Space Weather in Ionosphere and Thermosphere

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Solar flares
These explosions on the sun's surface occur without warning and can launch huge amounts of X-rays, other radiation and particles into the ionosphere, the outer edge of Earth's atmosphere.

Diverted particles

Magnetic field lines

Coronal mass ejections
These slow-moving "space hurricanes" occur when the sun ejects part of its outer atmosphere.

Solar winds
Streams of gas particles and magnetic clouds pour from the sun's surface in all directions.

Earth's magnetic field
Earth's atmosphere is least protective around the polar regions, so those areas are most easily disrupted by solar weather.

Vulnerable to space weather

Satellites and GPS devices
Radiation storms can befuddle satellites, delaying or garbling radio waves and mucking up sensitive electronic controls.

Oil pipelines
Aboveground pipelines can conduct stray currents and become corroded. Alaska's lines are vulnerable because they're so near the North Pole.

Aircraft communications
Transmissions that depend on low-frequency radio waves become unreliable, especially near the North Pole.

International space station
No humans are closer — therefore more vulnerable — to space radiation than residents of the space station.

Power grid
Power lines can conduct currents that develop in the ionosphere. The grid is so interconnected that a few blown transformers can cripple a large area.

Water supply
Because water processing and distribution depend so heavily on electricity, a major loss of power would affect water delivery within days.

Sun and Earth are shown to approximate scale, but distance is not to scale.
Space Weather Effects and Timeline
(Flare and CME)

Flare effects at Earth:
~ 8 minutes (radio blackout storms)
Duration: minutes to hours

SEP radiation effects
reaching Earth: 20 minutes – 1 hour after the event onset
Duration: a few days

CME effects arrives @ Earth: 1-2 days (35 hours here)
Geomagnetic storms: a couple of days
Types of Storms
CME and SEP path are different

CME: could get deflected, bended, but more or less in the radial direction

Courtesy: Odstrcil

CME

SEPs

CME: could get deflected, bended, but more or less in the radial direction
CME impact and SEP (Solar Energetic Particle) impact are different!

Important distinction

CME impact @ Earth:
Geomagnetic Storm

Radiation storm @ Earth from SEPs

CME speed: 300 – 3500 km/s
SEPs: fraction of c
Light speed c: 3 x10^5 km/s
SEPs: ion radiation storms
Potentially affect everywhere in the solar system

Courtesy: SVS@ NASA/GSFC
Geomagnetic Storms:
CME interaction with Earth (magnetic field)

Geomagnetic storms due to CIRs are at most moderate
Ionospheric Dynamics/Storms
Day/night ionospheric structure

Day/night ionosphere is very different

D region 50 to 90 km;
E region 90 to 140 km;
F1 region 140 to 210 km;
F2 region over 210 km.
Composition of ionosphere
Ionosphere 101

Formed by solar EUV/UV radiation

Reflects, refracts, diffracts & scatters radio waves, depending on frequency, density, and gradients

Dielectric Properties

\[ \varepsilon = \left(1 - \frac{f_p^2}{f^2}\right) \varepsilon_o \]

\[ f_p \approx 9 \cdot 10^3 \sqrt{n_e} \]

TURBULENT PLASMA “BUBBLES”

Subject to Raleigh-Taylor instability at night \( \rightarrow \) formation of Equatorial Plasma Bubbles (EPBs)

Leads to highly variable reflection / refraction = “SCINTILLATION”

Scintillated GPS Signal

Courtesy: de la beaujardiere
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Recent scientific results show that the ionosphere is strongly influenced by forces acting from below.

Research remains to be done: How competing influences from above and below shape our space environment.
The daytime ionosphere exhibits significant variability in its motion and density. The source of these changes: unknown.

likely originates with modulation of neutral and/or ionized state variables along the magnetic field - need to be determined.

coupled ion-neutral dynamics critical
Space Weather Phenomena and Effects in the Ionosphere

Aurora – hemispheric power (satellite charging, scintillation)
Satellite drag due to neutrals
Equatorial bubbles/irregularities –scintillation, communication problems
Radio blackout -- solar flare

Polar Cap Absorption - solar energetic particles
Types of space weather events affecting nav and commu

- **UHF – GPS**
  - Energetic protons/particles – via SEE – affecting GPS satellites components
  - Geomagnetic storms/ionospheric storm – cause scintillations

- **VHF:**
  - Energetic protons - PCA
  - Geomagnetic storms
  - Solar radio emission associated with flare/CME

- **HF:**
  - Solar flares/x-ray
  - Energetic protons - PCA
  - Geomagnetic activities
Signals of different types with different purposes

GPS signal: Penetrate through the ionosphere
ALF: Absorption Limiting Freq.
1. SID (Sudden Ionospheric disturbance due to x-ray in solar flares dayside)
2. Solar energetic particle precipitation - particularly protons High-latitude
3. Geomagnetic storm disturbances Ubiquitous/global

Communication/Navigation Problem
Flare: SWx impacts

- Cause radio blackout through changing the structures/composition of the ionosphere (sudden ionospheric disturbances) – x ray and EUV emissions, lasting minutes to hours and dayside

- Affect radio comm., GPS, directly by its radio noises at different wavelengths

- Contribute to SEP – proton radiation, lasting a couple of days
Solar radio bursts can directly affect GPS operation

- Solar radio bursts during December 2006 were sufficiently intense to be measurable with GPS receivers. The strongest event occurred on 6 December 2006 and affected the operation of many GPS receivers. This event exceeded 1,000,000 solar flux unit and was about 10 times larger than any previously reported event. The strength of the event was especially surprising since the solar radio bursts occurred near solar minimum. The strongest periods of solar radio burst activity lasted a few minutes to a few tens of minutes and, in some cases, exhibited large intensity differences between L1 (1575.42 MHz) and L2 (1227.60 MHz). Civilian dual frequency GPS receivers were the most severely affected, and these events suggest that continuous, precise positioning services should account for solar radio bursts in their operational plans. This investigation raises the possibility of even more intense solar radio bursts during the next solar maximum that will significantly impact the operation of GPS receivers.

Cerruti et al., 2008, Space Weather
Ionospheric impact on signal path

Could cause potential problems
Sudden Ionospheric Disturbances – solar x-ray

✓ An SID can affect very low frequencies (e.g., OMEGA) as a sudden phase anomaly (SPA) or a sudden enhancement of signal (SES). At HF, and sometimes at VHF, an SID may appear as a short-wave fade (SWF).

✓ May last from minutes to hours, depending upon the magnitude and duration of the flare.

✓ Absorption is greatest at lower frequencies, which are the first to be affected and the last to recover. Higher frequencies are normally less affected and may still be usable.

Radio blackout events
Solar Radio Emission affecting VHF

- Type II radio emission
- Type IV radio emission
- Solar flares also create a wide spectrum of radio noise; at VHF (and under unusual conditions at HF) this noise may interfere directly with a wanted signal.
Solar energetic particles

- HF/VHF degradation in polar region (a.k.a. Polar Cap Absorption)
- Energetic particles have detrimental effects on the onboard systems of GPS satellites (SEE impacts on spacecraft component)
- Energetic particle events can persist for a few days at a time
Geomagnetic Storms

- CME storms
- CIR storms

Global impacts

Affect HF radio communication – especially when the signal passing through the auroral zone or ionospheric irregularities

GPS - scintillation

Geomagnetic storms may last several days, and ionospheric effects may last a day or two longer.
Scintillation

Basu et al., 1999
Phase Scintillation

GPS Satellites Tracking

Low Lat

kour_931104  Ap = 77

High Lat

eyl_931104  Ap = 77
Ionospheric Scintillation Indices

\[ S_4(f) = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}} \propto f^{-1.5} \]

\[ \sigma_\phi(f) = \sqrt{\langle \phi^2 \rangle - \langle \phi \rangle^2} \propto f^{-1} \]

- **S₄ and \( \sigma_\phi \) indices** – amplitude and phase scintillation, respectively
  - \( I \) – detrended signal intensity
  - \( \phi \) – detrended signal phase
  - Raw data is sampled at 20 or 10 ms (50 Hz or 100 Hz)
  - Frequency dependent
  - Measurements of phase scintillation susceptible to local oscillator errors of transmitter and receiver

- **ROT I – Rate of TEC index**
  - ROT – detrended rate of TEC derived from dual-frequency phase data
  - ROT data sampled at 30 sec (or 1 s)
  - Not susceptible to local oscillator errors, in principle

Courtesy: Pi at JPL
Equatorial Plasma Bubbles

- Plasma moves easily along field lines
- Upward plasma drift supports plasma against gravity → unstable configuration
- E-region “shorts out” electrodynamic instability during day
- At night, E-region conductivity too small to short-out E field
- Instability in plasma grows to form equatorial plasma bubbles (EPBs), which contain irregularities seen by radars (right image) & which disrupt communications
- Irregularities mainly present during quiet times

(Courtesy: de la beaujardiere)
plasma bubbles: typical east–west dimensions of several hundred kilometers contain irregularities with scale-lengths ranging from tens of kilometers to tens of centimeters (Woodman and Tsunoda). Basu et al. (1978) showed that between sunset and midnight, 3-m scale irregularities that cause radar backscatter at 50 MHz, co-exist with sub-kilometer scale irregularities that cause VHF and L-band scintillations. After midnight, however, the radar backscatter and L-band scintillations decay but VHF scintillations caused by km-scale irregularities persist for several hours.
Spacecraft Drag

• Spacecraft in LEO experience periods of increased drag that causes them to slow, lose altitude and finally reenter the atmosphere. Short-term drag effects are generally felt by spacecraft <1,000 km altitude.

• Drag increase is well correlated with solar Ultraviolet (UV) output and additional atmospheric heating that occurs during geomagnetic storms.

• Most drag models use radio flux at 10.7 cm wavelength as a proxy for solar UV flux. Kp is the index commonly used as a surrogate for short-term atmospheric heating due to geomagnetic storms. In general, 10.7 cm flux >250 solar flux units and Kp>=6 result in detectably increased drag on LEO spacecraft.

• Very high UV/10.7 cm flux and Kp values can result in extreme short-term increases in drag. During the great geomagnetic storm of 13-14 March 1989, tracking of thousands of space objects was lost. One LEO satellite lost over 30 kilometers of altitude, and hence significant lifetime, during this storm.
Satellite Drag

- Atmospheric drag magnitude:
  \[ a_{\text{drag}} = \frac{1}{2} \beta \rho v^2 \]

  - \( \beta = \frac{c_D A}{m} \)
  - is ballistic coefficient
  - \( \rho \) is atmospheric density

Solar cycle and space weather have strong impact on neutral atmospheric density

Increasing atmospheric drag impacts:
- Frequency of “Drag Make-Up” maneuvers for satellite to stay in control box
- Covariance

Uncertainty in predicted atmospheric drag impacts:
- Future satellite position predictions
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iSWA layout for ionosphere products