ESS 7
Lectures 18, 19 and 20
November 12, 15, and 17, 2010
Technology and Space
Weather
Space Weather Effects on Satellite Lifetimes: Atmospheric Drag

• A satellite would orbit forever if gravity was the only force acting on it.

• Near the Earth (<2000km) satellites are traveling within the Earth’s atmosphere.

• Collisions with the air cause them to slow down and drop to lower altitudes.

• During magnetic storms the atmosphere gets heated and the density increases.
An Example of Atmospheric Drag

• The increased drag can cause satellites to return to Earth.
• Even if they aren’t lost their orbits are changed and they may not be able to perform their functions.
Cleaning Low Earth Orbit (LEO)

Orbital Debris

Number of Satellites

- Most satellites are in LEO
- Magnetic storms remove space junk but also cripple active satellites.
Note: Artist's impression; size of debris exaggerated as compared to the Earth
**Geosynchronous Orbit (6.6 R_E) Satellites**

- Geosynchronous orbit where a satellite orbits the Earth in 24 hours is in the radiation belts.
- Over 100 satellites orbit – used for communications, weather forecasts etc.
Magnetic Storms Populate the Radiation Belts

Outer Belt Relativistic Electrons

Inner Belt (Protons)

Plasma sheet electrons
Space Environment Effects: Surface Charging
Effects of Surface Charging

- Spacecraft charging is a variation of the electrostatic potential of the spacecraft surface with respect to the surrounding plasma. The resulting discharges can:
  - Cause spurious electronic switching
  - Breakdown vehicle thermal coatings.
  - Degrade amplifiers and solar cells
  - Degrade optical sensors.

- Photoionization frees electrons from the spacecraft and it develops a positive charge.
  - Electrons may form a negative cloud near the spacecraft.
  - If the entire surface was a homogeneous conductor this would not be a problem but this isn’t the case.
  - Differential charging of the sunlit surface with respect to the dark surface.

- Electrons with energies of a few keV can penetrate the skin of the spacecraft and charge it negatively.
Surface Charging: SCATHA Satellite Observations.

- Following this substorm while SCATHA was in eclipse the spacecraft charged to 20kV.
Space Environment Effects: Deep Dialectic Charging
Examples of Deep Dielectric Charging

- Electrons with energies between 2 and 10 MeV have enough energy to get deep into satellite surfaces.
- The excess charge spreads out evenly on conducting surfaces but the charge accumulates on dielectric surfaces resulting in potential differences between different parts of the satellite.
- Eventually static discharges will occur. This can happen on electron circuitry.
- Left plot shows count rate of 3 MeV electrons versus time. Arrows show times when the spacecraft star tracker had anomalies. Right plot shows >2MeV electrons and anomalies.
High Energy Electrons: Deep-Dialectric Charging

1. Electrons bury themselves in the insulator

2. Electrons slowly leak out of the insulator

3. Influx of electrons increases to levels higher than the leakage rate

4. Electrons build up faster than they leak off

5. Discharge (electrical spark) that damages or destroys the material
Surface Damage in a C2 MOS Capacitor
Space Environment Effects: Single Event Upsets
Effects of Single Event Upsets

• Single Event Upsets are bit flips in digital micro-electronic circuits.
  – Damage to stored data.
  – Damage to software.
  – Stop central processing unit (CPU).
  – Cause CPU to write over critical data tables.
  – Create faulty commands.

• Caused by high energy ions ionizing silicon electronics.
  – Galactic cosmic rays.
  – SEPs
  – Radiation belts.
Background caused by Solar Energetic Particles
Launches must be Postponed During Solar Particle Events

- Launches for a number of rockets must be postponed if the flux of $>50\text{MeV}$ protons exceeds 100 pfu.

- The proton fluxes interfere with the guidance system.
What Would Satellite Operators do if they had Accurate Space Weather Forecasts?

• Instruments and/or spacecraft turned off or safed

• Maneuver planning

• Anomaly assessments

• Orbit determination accuracy

• Increased spacecraft and instrument monitoring for health and safety during solar storms
Faraday’s Law

• A time variable magnetic field can induce an electric field.

\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \]

• A time varying magnetic field is how an electrical generator works.

• Space weather events make a time varying magnetic fields.

• This can induce a voltage in wires or things like wires.
Geoelectric Field is caused by changes in the magnetic field, especially by pulsations.
Carrington Event, Sep. 1 1859
New York Times Sep. 2 1859

"We came into the office to take steamer news from Quebec, but from the eccentric freaks of the batteries, caused by the Northern Lights, could scarcely do anything. One moment the batteries would burn over, and we would have so strong a circuit that the armatures would not come away from the magnet; the next moment there would be no current at all. At Bangor it was the same. At Montreal and Quebec it was much worse, for I went home about 12 o'clock, and very little of the news had been obtained. As there is no mention of the steamer in the papers of this morning, I presume what came was not given out.

This phenomena is most striking, and shows what a line in the Northern regions would have to contend with.

The exhibition was most singular and beautiful, and I have never seen it surpassed but once. But I should have been much pleased if the entertainment had closed sooner, and enabled us to get our news through."
• A magnetic storm in 1989 caused induced current which damaged this transformer.
• It caused a black out that shut off power for 6 million people for 9 hours.
What Damages Transformers?

• Changing ionospheric currents induce changing magnetic fields, which induce currents in long wires

• Corpuscular radiation from aurora charge conductors (like long straight wires)

• Variable magnetic fields exert force on electrical components in transformer.
North America Electric Reliability Corporation (NERC)

- NERC is the Federal Energy Regulatory Commissions electric reliability coordinator.
- Organized into a series of regional coordinators.
- Develops and enforces reliability standards.
Trans-continental/oceanic Fiber Optic Cables

- Fiber optics use light instead of current to carry signals. They should not be susceptible to induced currents.

- However, most 1000+km long lines need relays to boost the signal strength. These need power and hence copper wires running to them.

"Courtesy of Windows to the Universe, http://www.windows.ucar.edu"
Pipeline Corrosion

- A current in a pipeline enhances corrosion.
- The trans-Alaska pipeline is basically a long conductor at high latitude where there are changing magnetic fields even during substorms.
AM and HF Radio Propagation

- We can take advantage of refraction and reflection by using the ionosphere to have “over-the-horizon” communication (Marconi).
- Frequency needs to be less than the “critical” frequency (or plasma frequency) of the ionosphere (typically around 10 MHz).
- $F_{\text{critical}} = 9\sqrt{n_e}$ where the density is in m$^{-3}$. 
Danger to Aviation

• High frequency (3-30MHz) communications problems in polar regions.
• By 2018 estimated 1.8 million passengers between US and China.
Satellite Communications

- Typically very high frequency so ionospheric effects are minimized (but not eliminated)
- GPS - signal delays and refraction give errors in position.
Satellite Signal Scintillation

- High frequency changes in signal strength variations
- Same effect as “twinkle” in star light
- Due to interference of ionospheric irregularities
- Causes signal connect loss/drop outs
GPS (NAVSTAR) Animation

A simulation of the original design of the GPS space segment, with 24 GPS satellites (4 satellites in each of 6 orbits), showing the evolution of the number of visible satellites from a fixed point (45°N) on earth (considering "visibility" as having direct line of sight). The parameters used to simulate the orbits are: eccentricity (e) 0.05, inclination (i) 55° and a separation between orbits of 60° in the right ascension of the ascending node. Within each orbit, the four satellites are evenly spaced (the instant of pass through perihelion being arbitrary for the first satellite in each orbit). The orbital period of the satellites was taken to be 12 hours. The earth was considered a perfect sphere with a radius of 6400 km. The time in the animation is running about 2880 times faster than real time (half a minute representing 24 hours), as clearly seen in the rotation of earth. The simulation was created using MATLAB and converted to animated gif format using Adobe ImageReady.

El Pak - Wikipedia
Danger to Aviation at Lower Latitudes

- The FAA Wide Area Augmentation System (WAAS) is used for navigation at lower latitudes.
- WAAS uses the GPS satellites.
- In 2005 aircraft in the western U.S. lost contact with the GPS satellites due to interference from a large solar flare.

GPS Nominal Constellation
24 Satellites in 6 Orbital Planes
4 Satellites in each Plane
20,200 km Altitudes, 55 Degree Inclination
WAAS Altitude Errors

• Ionosphere Disturbances impact vertical error limits, defined by the FAA’s Lateral Navigation Vertical Navigation (LNAV/VNAV) specification to be no more that 50 meters.

• Commercial aircraft unable to use WAAS for precision approaches. Space weather can cause errors greater than 50 meters.
Summary of Perils

- Atmospheric drag
- Electronic failures
  - Surface charging
  - Deep dielectric charging
  - Single event upsets
- Ground failures
  - Induced electric field lead to induced currents
  - Destruction of long wires
- Communications
  - High frequency radio – Plasma frequency
  - Refraction of signal from satellites
  - Satellite Scintillation
- Navigation
  - GPS satellites are in 4 $R_E$ circular orbits
  - Radiation damage
  - Noise from solar radio bursts
  - Errors in altitude of aircraft.
What Causes What? (CIR Versus CME Storms)

• The responses of the magnetosphere to CIR and CME driven storms are different.
• As a result the space weather effects are different.
• CIR driven storms cause more problems for space assets.
• CME driven storms cause more problems for electrical systems.
Review of CME Properties

- Occur predominately during solar maximum, are mostly radial structures, and drive storms with time scales of days.
- Frequently are composed of 3 parts:
  - Forward Shock: If the speed differential between the remnants of the coronal ejecta and the slow, upstream solar wind is greater than the magnetosonic wave speed (50–70 km/s), a forward shock is formed. Typical shocks of Mach 2-3 are observed. The changes pass a given point in minutes.
  - Sheath region: between the shock and the cloud the field and density are compressed and turbulent, ~ 9-24 nT (dependant on the Mach number of the shock), timescale on the order of hours.
  - Magnetic cloud: slow varying (~ day), strong magnetic fields (10-25 nT), low density, low ion temperature as compared to background solar wind.
Graphical view of ICME (a.k.a CME and Magnetic Cloud)

Figure 2 from Gonzalez et al., 1999.
CIR Properties

- Occur predominately during the descending phase of solar cycle, are nearly azimuthal in profile, and last up to a week.
- Frequently lack of sudden impulse (no forward shock at 1 AU – shocks typically form between 2-3AU) but can contain the typical 3 phases of a magnetic storm.
- They are characterized by strong magnetic fields ~ 30 nT (due to high and low speed stream compression)
- $B_z$ fluctuates throughout interval (due at least in part by intense Alfvén wave activity embedded in high speed streams see Smith et al., 1995).
Cartoon of CIR

Figure 4 from Tsurutani et al., 2006.

Figure 6 from Gonzalez et al., 1999.
More on CME and CIR Storms

**CME:**
- Can create major storms (Dst < -100 nT)
- *Initial phase:* sudden commencement caused by forward shock, $\tau \sim$ min-hrs.
- *Main phase:* initiated by a southward IMF and enhances nightside convection thus ring current increases, $\tau \sim$ hrs.
- *Recovery phase:* when the ring current begins to decay - $\tau \sim$ days.

**CIR**
- Due to highly oscillatory nature of the Bz GSM field, the resultant storms are weak to moderate (Dst>-100 nT)
- *Initial phase:* caused by an increase in ram pressure from the HCSPS but density increase is gradual, sudden commencements are rarely observed.
- *Main phase:* caused by CIR
- *Recovery phase:* high speed stream contains Alfvenic waves which create intense AE increases.
Solar Energetic Particles

- Solar energetic particle events are enhanced fluxes of subrelativistic and relativistic ions that have durations of hours to days. They are known to be associated with flares and interplanetary shocks (Borovsky & Denton 2006).

- Frequently accompany CME (with shocks) driven storms, but rarely with CIRs at Earth (because shock typically hasn’t steepened yet).
Enhanced relativistic electrons (> MeV) in the outer radiation belt.

CME driven storms:
- Less severe

CIR driven storms
- Can be severe, enhanced fluxes peak during declining solar cycle.
Formation of new Radiation belt

- Usually caused by the capture of SEP ions during strong compression of the magnetosphere, but new inner electron belt has also been created from large compression of a SSC.

- CME driven process not related to CIRs.
Aurora

- Great auroras are predominately due to CME driven storms and peak during solar maximum.

- Low intensity aurora over the entire oval is observed during CIR driven storms in the recovery phase.

Aurora Australis appearing in the night sky at Swifts Creek, 100km north of Lakes Entrance, Victoria, Australia. Ca. Nov. 15 2005. Wikipedia.
Ionospheric Effects

CME affect:

- GIC: geomagnetically induced currents which are hazardous to Earth based electrical systems.
  - Caused by rapid intensification of ionosphere currents that are driven from shock compression of the magnetosphere or a substorm.
  - Occur predominately during solar max and/or the early declining phase

Brodsky & Denton, 2006
Homework

• Read Chapter 7
• Problems – 6.3, 6.5, 6.7
• Due Nov. 24, 2010