

Space Weather in the Ionosphere and Thermosphere

Chigomezyo Ngwira

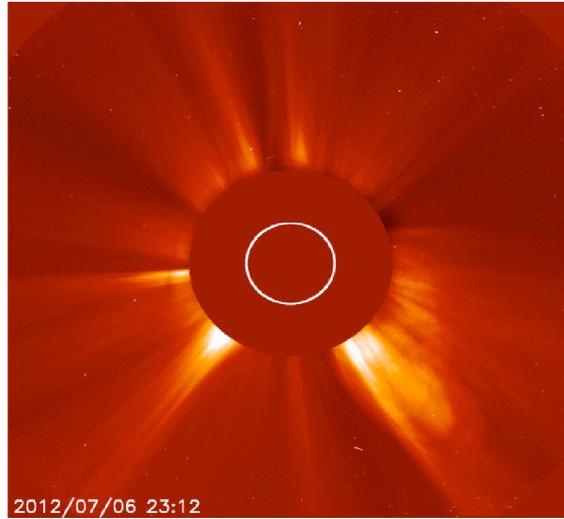
For SW REDI 2016

Content

- Introduction to the Ionosphere and Thermosphere
- Space weather Impacts on the Ionosphere and Thermosphere



Space Weather



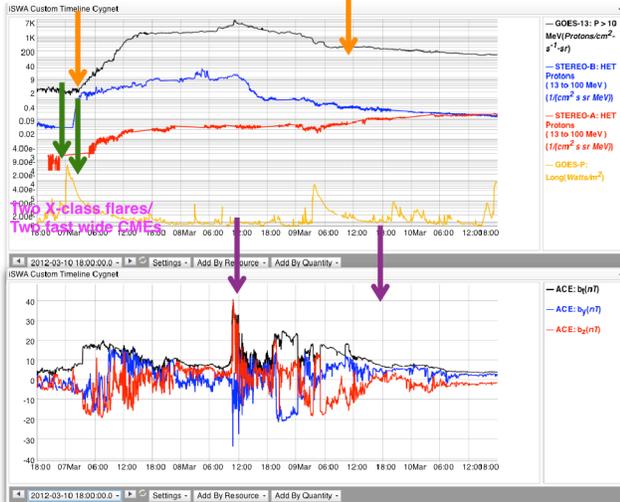
2012/07/06 23:12



Space Weather Effects and Timeline



(Flare and CME)

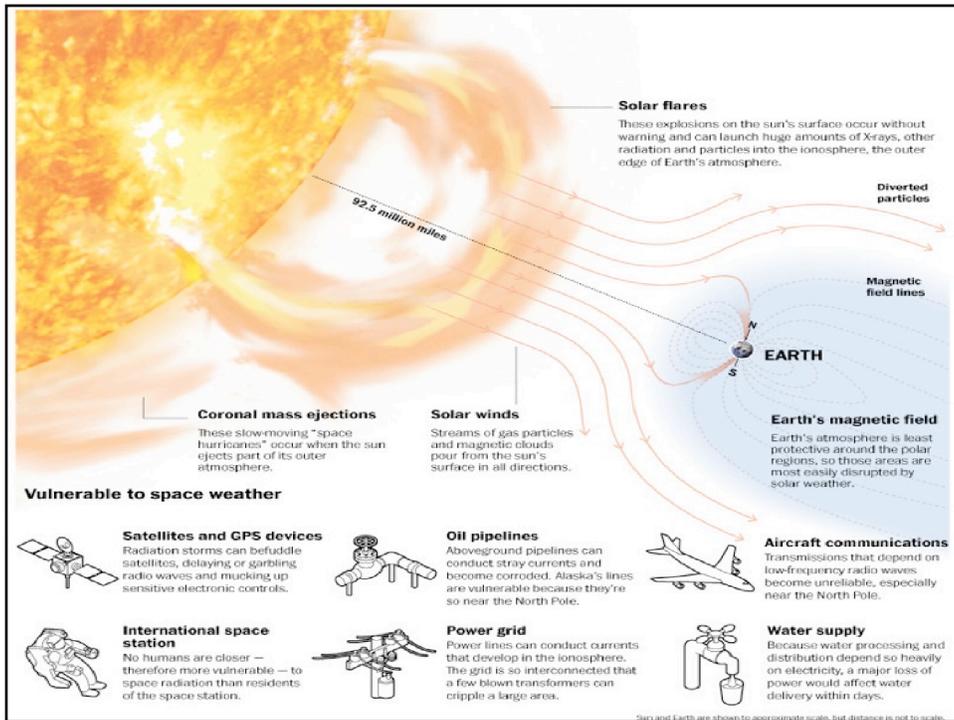


Flare effects at Earth:
 ~ 8 minutes (radio blackout storms)
 Duration: minutes to hours

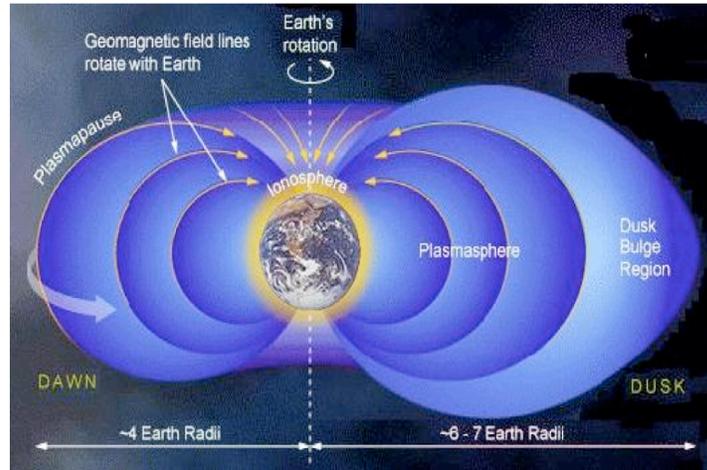
SEP radiation effects reaching Earth: 20 minutes – 1 hour after the event onset
 Duration: a few days

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

CME speed: 300 – 3500 km/s
 SEPs: fraction of c
 Light speed c: 3×10^8 km/s



Earth's Atmosphere



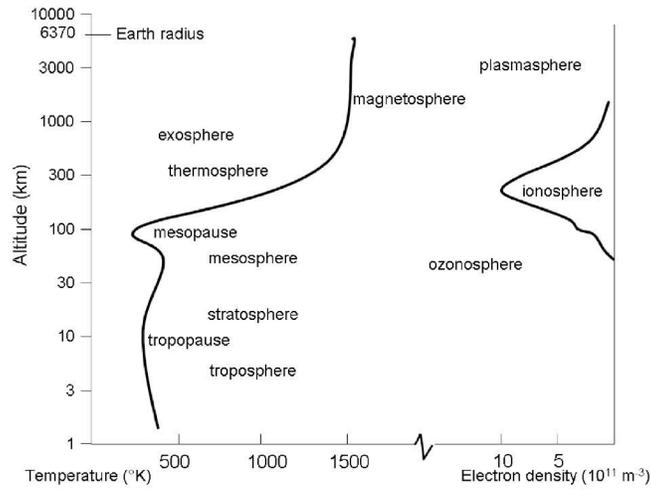
Mysteries of Sun movie

http://missionscience.nasa.gov/sun/sunVideo_05itm.html

Ionosphere

- The Earth's atmosphere is a layer of gases that surrounds the planet Earth and is retained by the Earth's gravity.
- The atmosphere absorbs ultraviolet radiation from the Sun, thereby protecting life on Earth.
- There is no definite end to the atmosphere, and no absolute boundary between the atmosphere and outer space.
- The ionosphere is the densest plasma region in the Earth's atmosphere generated by ionization from incoming solar radiation.
- The ionosphere contains some of the most complex chemical processes in the atmosphere, which makes for interesting, useful and exciting science.

Regions of atmosphere in terms of temperature and density

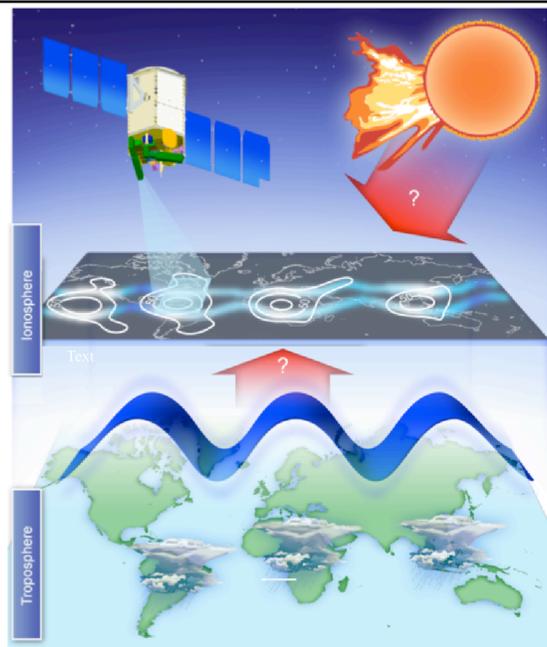


Courtesy of Lee-Anne McKinnell

The ionosphere is traditionally believed to be mainly influenced by forcing from **above** (solar radiation, solar wind/ magnetosphere)

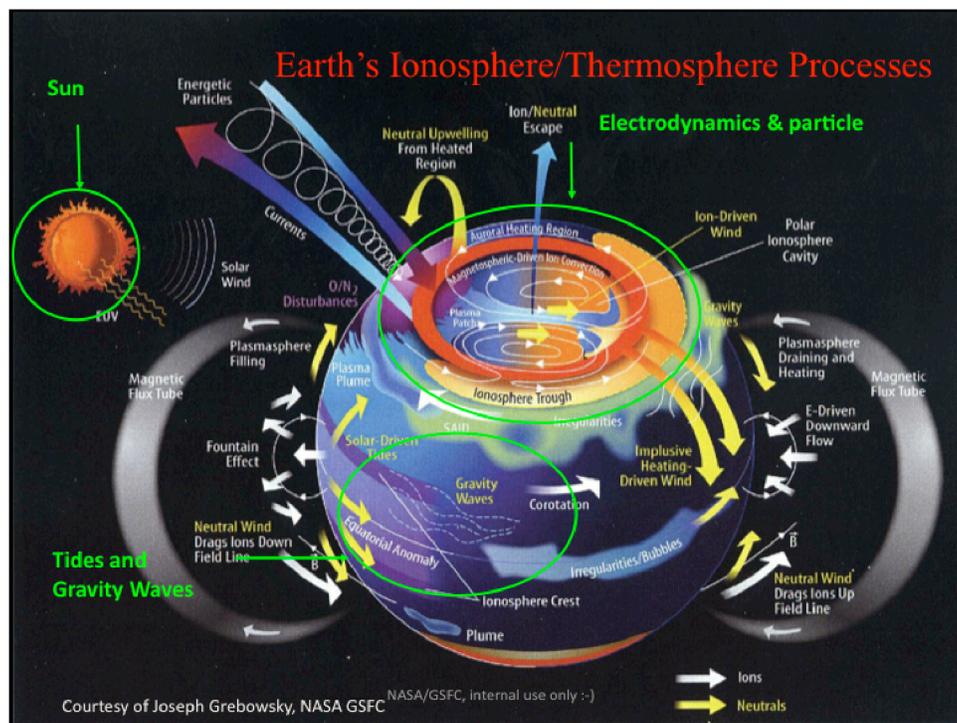
Recent scientific results show that the ionosphere is strongly influenced by forces acting from **below**.

**Research remains to be done:
How competing influences from above and below shape our space environment.**



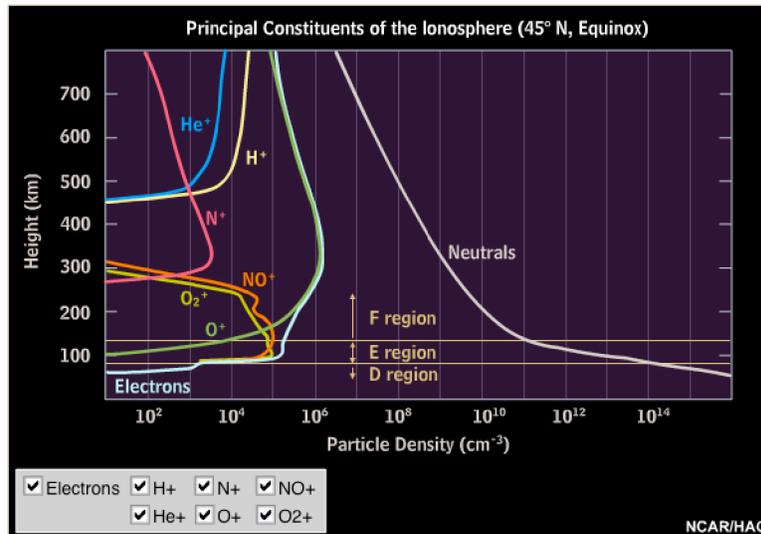
– A nice summary of our current understanding.

- The ionosphere is a highly variable, non-linear medium, which responds to changes in various geophysical parameters at different timescales



Various processes having different effects on the ionospheric density.

Composition of ionosphere

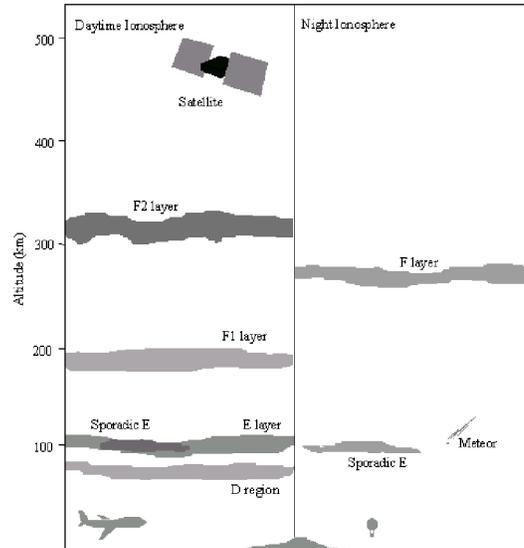


Day/night ionospheric structure

- Ionosphere is formed by solar EUV/UV radiation.

- 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.



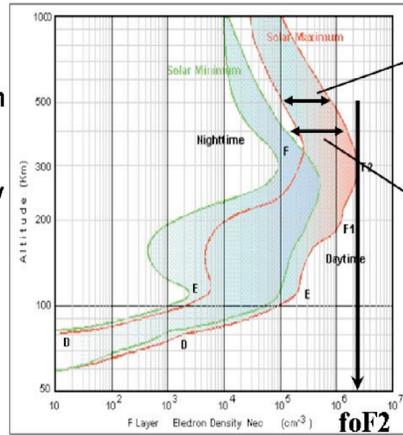
The ionosphere is variable

(highly non-linear and changing medium)

Seasonal variation
(1yr)

Magnetic activity
variation

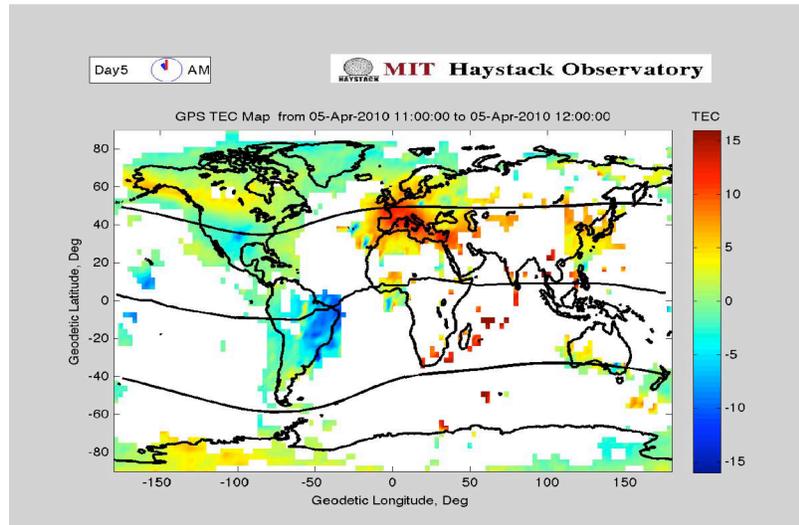
Latitude
dependence



Diurnal variation
(24 hrs)

Solar activity
variation
(22 yrs)

Global ionospheric density distribution



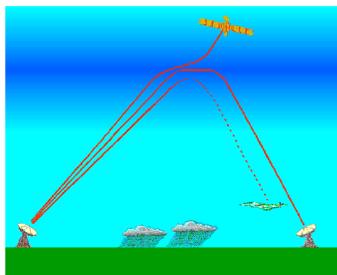
Ngwira et al., (AGU Books, 2015)

Ionospheric propagation

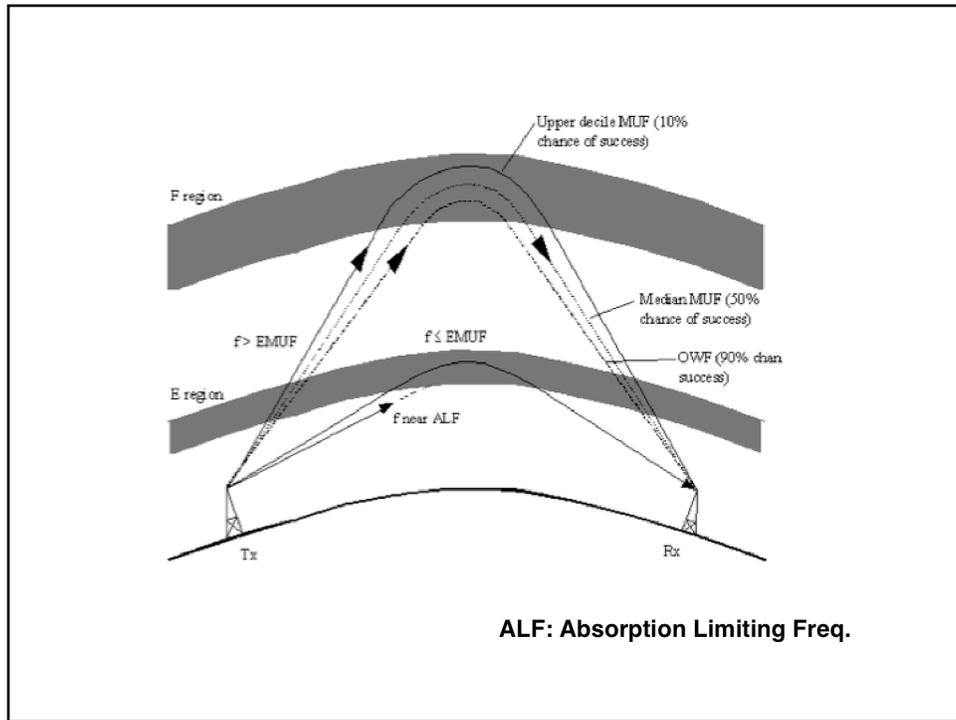
Reflects, refracts, diffracts & scatters
radio waves, depending on
frequency, density, and gradients

Plasma frequency

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



Leads to highly variable
reflection / refraction =
"SCINTILLATION"



maximum usable frequency (MUF)

Questions???

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

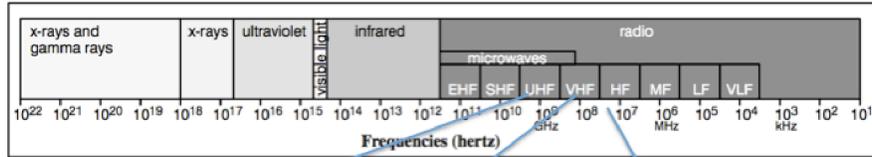
HF absorption map

Scintillation index S4

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



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

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.



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 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.

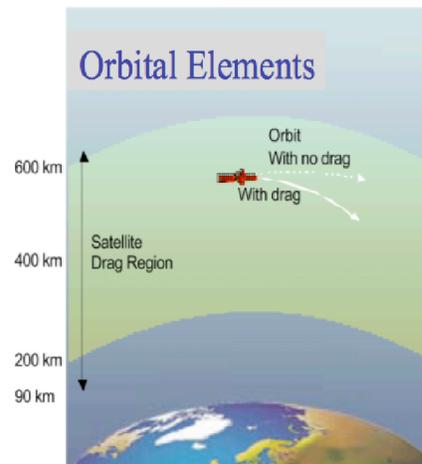
Why do we care about the thermosphere?



Spacecraft Drag



- One of the major concerns for satellites in space is orbital decay.
- Orbital decay can be caused by mechanical, gravitational and electromagnetic effects.
- Spacecraft in LEO experience periods of increased atmospheric 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.



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- **The orbital decay can be caused by a multitude of mechanical, gravitational, and electromagnetic effects. For bodies in a low Earth orbit, the most significant effect is the atmospheric drag.**
- **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**

Spacecraft Drag

- Most drag models use radio flux at 10.7 cm wavelength as a proxy for solar UV flux. K_p 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 $K_p \geq 6$ result in detectably increased drag on LEO spacecraft.
- Very high UV/10.7 cm flux and K_p 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: $a_{drag} = \frac{1}{2}\beta\rho v^2$
 $\beta = \frac{c_D A}{m}$ is ballistic coefficient, ρ is atmospheric density and
 $v \cong v_{sat}$ is the spacecraft velocity

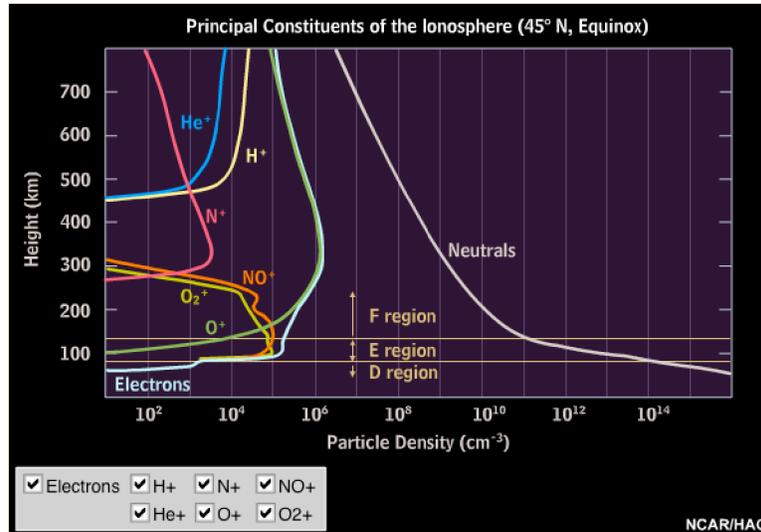
- Solar cycle and space weather have strong impact on neutral atmospheric density
- Increasing atmospheric drag impacts:
Frequency of “Drag Make-Up” maneuvers for satellite to stay in control box
- Uncertainty in predicted atmospheric drag impacts:
Future satellite position predictions

Quick Quiz??

You have two spacecraft: (1) at 800 km altitude and (2) at 300 km altitude.

Which spacecraft is most impacted by satellite drag and why?

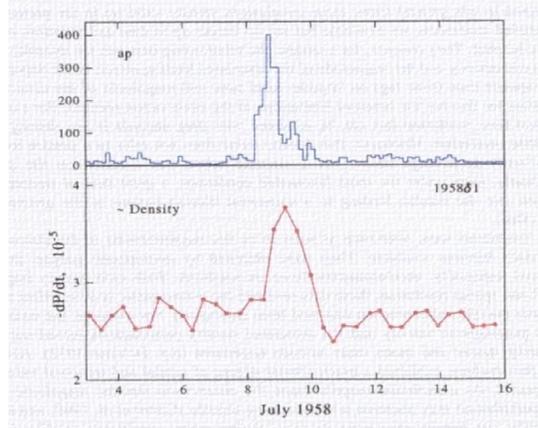
Composition of Ionosphere



Neutral Density and Satellite Drag: 1st observations

Extreme
Geomagnetic
Activity Indicated
by Auroral
Currents

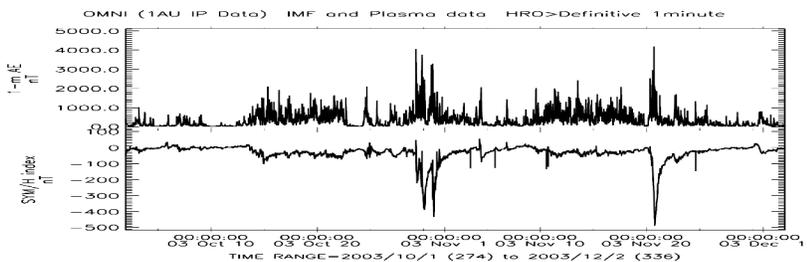
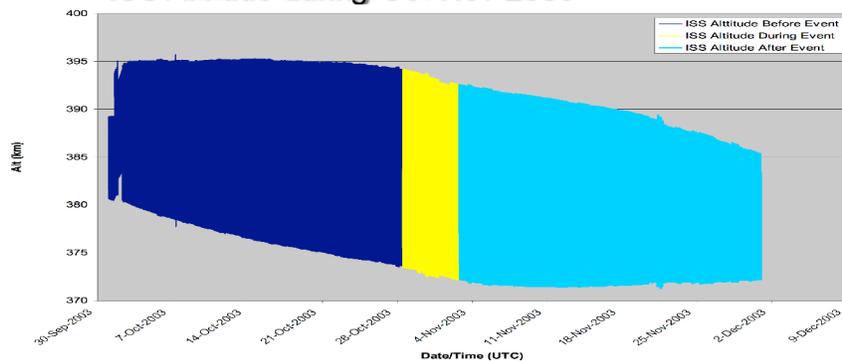
Rate of Orbital
Period Change



Sputnik Orbital Period Variation vs Day of July 1958

From Prolss (2011) after data from Jacchia 1959

ISS Altitude during Oct-Nov 2003



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.

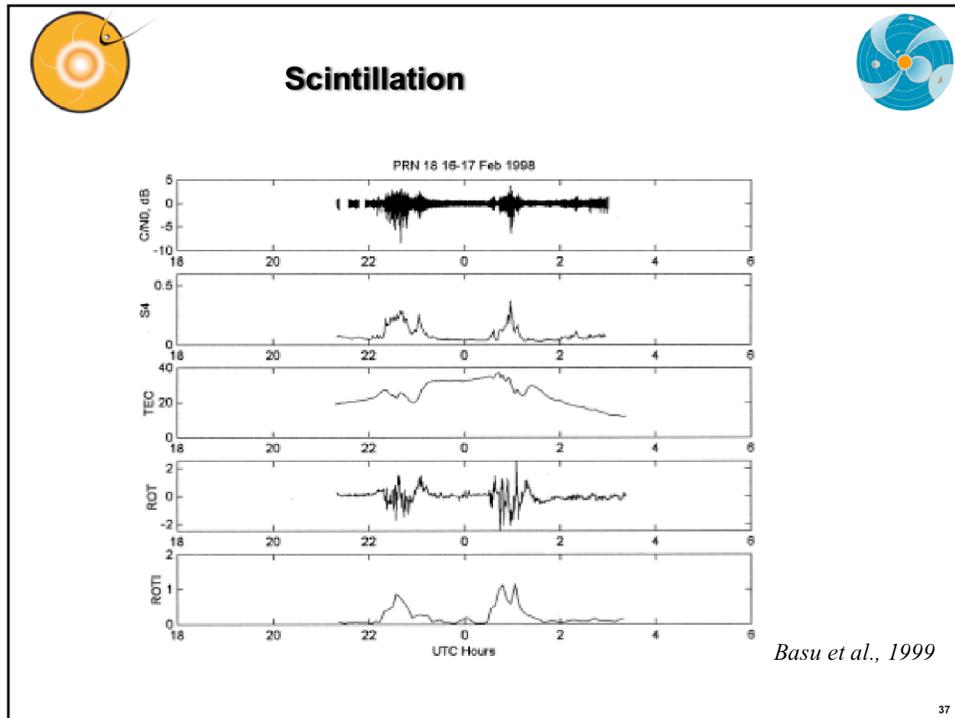
Journal of Atmospheric and Solar-Terrestrial Physics Volume 61, Issue 16,
1 November 1999, Pages 1219-1226

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

Ionospheric Scintillation

- 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 S_4 [Yeh and Liu, 1982], which describes the root-mean-square fluctuations in signal intensity, normalized by the average signal intensity:
- Irregularly 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.

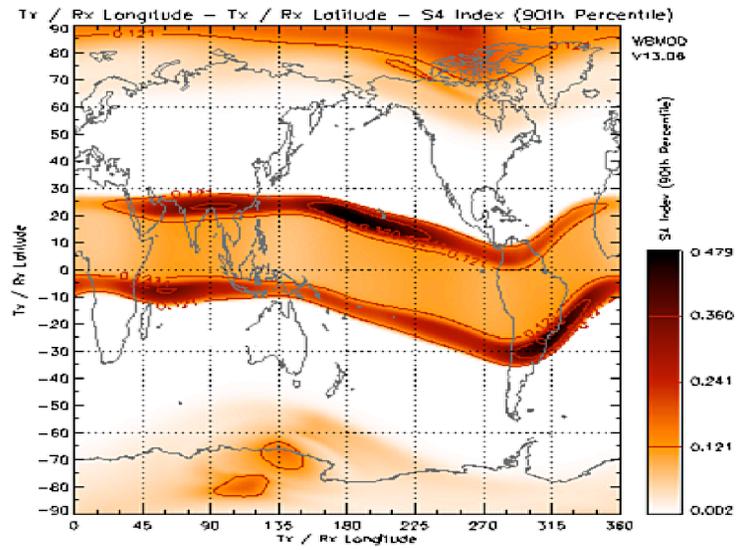


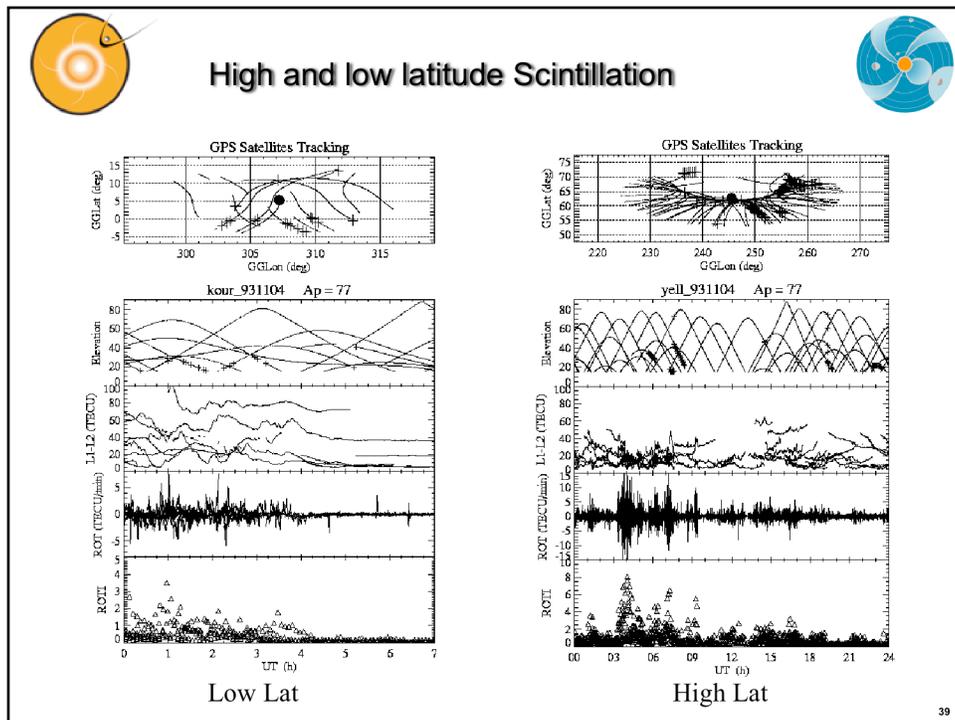
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Global Scintillation Distribution





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



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

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

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

$$\text{ROT} = c \frac{\Phi_I(t + \Delta t) - \Phi_I(t)}{\Delta t}$$

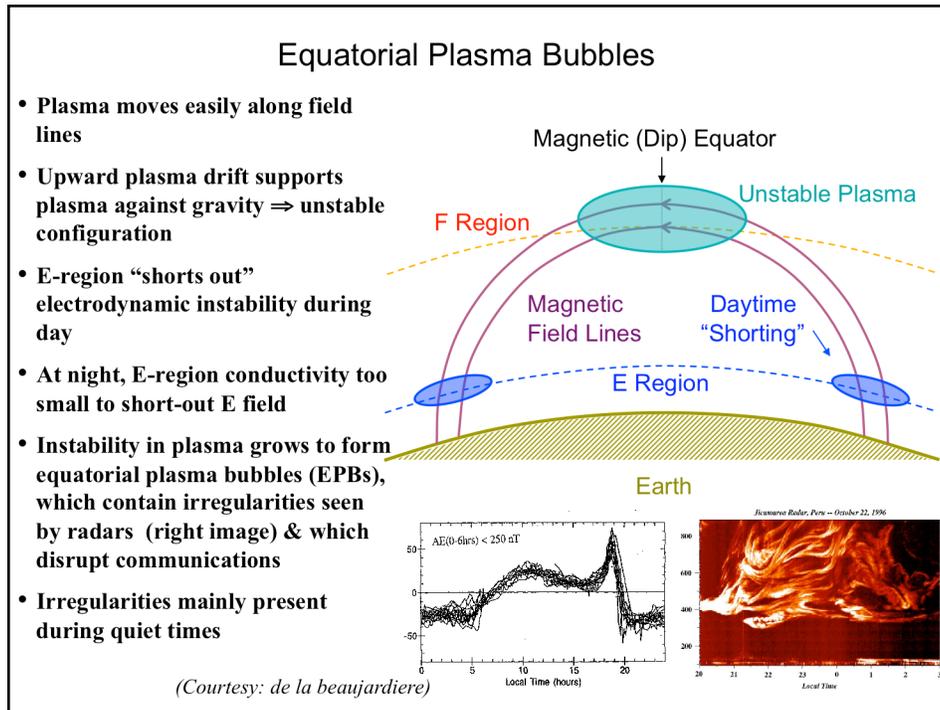
Courtesy: Pi at JPL

- **S₄ 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

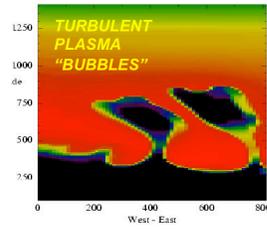


More prevalent at night - daytime EPB has also been observed.

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].

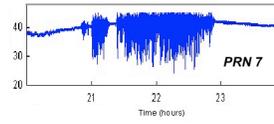
Plasma Bubbles

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



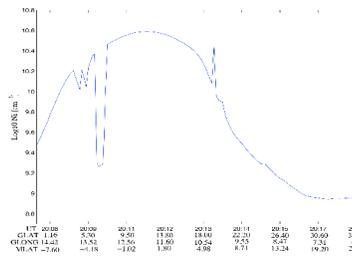
Courtesy: de la beaujardiere

Leads to highly variable
 reflection / refraction =
 "SCINTILLATION"



Scintillated GPS Signal

DMSP satellite
 Plasma density
 measurements



Ngwira et al., (JASTP, 2013)

iSWA layout for ionosphere products

http://bit.ly/iono_layout