, seven years short of its expected 12-year life span [51]. The spacecraft lost its earth lock and began spinning out of control, and was deemed unrecoverable several days later after constant attempts to regain contact had failed. Though PanAmSat Corp. officially declared that the loss of Galaxy IV was due to "tin whiskers", investigators outside of the corporation agree that the cause of the failure was in fact due to deep bulk charging brought on by the space environment [52]. High solar and magnetic activity occurred in early May, including a series of large solar flares. A large CME occurred on May 2, as well as an increase of the solar wind speed to 850 km/s on May 4. From early May until the end of the month, the magnetosphere was populated by an intense flux of highly relativistic electrons. Right before and on May 19, the fluences in each electron range peaked (Figure 5).

Figure 5. Relative Fluences of Highly Relativistic Electrons



Scientists believe that there is strong evidence that the conditions of the space environment in early May 1998 caused charge to build up inside of the satellite over a period of a couple of weeks, resulting in an electrical discharge within the satellite that crippled it.

Industries affected by the satellite outage were broadcasters, television networks, financial news and quote services, retailers, auto dealers, and hospitals [53]. Within one hour of the satellite outage, many industries were able to use Internet link-ups to continue news programs and other data, but many other industries were not as fortunate. Hartford Hospital in Hartford, Connecticut had its paging service, that includes over 3,000 pagers, shut down for over 13 hours. The disruption in pager service caused by the Galaxy IV outage also cost Pagemart Wireless, Inc. $3.8 million and AirTouch Paging $2 million in only two days of lost service [54]. The Galaxy IV satellite was insured for over $160 million.

Anik E1 and E2 – Bulk Charging

Anik E1 and E2 are Canadian satellites owned by Telesat that were launched in 1991 in order to distribute telecommunications throughout North America, as well as radio distribution and voice and data communications [55]. Anik E1 experienced attitude control problems on January 20, 1994, and communications with the satellite were lost for approximately eight hours. After this time period contact with the satellite was reestablished and the spacecraft was brought back under control, and normal operations resumed. Anik E2 also experienced attitude control problems on January 21, 1994. Unfortunately, it took five months to regain control of Anik E2; on June 21, 1994, control was finally regained. The official cause of the satellite outages has been determined and admitted by Telesat to have been deep dielectric discharges within the spacecraft circuitry. Anik E1 had been submerged in a cloud of high-velocity electrons for days following a period of high solar activity, as had been Anik E2 [56].

Telstar 401 – Cause Unknown

Telstar 401 was a communication satellite owned by AT&T that was launched on December 16, 1993 into geostationary orbit. AT&T lost contact with Telstar 401 on January 11, 1997, forcing the national television networks such as ABC, Fox, and PBS to reroute their broadcasting signals through Telstar 401's sister satellite, Telstar 402R [57]. Telstar 401 broadcasted to all 50 US states, as well as Puerto Rico and the US Virgin Islands. On January 17, 1997, Telstar 401 was declared permanently out of service after multiple attempts to gain control of the satellite failed.

AT&T was planning to sell Skynet Satellite Services to Loral Space and Communications Ltd. for $712.5 million before the failure, of which Telstar 401 was going to be a part of [57]. The approximate cost of Telstar 401 was $200 million, while the loss of the satellite was estimated to be about $132.5 million.

Intelsat 511 – Surface Charging

Intelsat 511 is a geosynchronous communications satellite that provides communication between the US and Australia. On October 7, 1995, Intelsat 511 lost its earth lock when it spontaneously fired its thrusters, causing a large attitude disturbance. Control of the spacecraft was regained shortly thereafter, but a long outage resulted as the spacecraft was maneuvered back into its proper orbit [58]. The official cause of the Intelsat 511 outage was deemed to be electrostatic discharging caused by the surface charging of the satellite. The discharging let to "phantom commands" within the spacecraft's circuitry, causing the thrusters to fire unintentionally [59].

Equator-S – Single-Particle Event

Equator-S is a German satellite used for weather research. On May 1, 1998, the Equator-S stopped sending data. It is believed that the processor system of the spacecraft suffered a latch-up on or shortly before May 1, caused by a single-particle event produced by the high solar activity at that time. Unfortunately, the satellite was already running on its redundant processor system because the main system had failed for the same reason on December 17, 1997 [60].

Recovery efforts were made by attempting to use a sequence of solar eclipses by the earth to drain the batteries of the satellite until the Equator-S powered down and the latch-up removed. Unfortunately, some of the satellite's back-up power was still working, and the plan failed.

GOES-8 and -10 – Cause Unknown (Possible Surface Charging)

The GOES satellites are geostationary weather spacecraft costing on average $300 million a piece, and are used by North America as the main source for weather information throughout the continent. Over several years the satellites have suffered multiple outages and problems, most of them minor and easily recoverable. Unfortunately, occasionally the satellites will suffer from a problem that keeps the satellite out of service for several days or has serious consequences. On October 26, 1998, the GOES-8 satellite suffered an earth-pointing malfunction and had to be taken offline for approximately 19 hours while the satellite restabilized. The cause of the malfunction is believed to have possibly been space weather-related, such as an electrostatic discharge either within the satellite or on its surface. While the GOES-8 satellite was able to come back online on October 27, the images it sent were misaligned as the spacecraft's navigation stabilized [61].

The GOES-10 satellite also suffered from a major malfunction in May 1998 when it was discovered that the spacecraft had stopped rotating. If the satellite is unable to rotate, it cannot point its solar arrays towards the sun as it moves, thereby leaving the spacecraft unable to produce electricity to keep operating. The malfunction occurred during the same time that the Galaxy IV and Equator-S satellites suffered outages, for which there is strong evidence that the high level of solar activity during the early weeks of May was the cause. After several tests on the satellite, it was discovered that GOES-10 still had the ability to rotate backwards. On August 8, 1998, the GOES-10 was brought back online and began relaying images of the surface of the United States – upside-down. Even though the images transmitted from GOES-10 were upside-down, they were clear and perfectly usable as data. The only catch was that programmers were required to rewrite the software that processes the GOES-10 images so that they are flipped right-side up when they are received on Earth [62].

3.3. Solutions

There are several ways a satellite company can protect its satellite against failures in space produced by the space environment. The initial step in avoiding space weather-induced problems is to minimize the potential for spacecraft anomalies by incorporating precautions into the design before launch. The spacecraft's orbital location is the greatest factor in determining design considerations to protect against the space environment. Such design considerations include selection of materials and coatings, selection of electronic components, protection of critical components (like the attitude control system), hardening of circuitry, strategic component placement to minimize environment interaction, and restrictions on subsystem operations [63]. Unfortunately, requirements for protecting against certain environmental concerns are often in conflict with requirements for other environmental concerns. The current approach to protecting against the space environment is to consider each design requirement separately and then integrate the solutions with each other in the final design. However, this approach has come under criticism for being too inefficient as missions and systems become more complicated.

Better testing of satellite components during the design phase can also protect against satellite failures by providing insight into how the spacecraft will perform in space and what to expect over several years of operation. Until 1991, predicted satellite performance was based on the tests done by the satellite manufacturers, which included exposing satellite electronics to short bursts of high radiation at room temperature [64]. It was generally believed that long term exposure to radiation in space would improve the satellite's defense due to self-healing effects. In reality, electronics began failing prematurely at considerably lower radiation levels than those on the laboratory tests. Scientists failed to realize that during laboratory tests, the thick insulation that surrounds electronics produces space-charge screening when exposed to high radiation for very short periods. In space, where the electronic equipment is exposed to lower radiation doses for longer periods of time, the screening effect does not occur and radiation damage ensues. Sandia National Laboratories has recently developed more accurate laboratory tests to determine the reliability of satellite components, consisting of exposing components to lower doses of radiation for several weeks at a time.

Other solutions to avoiding satellite anomalies caused by space weather can be implemented while the satellite is in orbit. Satellite operators can reorient their satellite to minimize damage caused by high-energy particle collisions when given warning of an incoming solar energetic particle (SEP) event [31]. Operators can also dump momentum stored in their momentum wheels by firing thrusters to prevent an orbital or orientational change due to a false command from a single event upset. A satellite controller can also choose not to upload commands to the spacecraft during SEP events. Having multiple satellites available to pick up the slack when one satellite is disabled due to the space environment is a precaution that satellite companies can take to ensure a minimum amount of service disruption due to a sun outage.

If, however, preventative measures are not successful and a satellite failure does occur, the ability to rendezvous with the satellite and repair it for a reasonable cost would be beneficial to the spacecraft industry. A possible way to salvage failed satellites orbiting idly in space is to employ an emergency satellite rescue and repair service that uses spacecraft debris as fuel [37]. Rescue and repair services that are able to remain in orbit to aid ailing satellites would be extremely valuable to the satellite industry and save billions of dollars of satellites now deemed worthless because there is currently no way of getting to the failed spacecraft to repair it that would cost less than just launching a new satellite. Rescue and repair services would also allow a margin of error for spacecraft designers and builders to work with, and should be seriously considered for use in the future.

Of course, knowing exactly what is causing a satellite problem in orbit is a crucial step in solving the problem. Unfortunately, the cause of a spacecraft failure often remains a mystery. Without being able to retrieve and examine the failed satellite from orbit, it is only speculation to say that the failure was caused for one reason or another, and the solution can only be guessed by trying to cure the symptoms. By implementing design precautions and being aware of the condition of the space environment that the satellite occupies, a satellite company can protect its investment before debilitating problems occur.

3.4. Summary

An often-asked question about satellite anomalies due to space weather is why certain satellites are affected and others are not. The phenomenon can be compared to tornado damage; one house can be destroyed while leaving the house next to it virtually untouched. Unfortunately, space weather is a “tornado” that cannot be seen or heard; only its affects can be evidence of its existence. It is sometimes very difficult to prove that space weather was the cause of a satellite failure because of the apparent randomness of the occurrences and the inability to retrieve and inspect most satellites from orbit. Though the effects of the space environment still remain largely mysterious, it is obvious that space weather has a large influence on technological systems on Earth, as well as in space. As more and more satellites are sent into space and people grow to increasingly rely on them for basic societal functions, the effects of the space environment will be felt greater than ever before.

Conclusion

Modern society increasingly relies on satellites in space with each passing year. Satellites provide a means of communication, weather data, research data, and Earth surface observations. Satellites cost several million dollars each. The majority are communications satellites that cost an average of $200 to $300 million. Though the cost of designing, building, and launching a satellite into space is decreasing as the new paradigm of "smaller, faster, cheaper" takes hold of satellite companies and organizations, the failure of a spacecraft in orbit is still a major loss. Both the cost of the satellite and the revenue it would have produced for the company are lost. An increasing number of satellites are being sent into Earth orbit each year with less protection against the space environment. It is therefore becoming more and more likely that a spacecraft that serves a vital technological function will fail and significantly disrupt the lives of people on Earth. This scenario has already occurred when the Galaxy IV satellite failed in May 1998 and 80% of all American pager traffic was cut off for several hours.

Satellite owners can lower the risk of failure due to space weather by being aware of the space environment. Designing a satellite so that it is hardened against the space environment and implementing safety orbital maneuvers during solar energetic particle events are ways to ensure a long and healthy lifetime for a spacecraft. Unfortunately, many of these protective measures are not being taken in order to reduce the cost of sending a satellite into orbit.

It is possible that no matter how well a spacecraft is protected against space weather, there will still be failures and outages that have origins in the space environment. The solar cycle is still not completely understood by scientists, though its effects are felt every day in the form of radio blackouts and temporary satellite outages. While the time when increased solar activity will occur can be predicted using the F10.7 index, the solar activity from day to day is unpredictable. Many satellite companies will not admit that the failure of one of their satellites was due to space weather in order to collect the insurance money on it, and to protect their reputations as the makers of a quality product. They will often either publicly state the cause of the satellite failure as having unknown origins or will state that the satellite failed due to some design flaw, rather than admit that their satellite was lost because it was not adequately protected from the space environment. The inability of satellite companies to predict the daily solar weather, plus less adequate protection against the space environment and the unwillingness of many satellite companies to admit to space weather failures, points to a future with an increasing number of satellites failing due to "mysterious" causes that can be traced back to the space environment.

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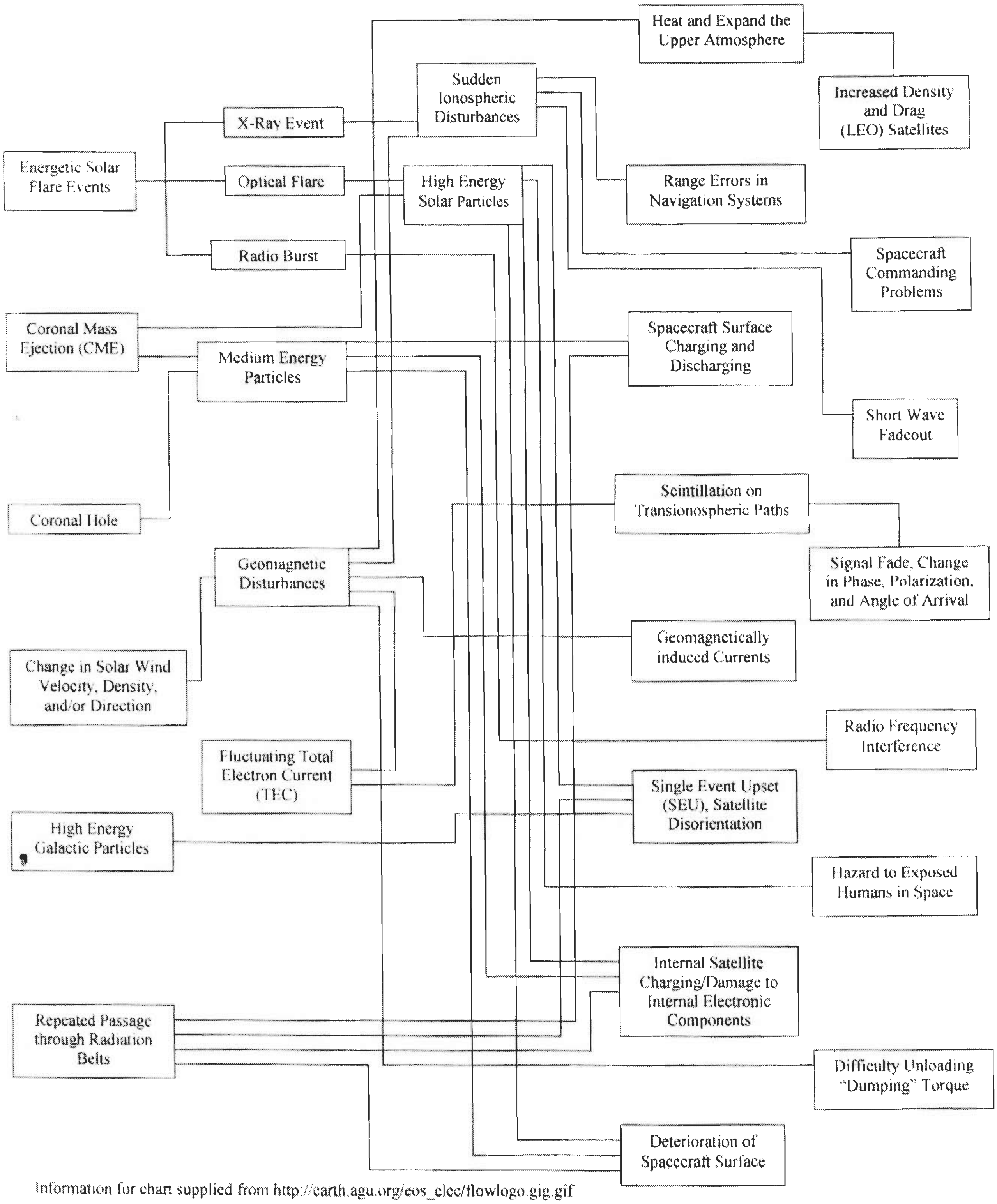
Appendix A. Space Weather Cause and Effect on Spacecraft Chart



Information for chart supplied from http://earth.agu.org/eos_elec/flowlogo.gig.gif

Appendix B. NOAA Space Weather Scales

NOAA Space Weather Scale for Geomagnetic Storms

Category		**Effect**	**Physical measure**	**Average Frequency (1 cycle = 11 years)**
Scale	**Descriptor**	**Duration of event will influence severity of effects**		
Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	**Extreme**	**Power systems:** : widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.)**.	Kp = 9	4 per cycle (4 days per cycle)
G 4	**Severe**	**Power systems:** possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** may experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.)**.	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	**Strong**	**Power systems:** voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems.	Kp = 7	200 per cycle (130 days per cycle)

		Other systems: intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.)**.		
G 2	**Moderate**	**Power systems:** high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.)**.	Kp = 6	600 per cycle (360 days per cycle)
G 1	**Minor**	**Power systems:** weak power grid fluctuations can occur. **Spacecraft operations:** minor impact on satellite operations possible. **Other systems:** migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine)**.	Kp = 5	1700 per cycle (900 days per cycle)

* Based on this measure, but other physical measures are also considered.

** For specific locations around the globe, use geomagnetic latitude to determine likely sightings

NOAA Space Weather Scale for Solar Radiation Storms

Category		**Effect**	**Physical measure**	**Average Frequency (1 cycle = 11 years)**
Scale	**Descriptor**	**Duration of event will influence severity of effects**		
Solar Radiation Storms			Flux level of $\geq$10 MeV particles (ions)*	Number of events when flux level was met (number of storm days**)
S 5	**Extreme**	**Biological:** unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); high radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 100 chest x-rays) is possible. **Satellite operations:** satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible.	10^5	Fewer than 1 per cycle

		Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.		
S 4	**Severe**	**Biological:** unavoidable radiation hazard to astronauts on EVA; elevated radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 10 chest x-rays) is possible. **Satellite operations:** may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	**Strong**	**Biological:** radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in commercial jets at high latitudes may receive low-level radiation exposure (approximately 1 chest x-ray). **Satellite operations:** single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	**Moderate**	**Biological:** none. **Satellite operations:** infrequent single-event upsets possible. **Other systems:** small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	**Minor**	**Biological:** none. **Satellite operations:** none. **Other systems:** minor impacts on HF radio in the polar regions.	10	50 per cycle

* Flux levels are 5 minute averages. Flux in particles·s^{-1}·ster^{-1}·cm^{-2}. Based on this measure, but other physical measures are also considered.

** These events can last more than one day.

NOAA Space Weather Scale for Radio Blackouts

Category		**Effect**	**Physical measure**	**Average Frequency (1 cycle = 11 years)**
Scale	**Descriptor**	**Duration of event will influence severity of effects**		

Radio Blackouts			GOES X-ray peak brightness by class (and by flux*)	Number of events when flux level was met; (number of storm days)
R 5	**Extreme**	**HF Radio:**Complete HF (high frequency**) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2 x 10^{-3})	Less than 1 per cycle
R 4	**Severe**	**HF Radio:** : HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. **Navigation:** Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	**Strong**	**HF Radio:** Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. **Navigation:** Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	**Moderate**	**HF Radio:** Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. **Navigation:** Degradation of low-frequency navigation signals for tens of minutes.	M5 (5 x 10^{-5})	350 per cycle (300 days per cycle)
R 1	**Minor**	**HF Radio:** Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. **Navigation:** Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

* Flux, measured in the 0.1-0.8 nm range, in W·m^{-2}. . Based on this measure, but other physical measures are also considered.

** Other frequencies may also be affected by these conditions.

NOAA Space Weather Scales provided by the National Oceanic and Atmospheric Administration

Appendix C. Physics Capstone: The Physics of Spacecraft Drag

Spacecraft drag due to the space environment, or rather how much fuel is used to overcome the drag, is the largest determiner of the lifetime of a spacecraft in orbit between 120 and 600 km above the Earth [a]. In this range, a satellite is considered to be in the Earth's thermosphere, a region of the atmosphere that absorbs ultraviolet radiation from the sun. The radiation energy that is absorbed consequently increases the temperature of the thermosphere and varies according to the solar radio flux F10.7 and the geomagnetic index Ap. The density of the atmosphere varies with height and temperature, and can be calculated using the expression

$$\rho = 6\times10^{-10}\exp[-(r-175)/H] \quad \text{(Eq.1)}$$

where r is the altitude at which the satellite is orbiting above the earth and H is the atmospheric density scale height. The atmospheric density scale height is defined as:

$$H = {}^{T}\!/_{m} \quad \text{(Eq.2)}$$

where T is the temperature of the thermosphere and m is the effective atmospheric molecular mass and varies with altitude. The temperature of the thermosphere varies according to the solar radio flux F10.7 and the geomagnetic index Ap. The value of the atmospheric density scale for varying heights can often be found in tables contained in many spacecraft mission and design textbooks. When the temperature of the thermosphere increases, the value of H increases, which increases the value of the atmospheric density. Therefore, when the temperature of the thermosphere is increased due to solar activity, it expands and increases the density that a satellite in LEO must navigate at fixed altitudes. Due to the 11-year solar cycle of decreasing and increasing solar activity, satellites decay more rapidly during solar maximum than solar minimum. The density at any given height in the atmosphere can be determined by knowing the altitude of the spacecraft plus the space environmental conditions.

When a satellite's orbit begins to decay, there is a change in the orbital radius, period, and velocity of the spacecraft which decreases the spacecraft's lifetime. The orbital decay is due to the drag produced by the atmosphere in which the spacecraft is orbiting. In order for the satellite to stay in a stable orbit, it must have a velocity in the tangential direction that satisfies the equation for the force that is pulling the satellite towards the Earth, in order to keep the system in equilibrium.

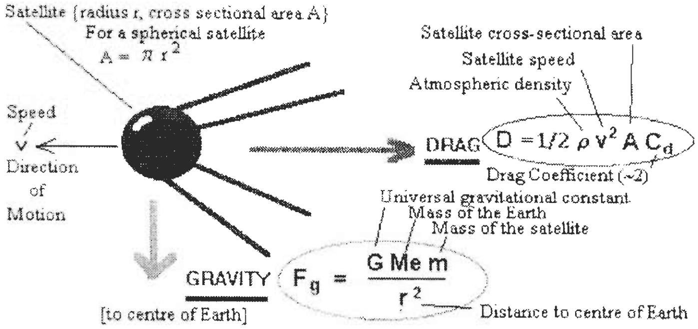


Figure A: Illustration of the forces acting on a satellite in orbit.

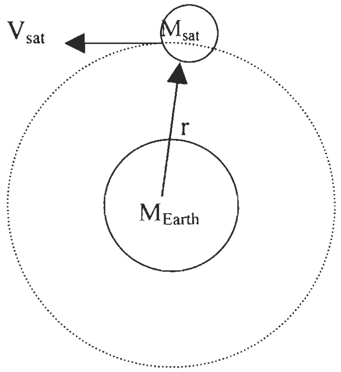


Figure B. Simplified satellite-Earth system.

Figures A shows the specific forces acting on a satellite in orbit around the Earth while figure B. illustrates the two-body system of a satellite and the Earth. Reentry of the satellite is assumed to have occurred when the spacecraft's orbit falls below 180 km.

The drag, *D*, imposed on an object is given by equation 3:

$$D = \frac{1}{2}\rho V^2 A C_d \quad \text{(Eq.3)}$$

where ρ is the atmospheric density, V is the velocity of the satellite, A is the cross sectional area of the satellite, and C_d is the drag coefficient. The drag coefficient is based on the shape of the spacecraft, and is generally assumed to have a value of 2 for the average satellite [b]. Since $D = -F = ma$, the tangential deceleration of the satellite due to drag can be calculated by manipulating Eq.3:

$$a_d = -\frac{1}{2}\rho(C_d \cdot A / m)V^2 \quad \text{(Eq.4)}$$

with m being the satellite mass. The expression $m/C_d{\cdot}A$ is a specific quantity known as the ballistic coefficient, which serves as a measure of how the spacecraft will react to drag. Satellites with high ballistic coefficients will be affected less by increased atmospheric density than satellites with low ballistic coefficients. Ballistic coefficients usually range from 60 kg/m^2 (low) to 200 kg/m^2 (high). Figure C shows the affects of atmospheric drag on satellites with different ballistic coefficients as well as their orbital variations due to the solar cycle.

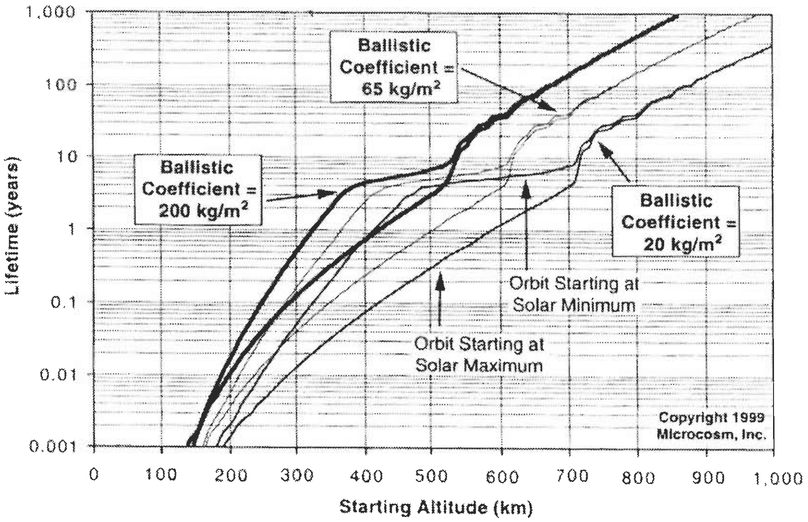


Figure C. Spacecraft lifetime v. starting altitude for different ballistic coefficients and solar cycle times

The affects of drag must be included in the calculations of each characteristic of the satellite's orbit, including the ballistic coefficient and the atmospheric drag at the desired height. The orbital radius is the distance that the satellite orbits the Earth as measured from the center of gravity of the system, which for all practical purposes is the center of the Earth. For a circular orbit, the change in the orbital radius with each revolution, r_{rev}, is defined in Eq.3:

$$\Delta r_{rev} = -2\pi (C_d \cdot A/m)\rho r^2 \quad \text{(Eq.5).}$$

The change in the period per revolution of the satellite is:

$$\Delta P_{rev} = -6\pi^2 (C_d \cdot A/m)\rho r^2 / V \quad \text{(Eq.6).}$$

The change in velocity after each revolution is:

$$\Delta V_{rev} = \pi(C_d \cdot A/m)\rho r V \quad \text{(Eq.7).}$$

The velocity V of the satellite in circular orbit can be calculated as $V = \sqrt{\frac{\mu}{r}}$, where $\mu = G \cdot m_{Earth}$ $= 3.986 \times 10^{14}$ m^3/s^2.

By studying the equations for the change in orbital radius, period, velocity, and orbital lifetime, it can be seen that as spacecraft drag increases, the spacecraft begins to accelerate towards the Earth, its period decreases, and it picks up speed, all of which can be expected. The orbital lifetime also decreases as the spacecraft drops closer to the surface of the Earth while it constantly decelerates.

Example: A 100 kg spherical satellite with a diameter of 1 meter is in orbit 300 km above the surface of the Earth. Assuming that $\rho = 1.95 \times 10^{-11}$ kg/m^3:

The period of the satellite is:

$$P = 2\pi\sqrt{\frac{r^3}{\mu}} = 2\pi\sqrt{\frac{(6.68\times10)^3}{3.986\times10^{14}}} = 5431s = 1.5 hours \quad , (r = r_{orbital} + r_{earth} = 6.68 \times 10^6 \text{ m})$$

The velocity of the spacecraft in orbit:

$$V = \sqrt{\frac{3.986\times10^{14}}{6.68\times10^6}} = 7725 m/s$$

The deceleration due to drag:

$$a_d = -\tfrac{1}{2}(1.95\times10^{-11})(2\cdot0.785/100)\cdot7725^2 = -9.13\times10^{-6}\,m/s^2$$

The change in orbital radius per revolution:

$$\Delta r_{rev} = -2\pi(2\cdot0.785/100)\cdot(1.95\times10^{-11})\cdot(6.68\times10^6)^2 = -86m$$

(0.03 % decrease per revolution)

The change in period per revolution:

$$\Delta P_{rev} = -6\pi^2(2\cdot0.785/100)\cdot(1.95\times10^{-11})\cdot(6.68\times10^6)^2/7725 = -0.10s$$

(1.84 x 10^{-3} % decrease per revolution)

The change in velocity per revolution:

$$\Delta V_{rev} = \pi(2\cdot0.785/100)\cdot(1.95\times10^{-11})\cdot(6.68\times10^6)\cdot7725 = 0.05m/s$$

(6.47 x 10^{-4} % increase per revolution)

The satellite is assumed to have reentered the Earth's atmosphere when it has reached an orbital radius of 180 km (a period of 5285s). Since the orbit of the satellite is decaying at -0.10s per revolution, the amount of revolutions the satellite will make before reaching the reentry orbit is approximately 1460 revolutions, which is 92 days. This is the orbital lifetime of the example spacecraft.

The lifetime of this satellite is very short without orbital maintenance. When solar activity occurs and satellite drag is increased, a spacecraft can end up falling like a rock out of the sky if the satellite controllers are not prepared to react quickly to the problem, as was the case of the Solar Maximum Mission satellite when a major geomagnetic storm occurred in mid-December 1989 (Figure D).

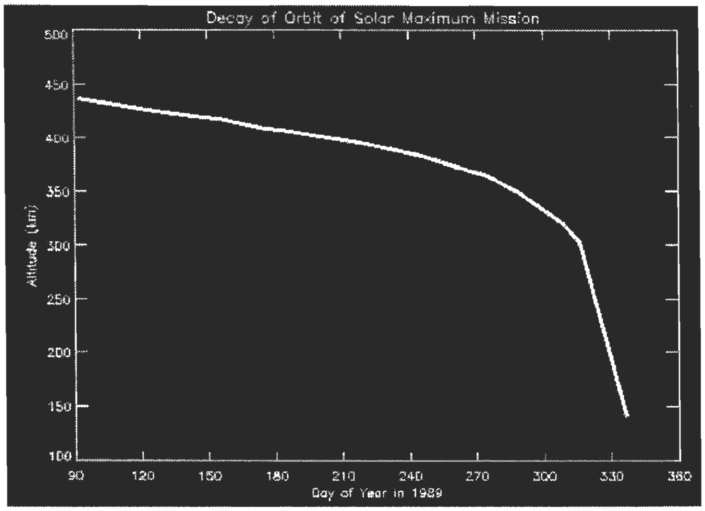


Figure D. Orbital decay of the Solar Maximum Mission in 1989.

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