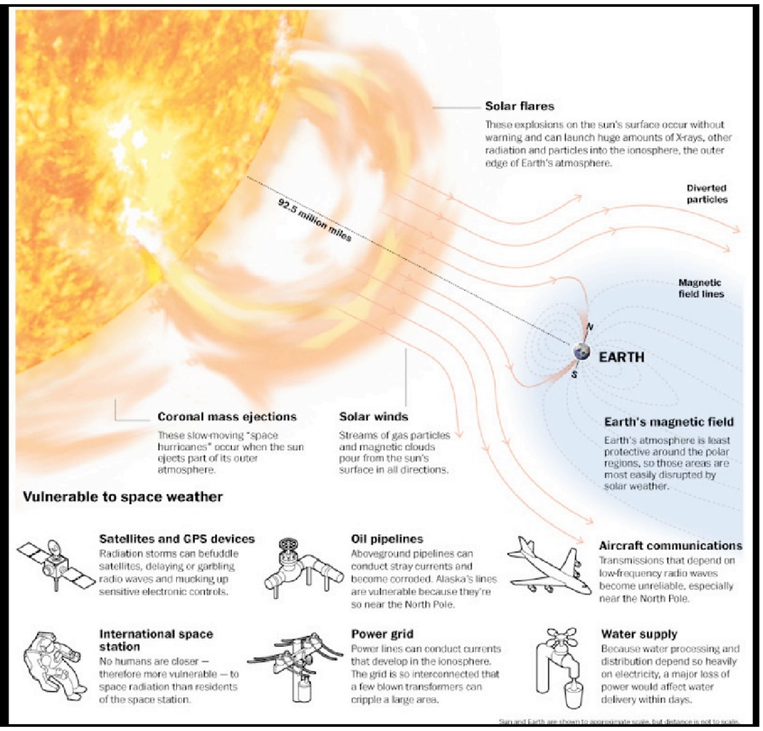
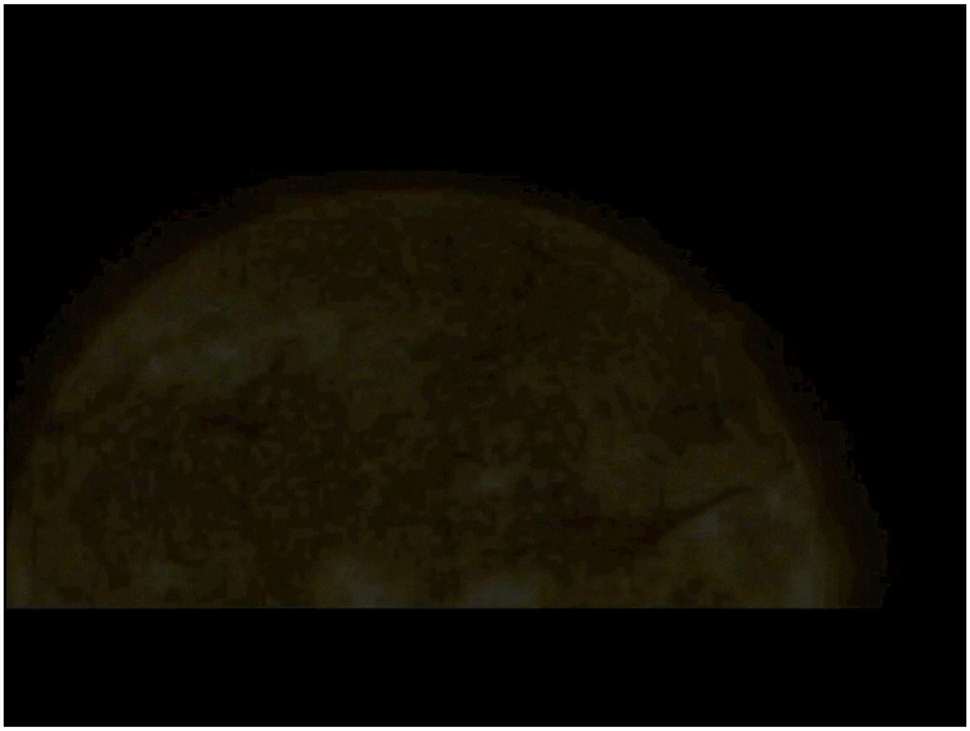
Space Weather in Ionosphere and Thermosphere

Yihua Zheng

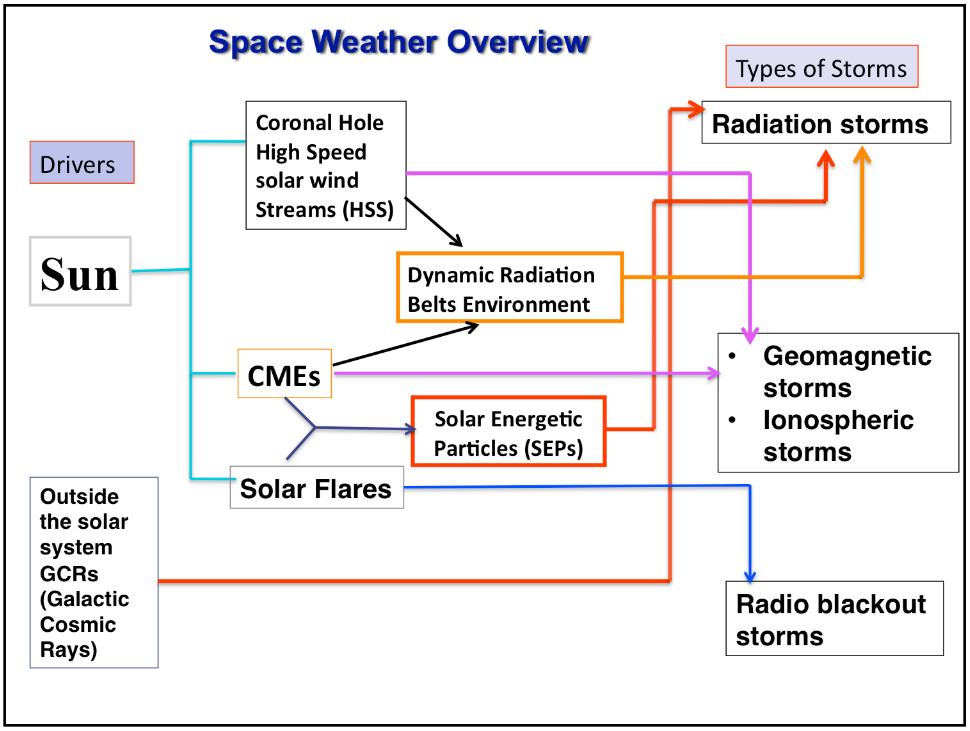
SW REDI 2016 SSMO

Space Weather Illustrated



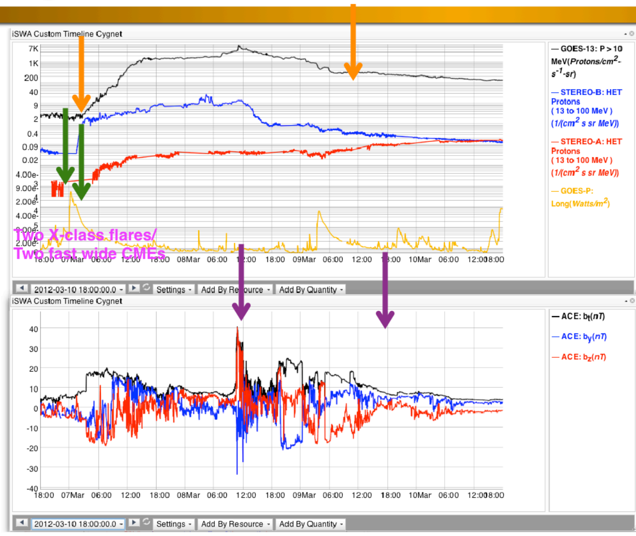


Space Weather in a nutshell


Space Weather Overview
Types of Storms
Drivers
Sun
Coronal Hole High Speed solar wind Streams (HSS)
Dynamic Radiation Belts Environment
CMEs
Solar Energetic Particles (SEPs)
Solar Flares
Outside the solar system GCRs (Galactic Cosmic Rays)
Radiation storms
Geomagnetic storms
Ionospheric storms
Radio blackout storms

Space Weather Effects and Timeline

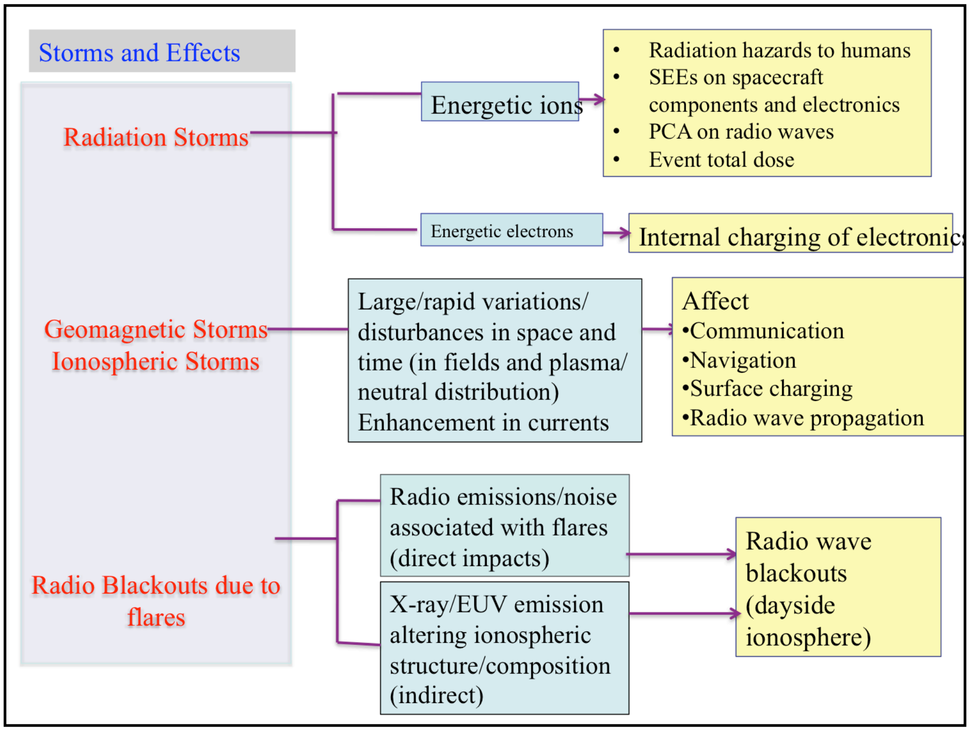
(Flare and CME)



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

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

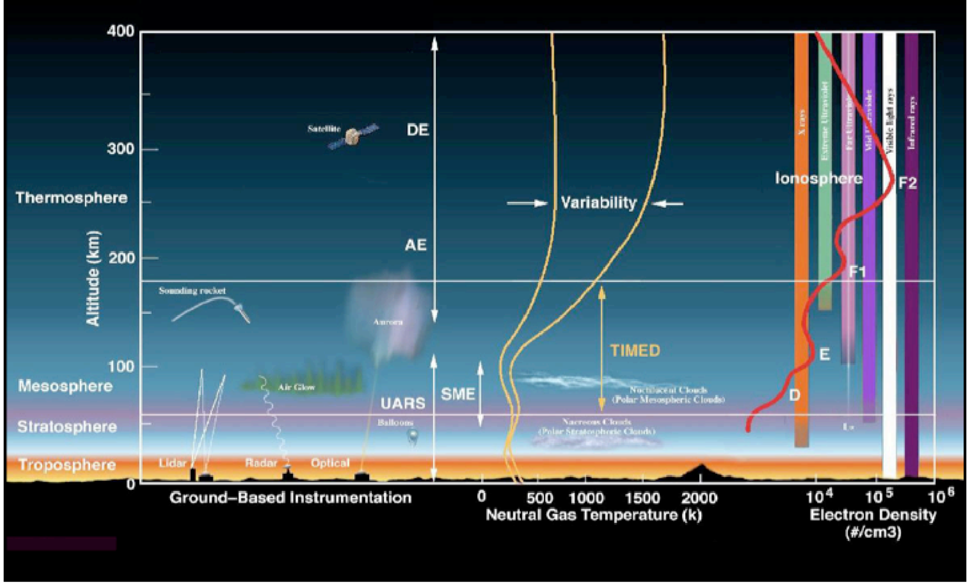
CME effects arrives @ Earth: 1-2 days (35 hours here)
Geomagnetic storms: a couple of days



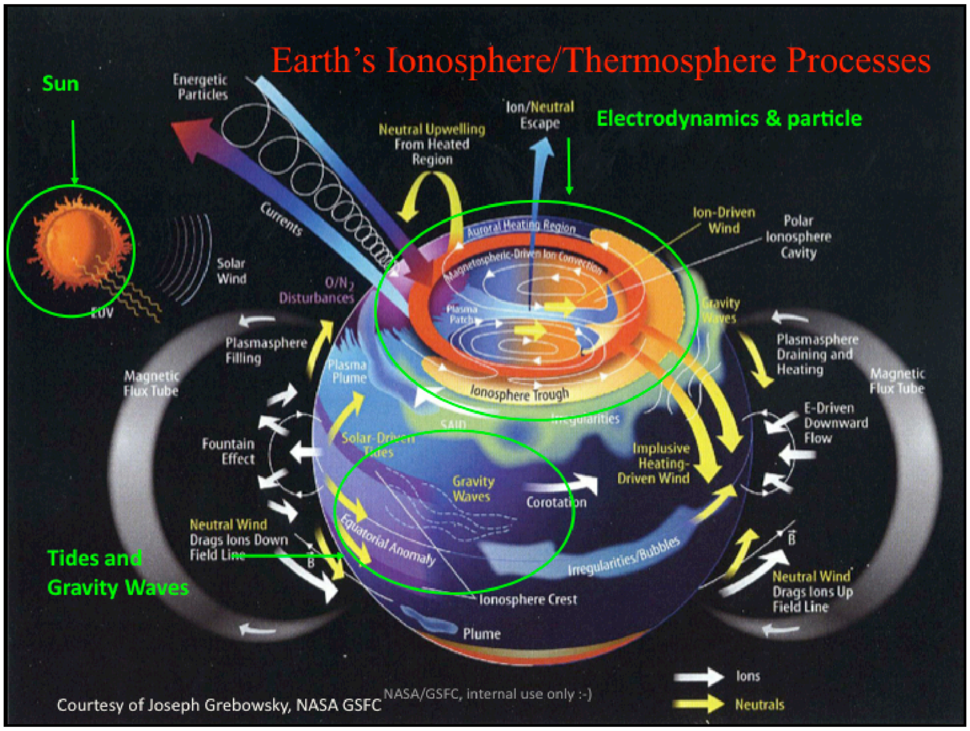
Storms and Effects
Radiation Storms
Energetic ions
Radiation hazards to humans
SEEs on spacecraft components and electronics
PCA on radio waves
Event total dose
Energetic electrons
Internal charging of electronic
Geomagnetic Storms
Ionospheric Storms
Large/rapid variations/ disturbances in space and time (in fields and plasma/ neutral distribution)
Enhancement in currents
Affect
•Communication
•Navigation
•Surface charging
•Radio wave propagation
Radio Blackouts due to flares
Radio emissions/noise associated with flares (direct impacts)
X-ray/EUV emission altering ionospheric structure/composition (indirect)
Radio wave blackouts (dayside ionosphere)

Ionospheric Dynamics/Storms

Ionosphere - Thermosphere Overview



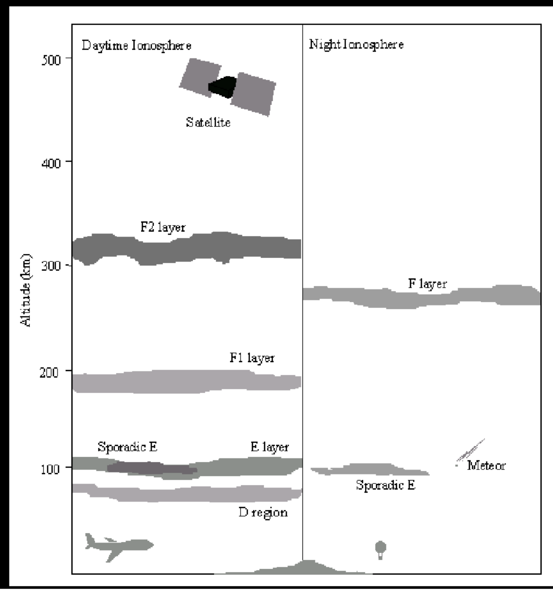
The ionosphere is a highly variable and complex physical system. It is produced by ionizing radiation from the sun and controlled by chemical interactions and transport by diffusion and neutral wind.

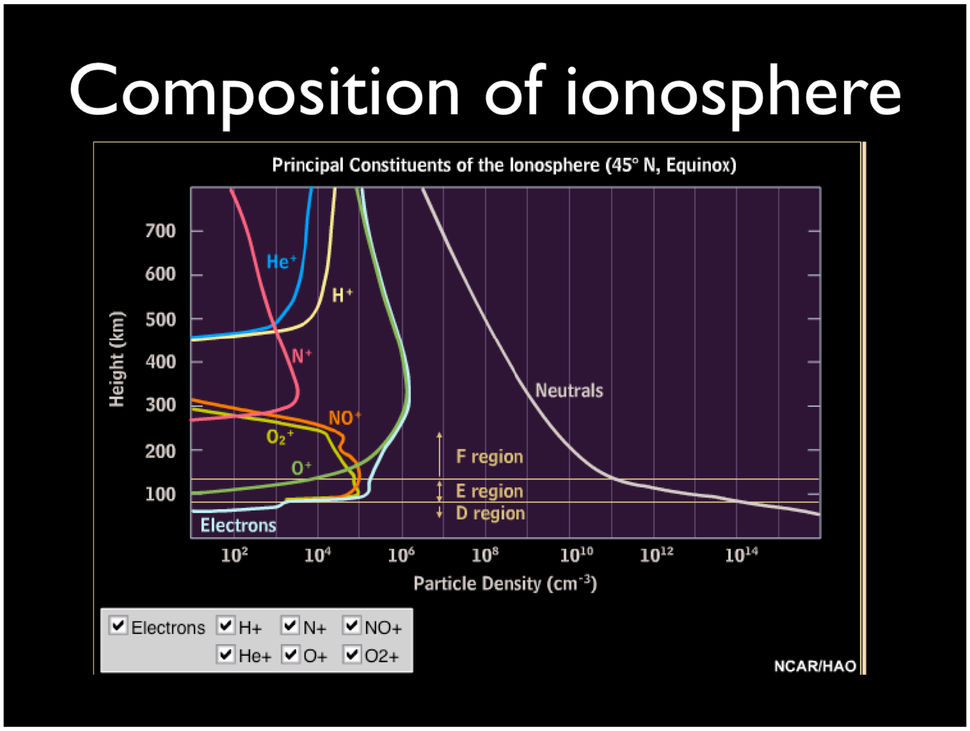

Earth's Ionosphere/Thermosphere Processes
Sun
Energetic Particles
Ion/Neutral Escape
Electrodynamics & particle
Neutral Upwelling From Heated Region
Currents
Solar Wind
EUV
O/N2 Disturbances
Auroral Heating Region
Magnetospheric-Driven Ion Convection
Plasma Patch
Ion-Driven Wind
Polar Ionosphere Cavity
Gravity Waves
Plasmasphere Filling
Plasmasphere Draining and Heating
Magnetic Flux Tube
Magnetic Flux Tube
Plasma Plume
Ionosphere Trough
SAID
Irregularities
E-Driven Downward Flow
Fountain Effect
Solar-Driven Tides
Implusive Heating-Driven Wind
Gravity Waves
Corotation
Neutral Wind Drags Ions Down Field Line
Equatorial Anomaly
Irregularities/Bubbles
Tides and Gravity Waves
Ionosphere Crest
Neutral Wind Drags Ions Up Field Line
Plume
Ions
Neutrals
Courtesy of Joseph Grebowsky, NASA GSFC
NASA/GSFC, internal use only :-)

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.





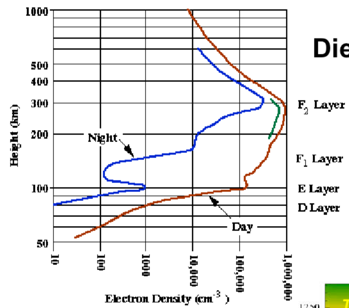
seven important constituents of the ionosphere - ionized forms of six gases plus free electrons - still more neutral

The various regions of the ionosphere have higher concentrations of charged particles (ions) than do other parts of the thermosphere, which consists mostly of electrically neutral atoms and molecules

Ionosphere 101

Formed by solar EUV/UV radiation

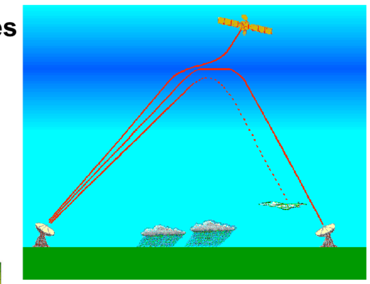
Reflects, refracts, diffracts & scatters radio waves, depending on frequency, density, and gradients



Dielectric Properties

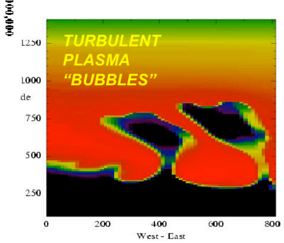
$$\varepsilon = \left(1 - \frac{f_p^2}{f^2}\right)\varepsilon_o$$

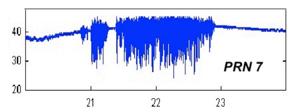
$$f_p \approx 9 \cdot 10^3 \sqrt{n_e}$$



Leads to highly variable reflection / refraction = "SCINTILLATION"

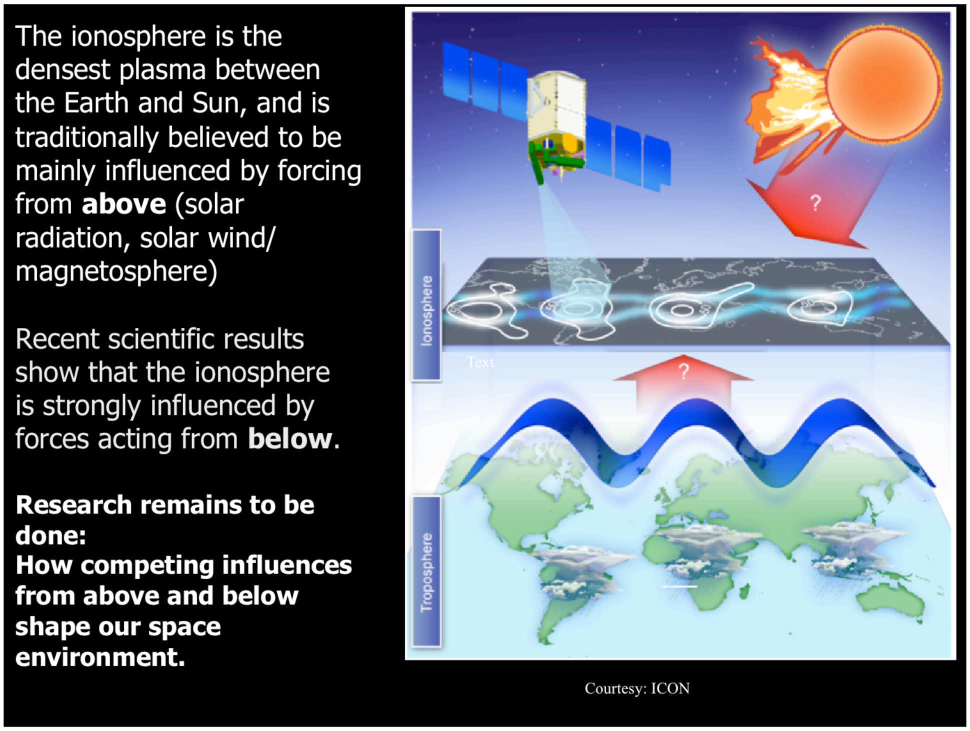
Subject to Raleigh-Taylor instability at night →formation of Equatorial Plasma Bubbles (EPBs)





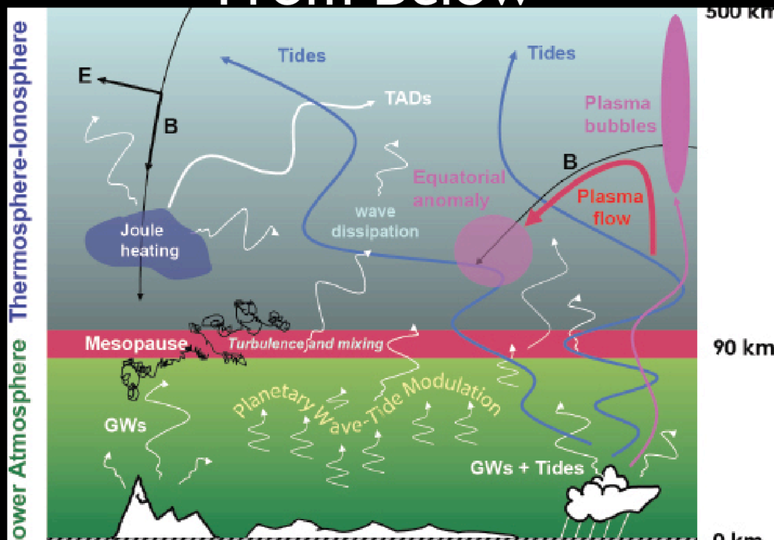
Scintillated GPS Signal

Courtesy: de la beaujardiere



A nice summary of our current understanding

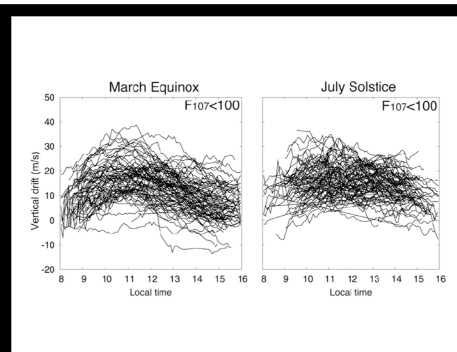
From Below

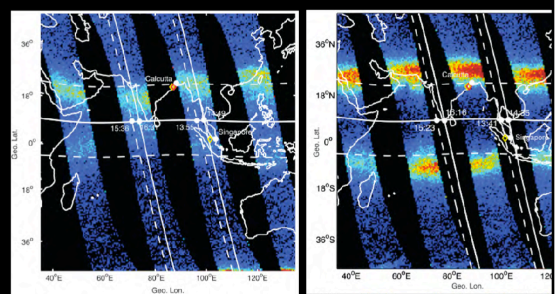


Various mechanisms through which lower-atmosphere processes influence the ionosphere and thermosphere (Courtesy of Jeffrey M. Forbes, Univ. Colorado

The daytime ionosphere exhibits significant variability in its motion and density.
the source of these changes: unknown

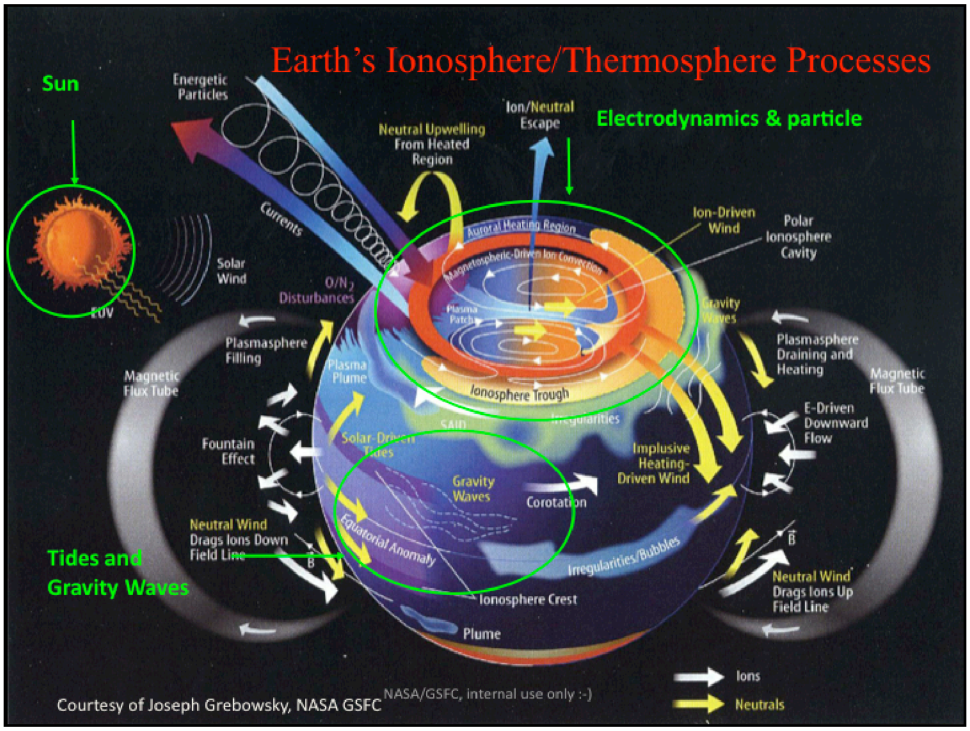
likely originates with modulation of
neutral and/or ionized state variables along the magnetic field - need to be determined





coupled ion-neutral dynamics

critical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Neutrals
Courtesy of Joseph Grebowsky, NASA GSFC
NASA/GSFC, internal use only :-)

Space Weather Phenomena and Effects in the Ionosphere

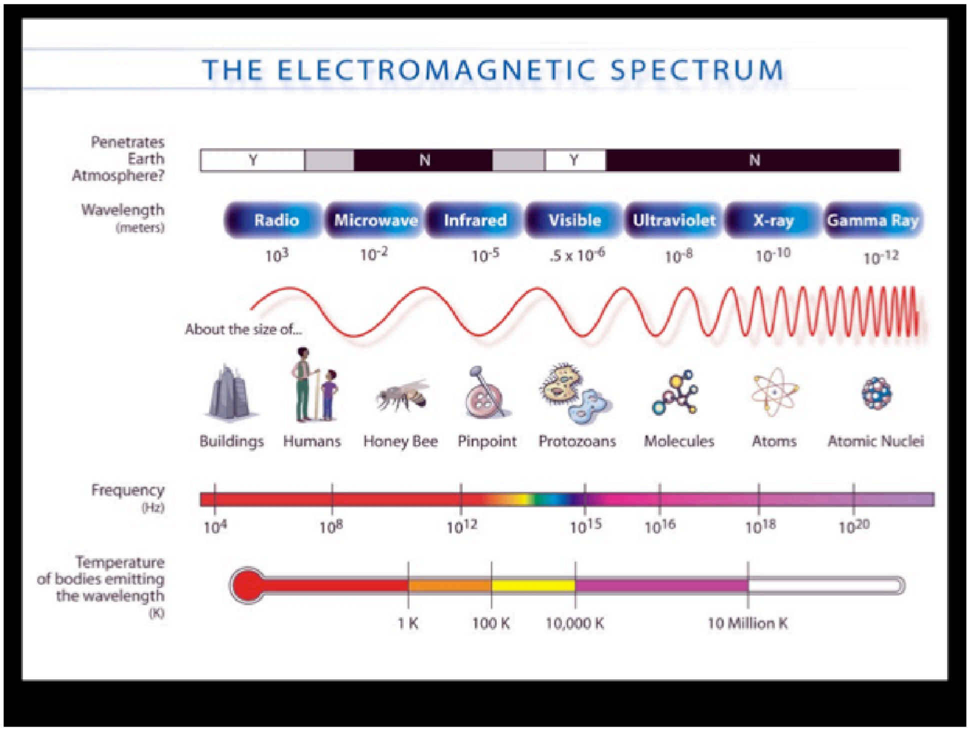
Aurora – hemispheric power (satellite charging, scintillation)
Satellite drag due to neutrals
Equatorial bubbles/irregularities –scintillation, communication problems
Radio blackout -- solar flare

Polar Cap Absorption - solar energetic particles

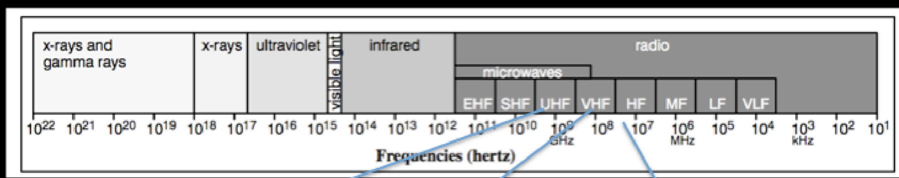
Products demo

Auroral power
Auroral oval
TEC map
CTIPe products
HF absorption map

Scintillation index S4


THE ELECTROMAGNETIC SPECTRUM
Penetrates Earth Atmosphere?
Y
N
Y
N
Wavelength (meters)
Radio
Microwave
Infrared
Visible
Ultraviolet
X-ray
Gamma Ray
10^3
10^{-2}
10^{-5}
$.5 \times 10^{-6}$
10^{-8}
10^{-10}
10^{-12}
About the size of...
Buildings
Humans
Honey Bee
Pinpoint
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^4
10^8
10^{12}
10^{15}
10^{16}
10^{18}
10^{20}
Temperature of bodies emitting the wavelength (K)
1 K
100 K
10,000 K
10 Million K

Types of space weather events affecting nav and commu



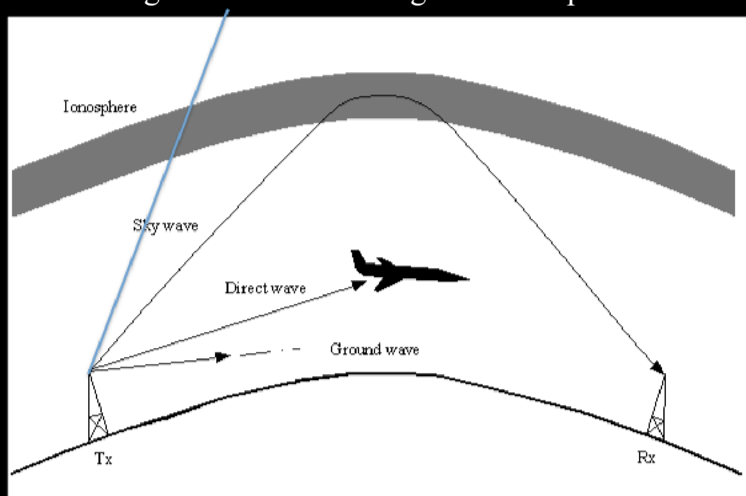
UHF – GPS
- Energetic protons/ particles – via SEEs - affecting GPS satellites components
- Geomagnetic storms/ ionospheric storm - cause scintillations

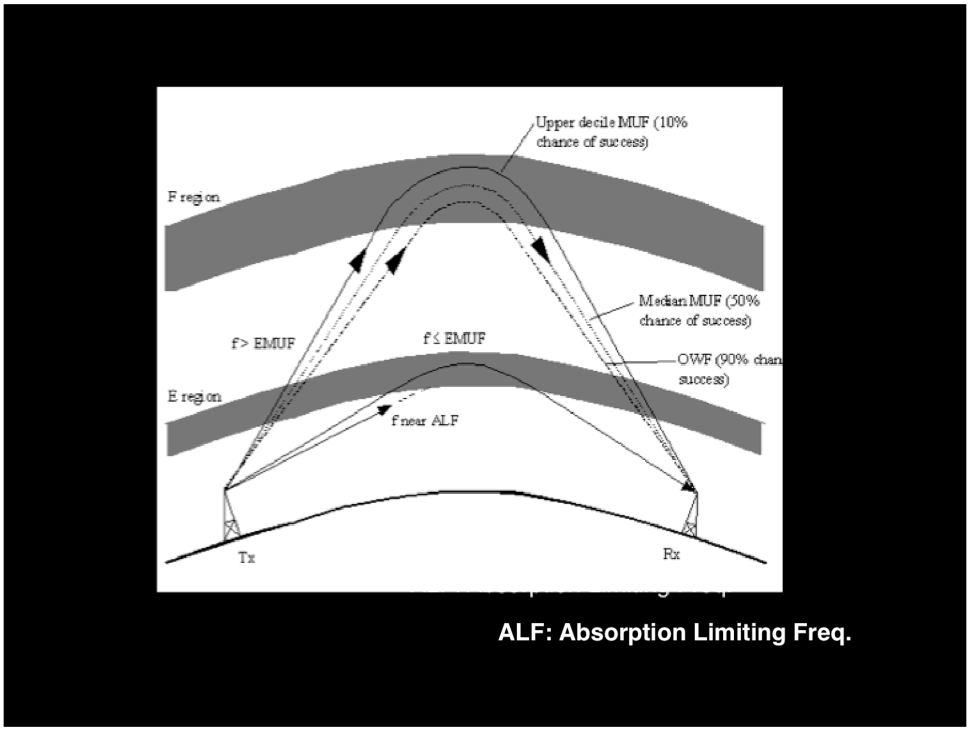
VHF:
- Energetic protons - PCA
- Geomagnetic storms
- Solar radio emission associated with flare/CME

HF:
- Solar flares/x-ray
- Energetic protons - PCA
- Geomagnetic activities

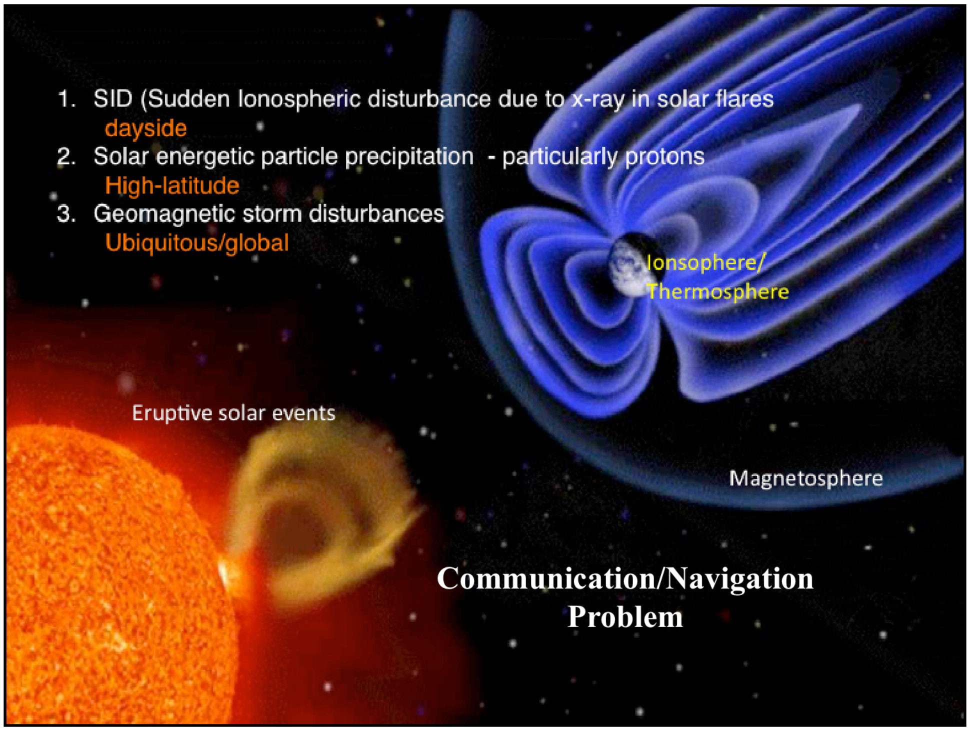
Signals of different types with different purposes

GPS signal: Penetrate through the ionosphere





maximum usable frequency (MUF)


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
Ionsophere/
Thermosphere
Eruptive solar events
Magnetosphere
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

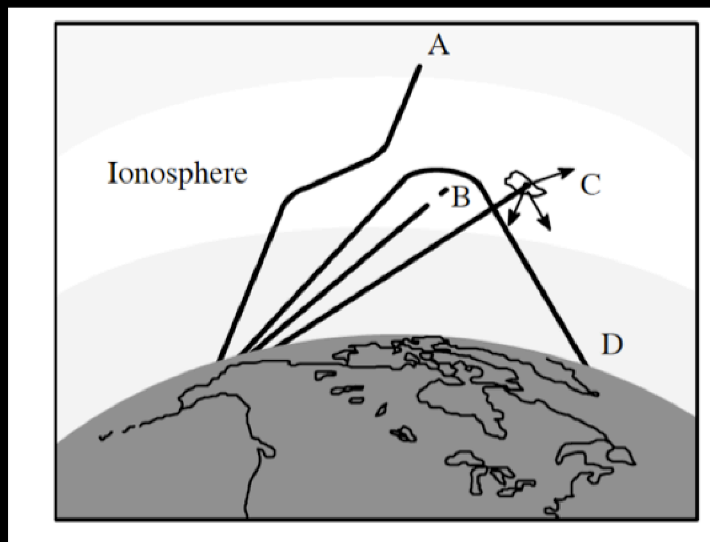
Solar radio bursts can directly affect GPS operation

- 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

Cerruti, A. P., P. M. Kintner Jr., D. E. Gary, A. J. Mannucci, R. F. Meyer, P. Doherty, and A. J. Coster (2008), Effect of intense December 2006 solar radio bursts on GPS receivers, *Space Weather*, 6, S10D07, doi: 10.1029/2007SW000375.

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

Radiation Storms

- 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

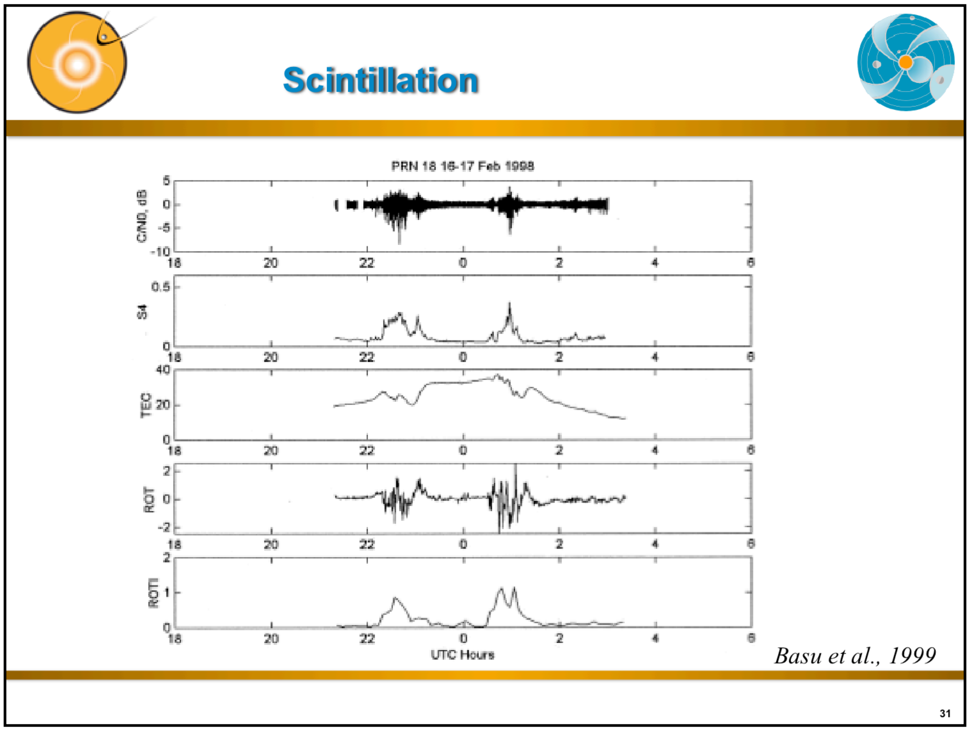
Global impacts

- CME storms
- CIR storms

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.



Radio scintillation is the term used to represent the random fluctuations in signal phase and amplitude that develop when the radio waves propagate through ionospheric electron density irregularities. A measure of the degree of scintillation in the strength of a signal is the quantity S4 [Yeh and Liu, 1982], which describes the root−mean−square fluctuations in signal intensity, normalized by the average signal intensity:

ırregularly structured ionospheric regions can cause diffraction and scattering of trans-ionospheric radio signals. When received at an antenna, these signals present random temporal fluctuations in both amplitude and phase. This is known as ionospheric scintillation.

Severe scintillation of the GPS satellite signals can result in loss of satellite tracking, which degrades GPS positioning accuracy. Even when satellite tracking is maintained, scintillation can cause errors decoding the GPS data messages, cycle slips, and ranging errors.

Scintillation

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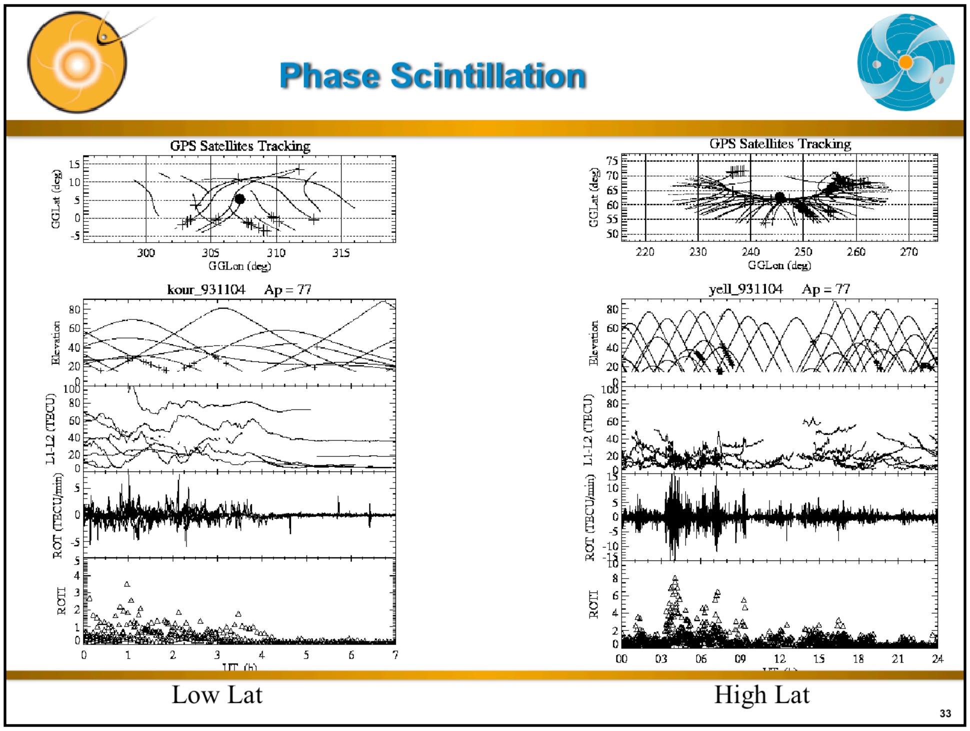


equatorial scintillation can occur even during relatively quiet conditions.

Generally, the region between 250 and 400 km, known as the F-region of the ionosphere, contains the greatest concentration of free electrons. At
times, the F-region of the ionosphere becomes disturbed, and small-scale irregularities develop. When sufficiently intense, these irregularities scatter radio waves and generate
rapid fluctuations (or scintillation) in the amplitude and phase of radio signals. Amplitude scintillation, or short-term fading, can be so severe that signal levels drop below a GPS
receiver's lock threshold, requiring the receiver to attempt reacquisition of the satellite signal. Phase scintillation, characterized by rapid carrier-phase changes, can produce
cycle slips and sometimes challenge a receiver's ability to hold lock on a signal.

Scintillation activity is most severe and frequent in and around

Ionospheric Scintillation Indices

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

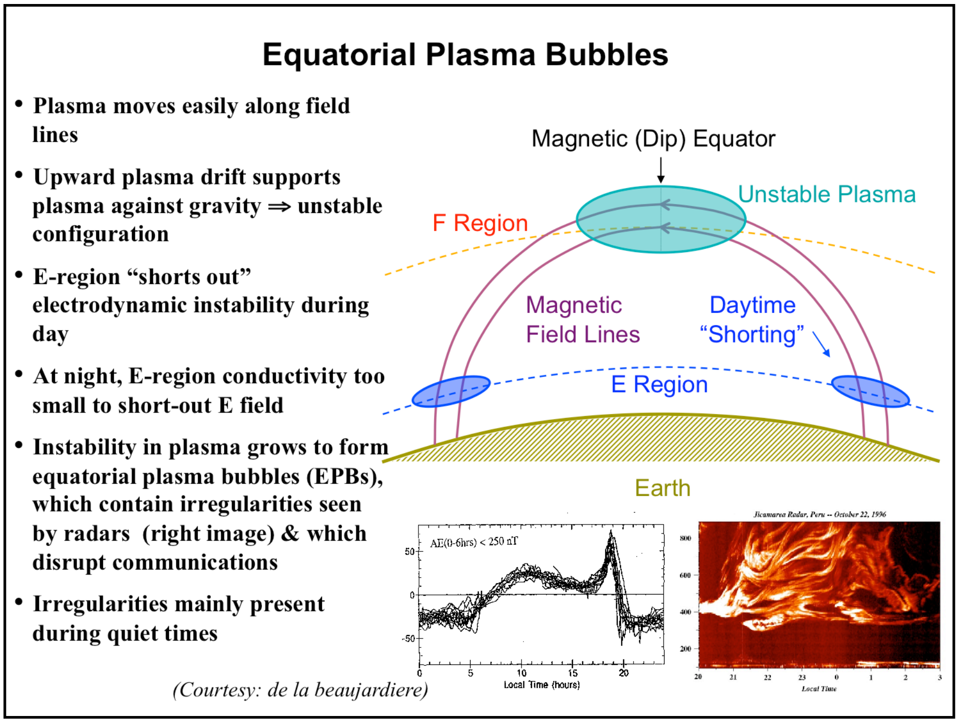
$$\sigma_\phi(f) = \sqrt{\langle \phi^2\rangle - \langle \phi\rangle^2} \propto f^{-1}$$

$$\mathrm{ROTI} = \sqrt{\langle \mathrm{ROT}^2\rangle - \langle \mathrm{ROT}\rangle^2}$$

$$\mathrm{ROT} = C\,\frac{\Phi_I(t+\Delta t) - \Phi_I(t)}{\Delta t}$$

- **S_4 and σ_ϕ indices – amplitude and phase scintillation, respectively**
  - I – detrended signal intensity
  - ϕ – 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
- **ROTI – 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



More prevalent at night - daytime EPB has also been observed.

Plasma bubbles are, in general, a nighttime phenomenon in the equatorial ionosphere [Woodman and La Hoz , 1976; Fejer and Kelley , 1980; Kelley , 1989]. The vertical plasma drift in the equatorial F region is upward during daytime and often shows an enhancement after sunset before it turns downward [Fejer et al ., 1991, 2008]. This prereversal enhancement in the vertical plasma drift moves the F region to higher altitudes and increases the growth rate of the Rayleigh-Taylor instability. 2010].

Ionosphere Irregularities

- 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.

Journal of Atmospheric and Solar-Terrestrial Physics Volume 61, Issue 16, 1 November 1999, Pages 1219-1226

March 3, 2010 – equatorial bubble is likely the cause of scintillation effects that affected military operations.

Scintillation activity was greatest during the equinoxes and solar maximum, although scintillation at Antofagasta, Chile was higher during 1998 rather than at solar maximum. Steenburgh et al., Space Weather, 2008

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.

New generation model: Moving to JBH09 (2009) atmospheric density model

Uses solar data from SET web sites

Includes 11 indices F10, S10, M10, Y10, F10-bar, S10-bar, M10-bar, Y10-bar, ap, Dst, Dtc

Satellite Drag

- Atmospheric drag magnitude:

$$a_{drag} = \frac{1}{2}\beta\rho v^2$$

$\beta = \frac{c_D A}{m}$ **is ballistic coefficient**

ρ is atmospheric density

$$v \cong v_{sat}$$

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

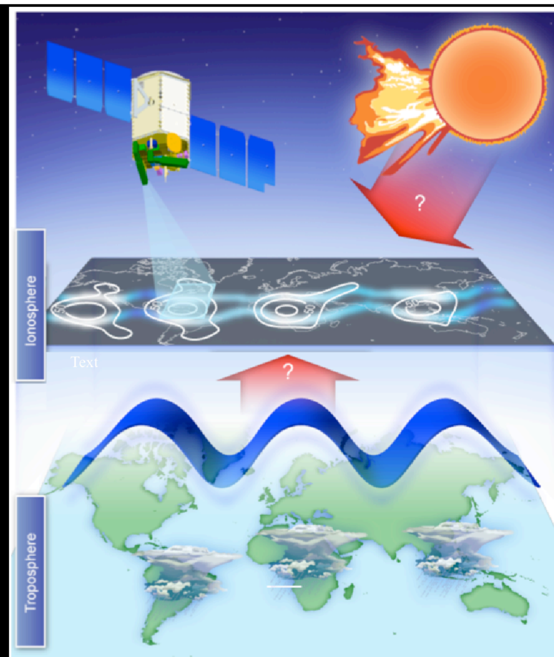
Uncertainty in predicted atmospheric drag impacts:

Future satellite position predictions

The ionosphere is the densest plasma between the Earth and Sun, and is traditionally believed to be mainly influenced by forcing from **above** (solar radiation, solar wind/ magnetosphere)

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.



Courtesy: ICON

A nice summary of our current understanding

iSWA layout for ionosphere products

http://bit.ly/iono_layout