Amateur Radio and Space Weather

What is space weather? Why do I care?

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Acknowledgments

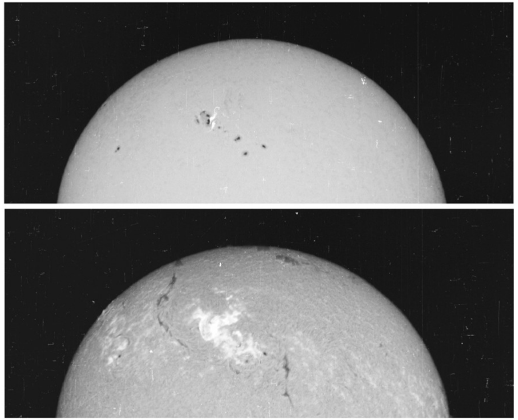
- Solar activity of September 06-08 2017: Patricia Doherty, BU; Mihail Codrescu, George Millward SWPC
- Delores Knipp, CU Boulder

Outline

- Hour 1 – Why
- Hour 2 – 3 The rest of the story
  - Ionosphere Structure
  - Short Wave Fade
  - D-region, Auroral Absorption
  - Maximum Usable Frequency depression

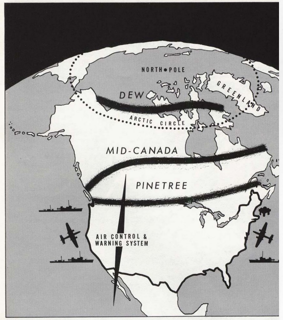
232	N24	5/18	East limb passage of one of the greatest activity complexes of Solar Cycle 20. Composed of three overlapped spot groups at time of first appearance, two of which were growing.
		5/20	Birth of fourth spot group on southern border of complex. Westward relative motion of this group, with respect to large spots to the north, may have contributed to conditions for great flare of 21 May in center of complex.
		5/21	"Collision" between central and western members of the complex, as growth and expansion of central member moved its leader spot into the follower plage of the western member. Large flare occurred over the neutral line between the groups.
		5/23	"Collision" and merger of leader of easternmost member with follower of central member, creating large "delta" magnetic configuration. Closest separation between the opposite-polarity spots coincided with great white-light, proton flare at 1840 UT (see *UAG Report 5*). These spots moved in a rotary pattern with respect to one another during 21-26 May.
		5/28	Additional great flare over the "delta" configuration.

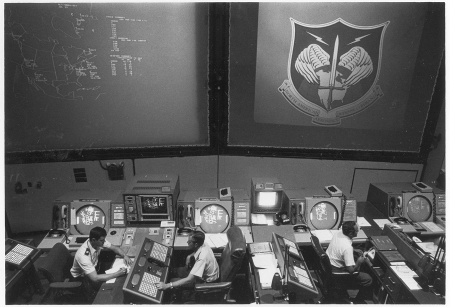
a



b

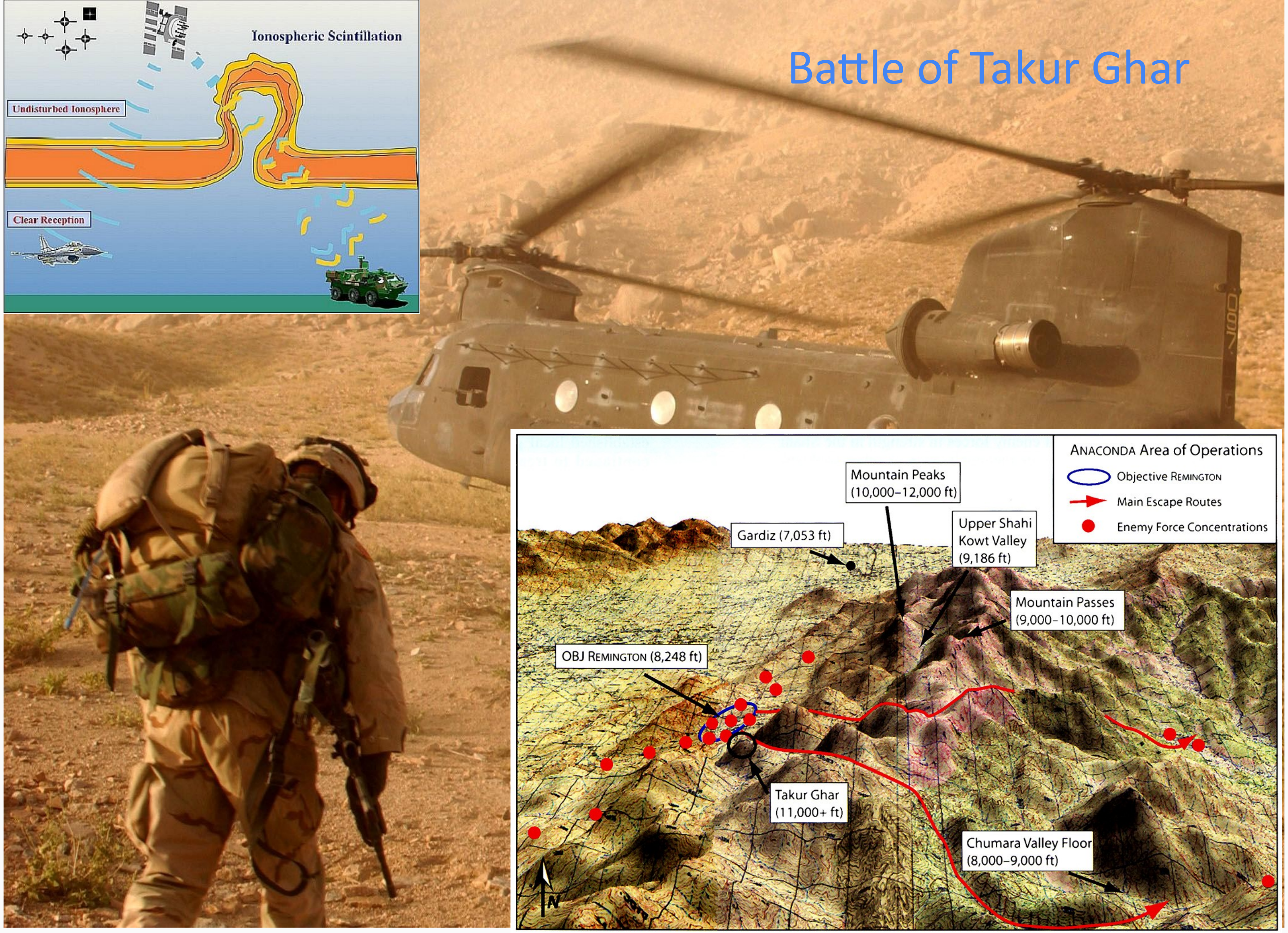
c





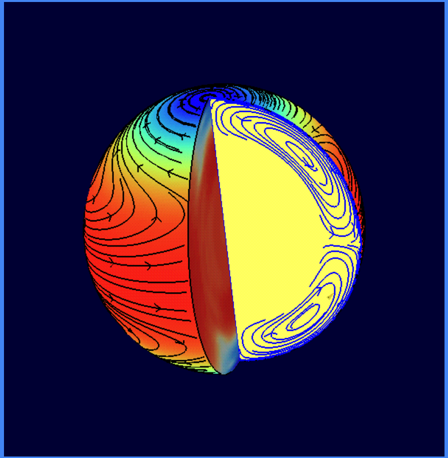
Volume 14, Issue 9,
http://onlinelibrary.wiley.com/doi/10.1002/2016SW001423/full#swe20344-fig-0001

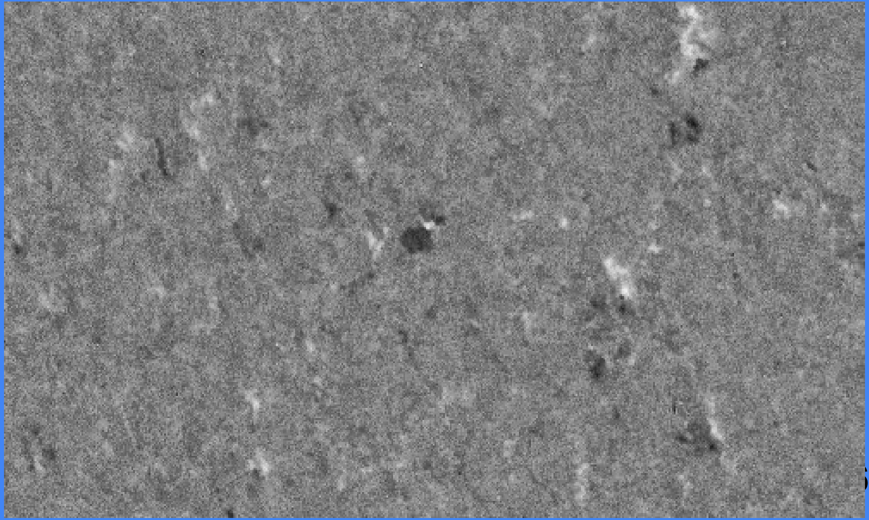
Battle of Takur Ghar



Ingredients

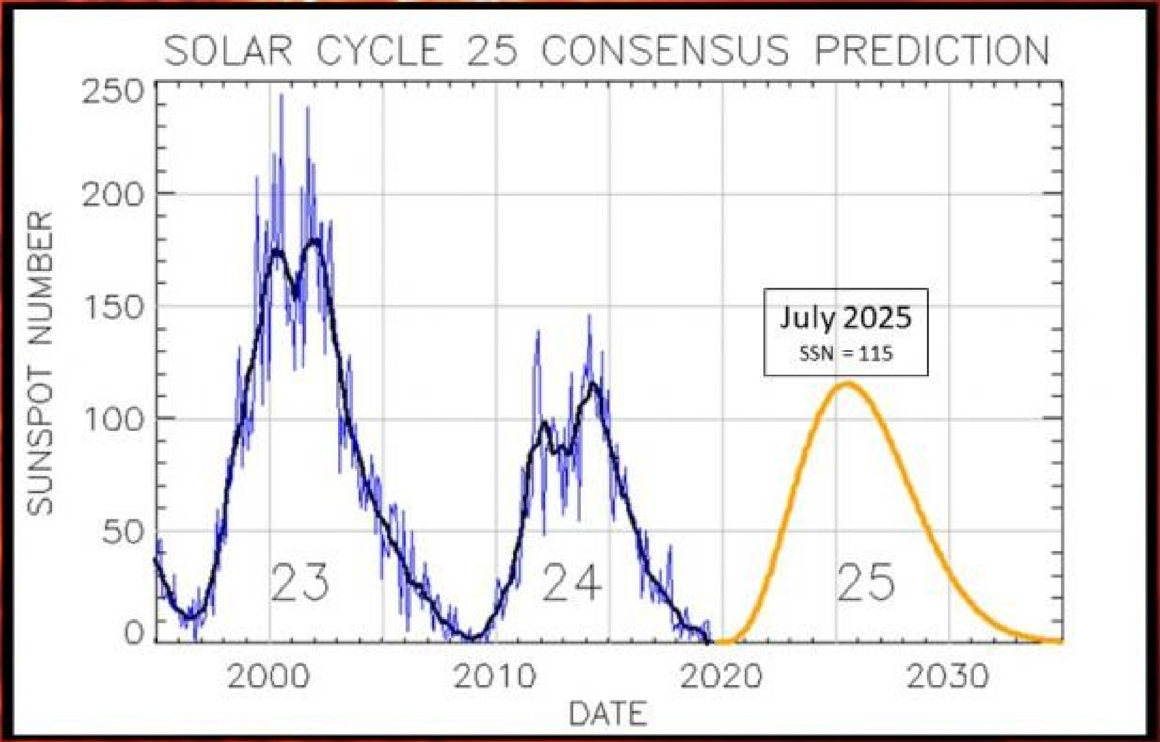
Magnetism
Convection
Differential Rotation
(~ 27 Days)





Solar Cycle 25 Forecast Update

- Released December 9th, 2019 -

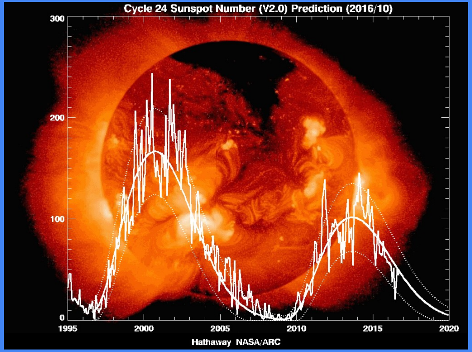


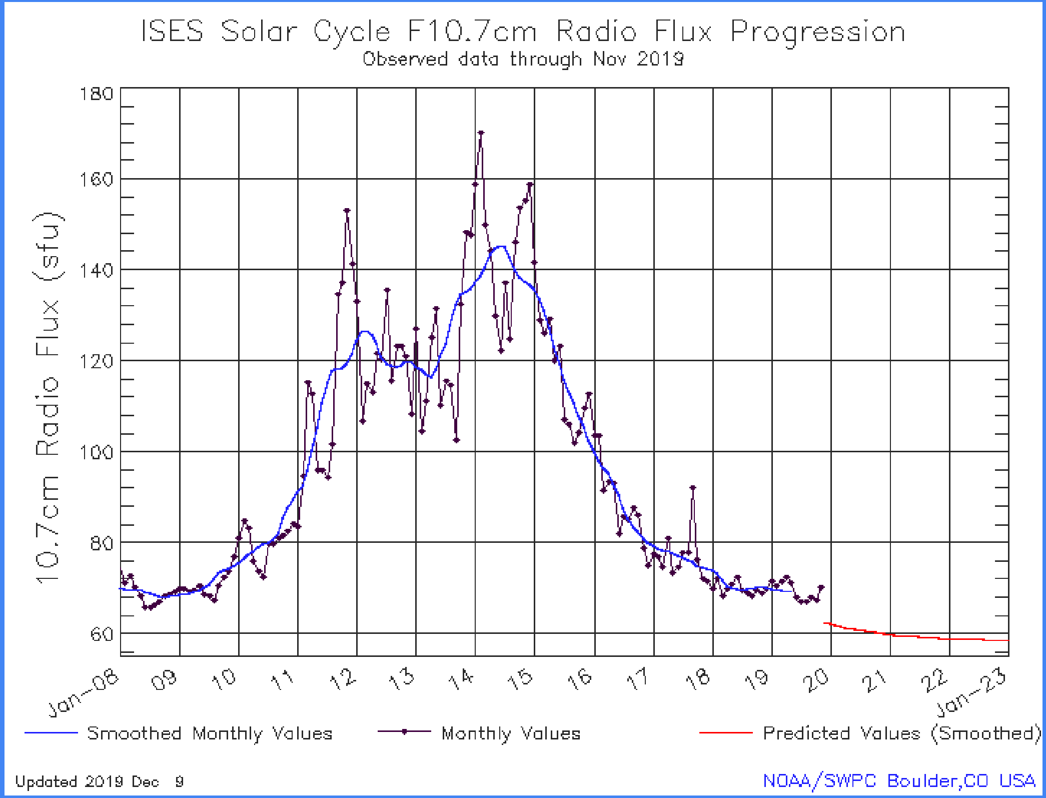
Solar Cycle 25 will have a peak SSN of 115 (± 10) in July 2025

Solar Cycle 24/25 minimum will occur in April, 2020 (± 6 months)

~ 11 Year
Solar Cycle

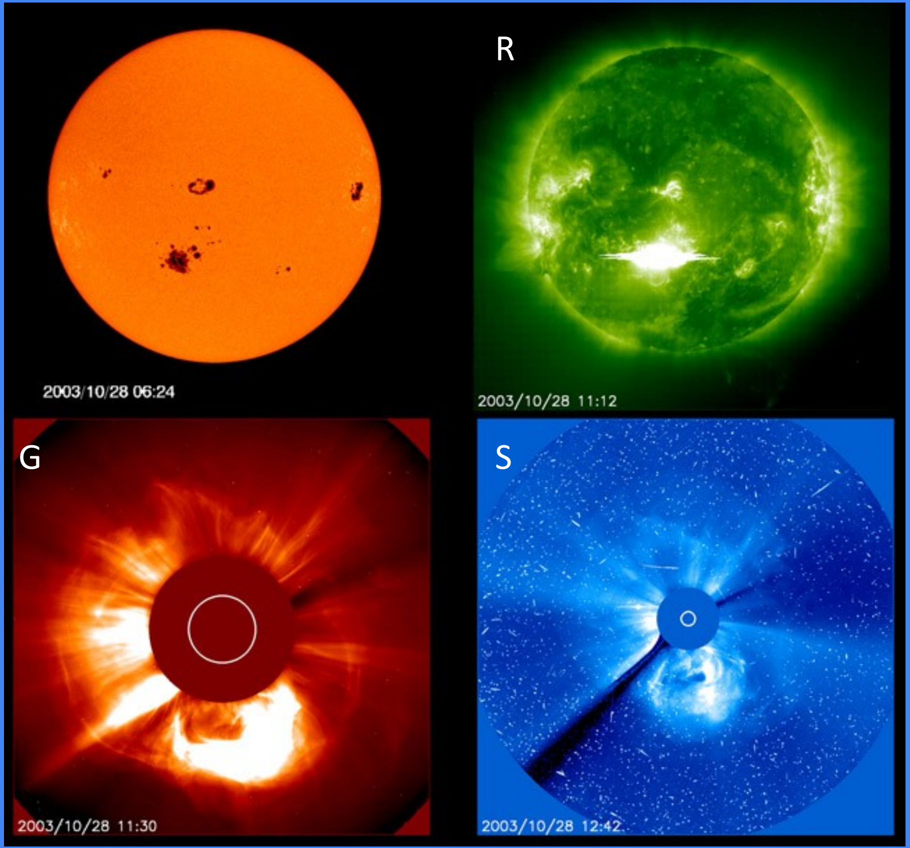
Peaked in 2014
Minimum expected in 2020



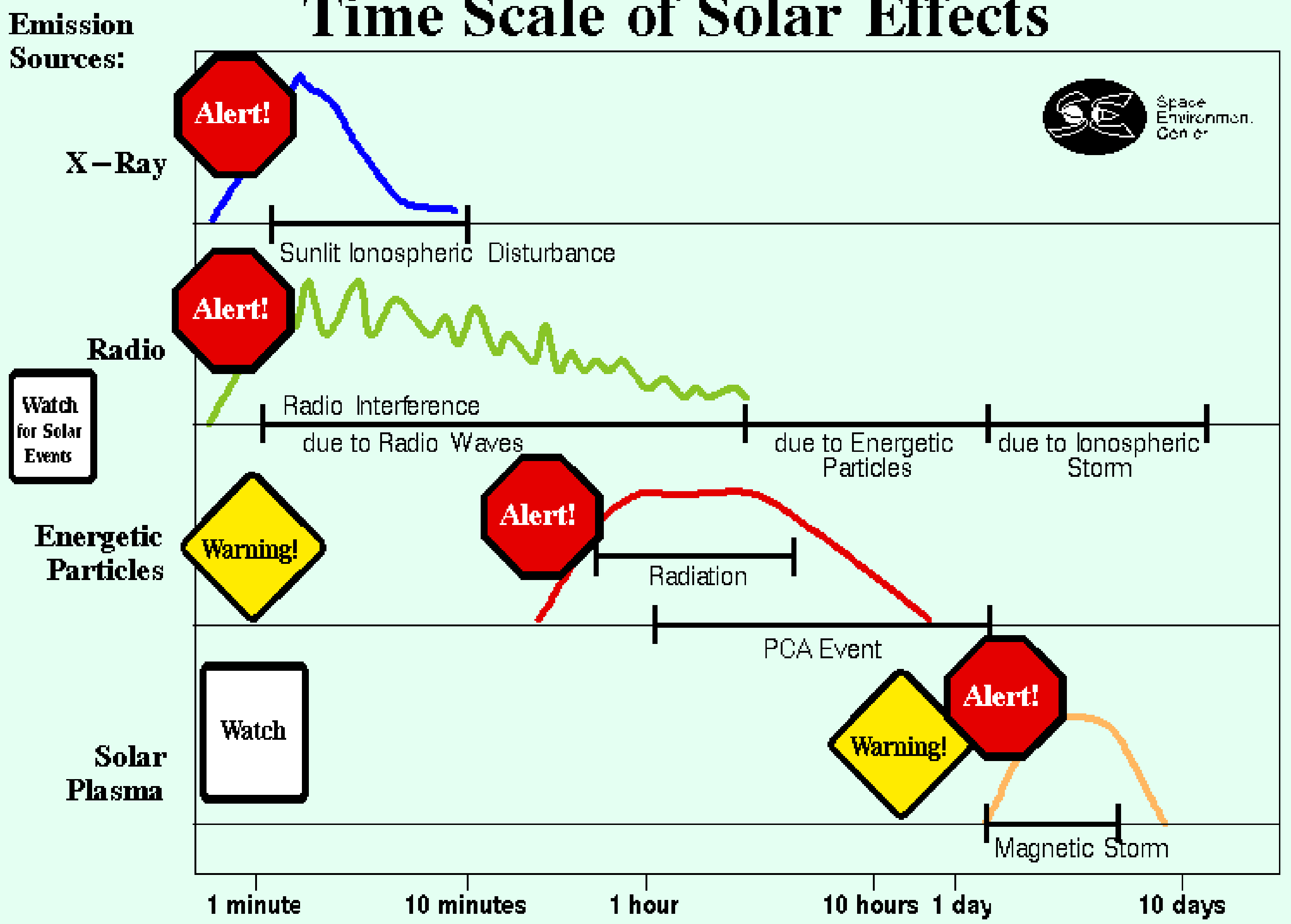


The Big 3 – R, S & G

- R = Radio Blackout
- S = Space Radiation Storm
- G = Geomagnetic Storm



Time Scale of Solar Effects



(Time 0 is 8 minutes after a solar event) **Log Scale of Time**

NOAA Space Weather Scales

http://www.swpc.noaa.gov/NOAAscales/

Category		Effect	Physical measure	Average Freq. (1 cycle = 11 yrs)
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
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 (2×10^{-3})	
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})	
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})	
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 (5×10^{-5})	
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})	

* Flux, measured in the 0.1-0.8 nm range, in $W \cdot m^{-2}$. Based on this measure, but other physical measures are als considered.
** Other frequencies may also be affected by these conditions.

Radio Blackouts

Category		Effect	Physical measure	Average Freq. (1 cycle = 11 yr)
Scale	Descriptor	Duration of event will influence severity of effects		
		Solar Radiation Storms	Flux level	Number of
S 5	Extreme	**Biological:** unavoidable high radiation hazard to astronauts on E vehicular activity); high radiation exposure to passengers and cre commercial jets at high latitudes (approximately 100 chest x-rays **Satellite operations:** satellites may be rendered useless, memory cause loss of control, may cause serious noise in image data, star- be unable to locate sources; permanent damage to solar panels po **Other systems:** complete blackout of HF (high frequency) comm possible through the polar regions, and position errors make navi operations extremely difficult.		
S 4	Severe	**Biological:** unavoidable radiation hazard to astronauts on EVA; radiation exposure to passengers and crew in commercial jets at h (approximately 10 chest x-rays) is possible. **Satellite operations:** may experience memory device problems a imaging systems; star-tracker problems may cause orientation pr solar panel efficiency can be degraded. **Other systems:** blackout of HF radio communications through th regions and increased navigation errors over several days are like		
S 3	Strong	**Biological:** radiation hazard avoidance recommended for astrona passengers and crew in commercial jets at high latitudes may rec radiation exposure (approximately 1 chest x-ray). **Satellite operations:** single-event upsets, noise in imaging syster reduction of efficiency in solar panel are likely. **Other systems:** degraded HF radio propagation through the pola navigation position errors likely.		
S 2	Moderate	**Biological:** none. **Satellite operations:** infrequent single-event upsets possible. **Other systems:** small effects on HF propagation through the pola navigation at polar cap locations possibly affected.		
S 1	Minor	**Biological:** none. **Satellite operations:** none. **Other systems:** minor impacts on HF radio in the polar regions.		

Radiation Storms

Category		Effect	Physical measure	Average Freq. (1 cycle = 11 yrs)
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
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. **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.)**.	Kp = 7	200 per cycle (130 days per cycle)
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)

Geomagnetic Storms

Phenomena Reference/Impacts

Solar Flare Radio Blackout (**R** Scale):

- No advance warning
- Effects last for 10's of minutes to several hours
- High Frequency (HF) communication on the sunlit side of the Earth
- VHF/UHF communication if significant radio burst on frequency (e.g. GPS)
- First indication significant S and G scale activity may be possible

Solar Radiation Storm (**S** Scale):

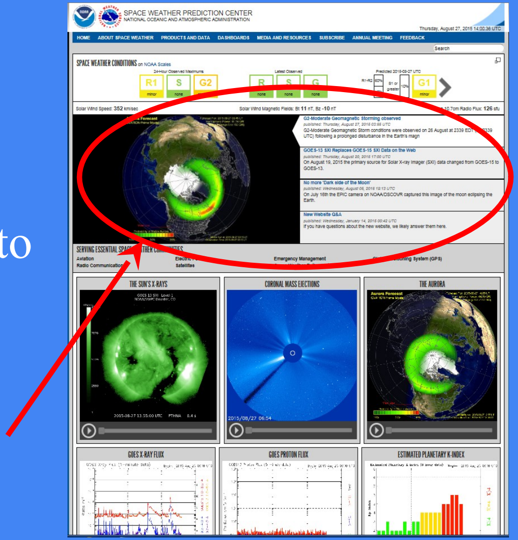
- Warnings possible on the minutes to hours time scale
- Effects can persist for several days
- Health and operation of satellites and International Space Station
- HF comm in the polar regions, affecting commercial airline ops

Geomagnetic Storm (**G** Scale):

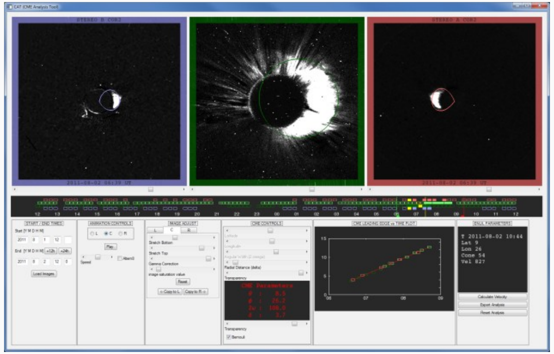
- Advance notice possible from just under a day to several days
- Effects last for one or more days
- Power grid operations and stability
- Global Navigation Satellite System (GNSS) accuracy and availability
- Aurora

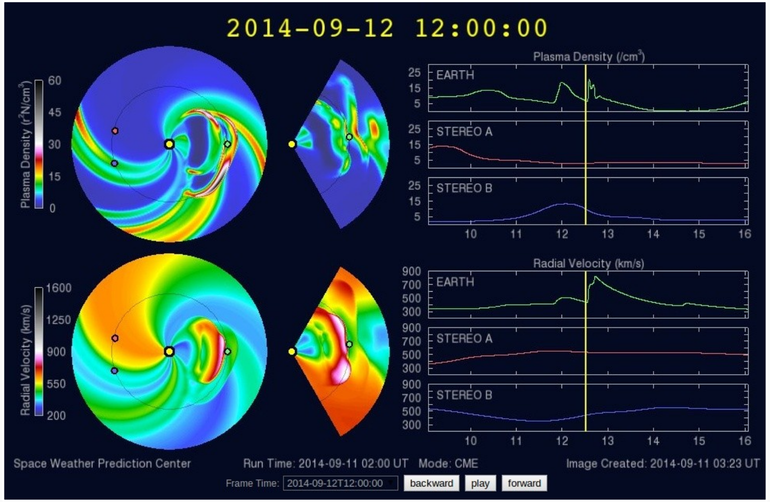
Information Dissemination

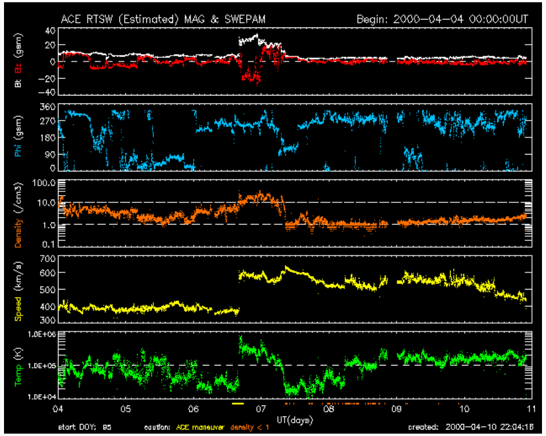
- **Phone** Contact for Critical Stakeholders: NASA, Commercial Airlines, Power Generation and Distribution, FEMA, etc.
- Product Subscription Service: **Email**-based, no cost subscription service open to all
- **Web**site: Data, products, and models all available there. Tops News heading that will provide updates for elevated space weather
- **Social Media** (Twitter, Facebook)
- **Traditional Media** Support during significant events

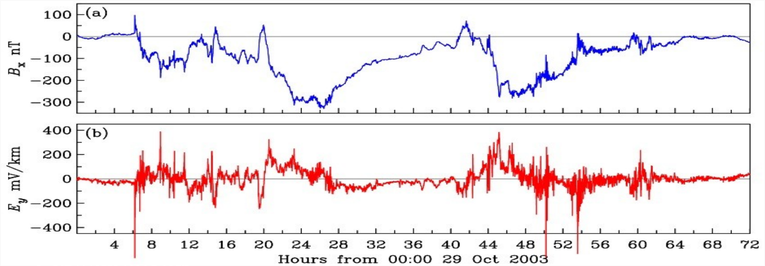


Geomagnetic Storm Sequence of Events



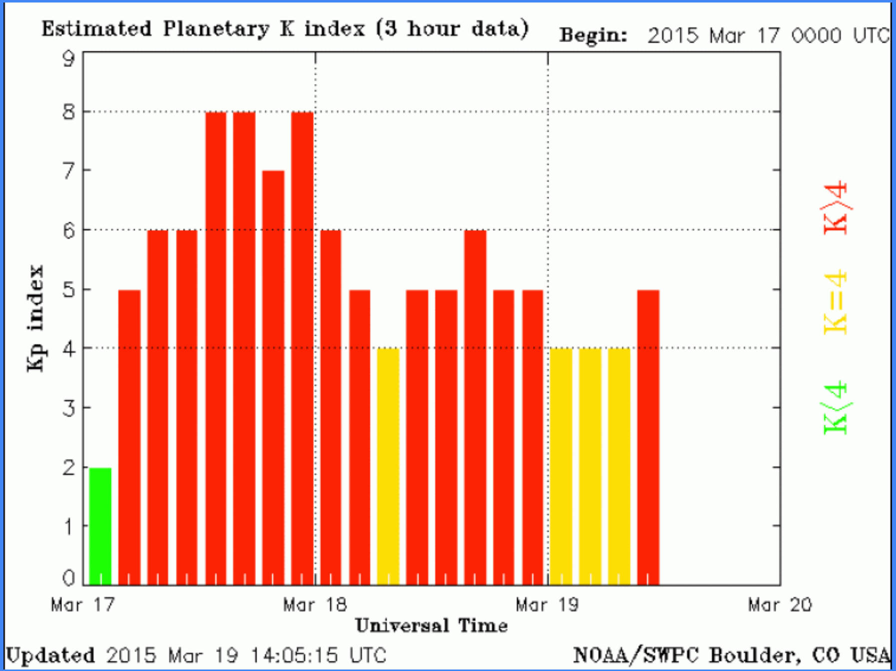






Practical Challenges

Issued: 2015 Mar 17 0030 UTC
Geophysical Activity Forecast: **G1 (Minor)** or greater geomagnetic storms are expected on 18 Mar associated with a combination of the recurrent southern pole connected coronal hole high speed stream (CH HSS) and CME arrival.



This summer was generally uneventful until...

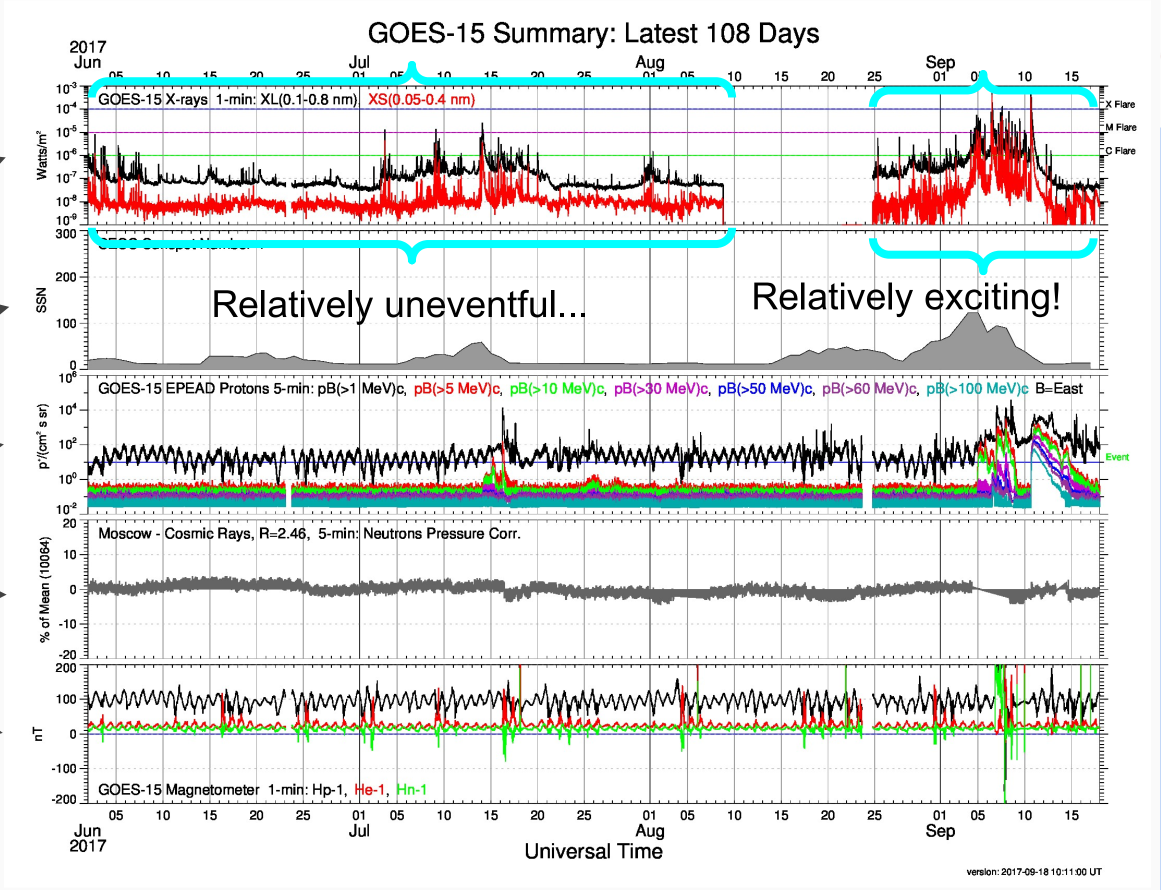
X-rays (@ Geo)

Sunspots

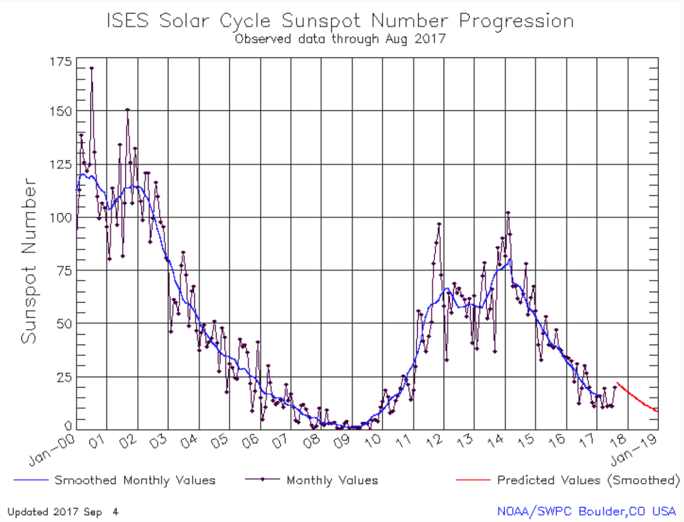
Particles (@ Geo)

Cosmic Rays

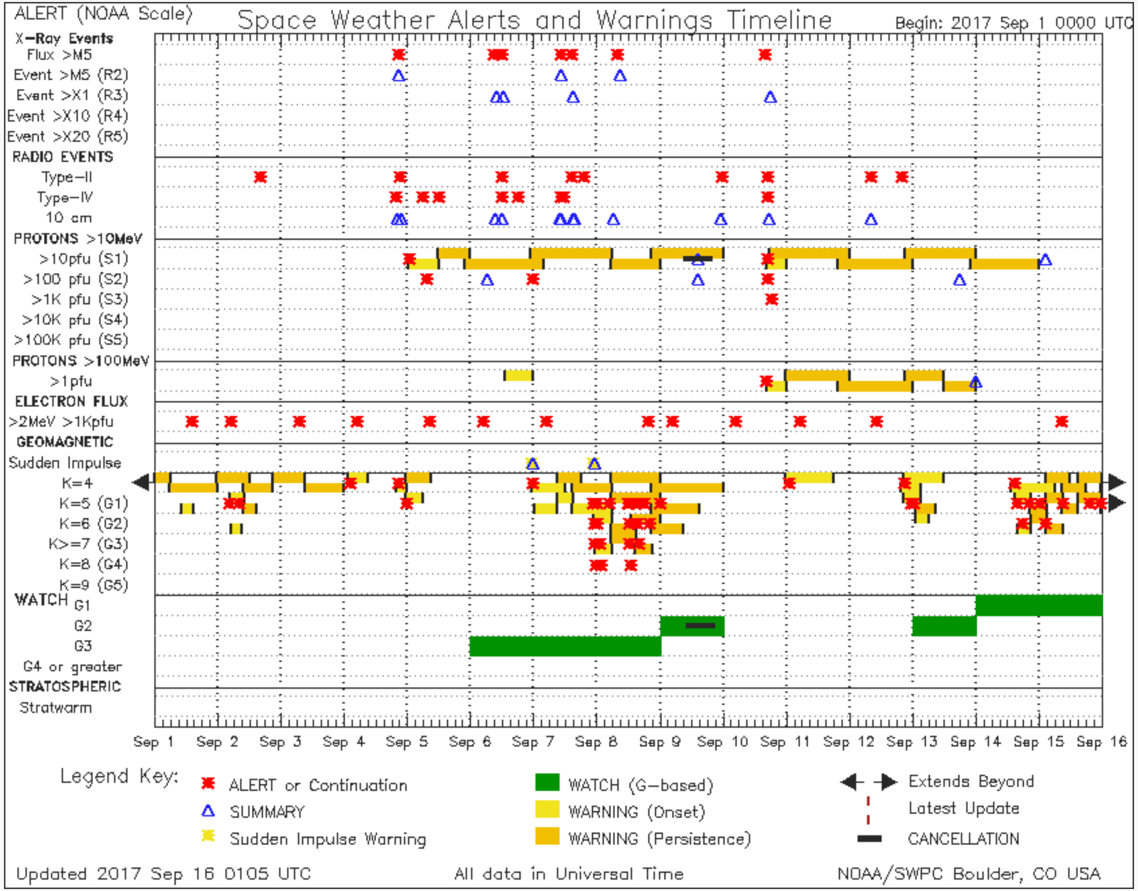
Magnetometer (@ Geo)



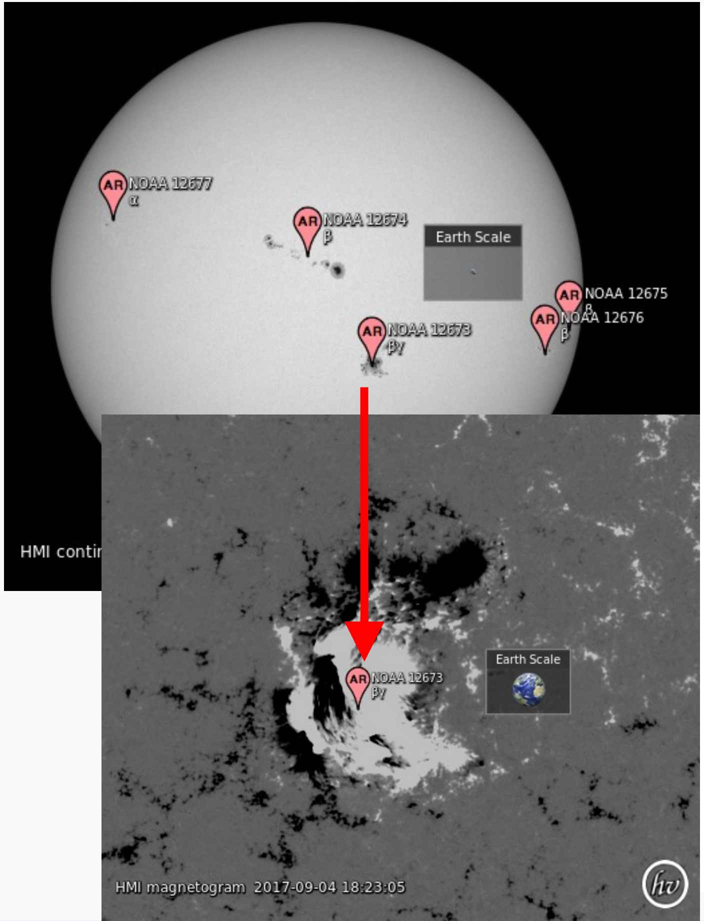
Cycle vs Watches, Warnings and Alerts Timeline 01 Sep - 16 Sep 2017

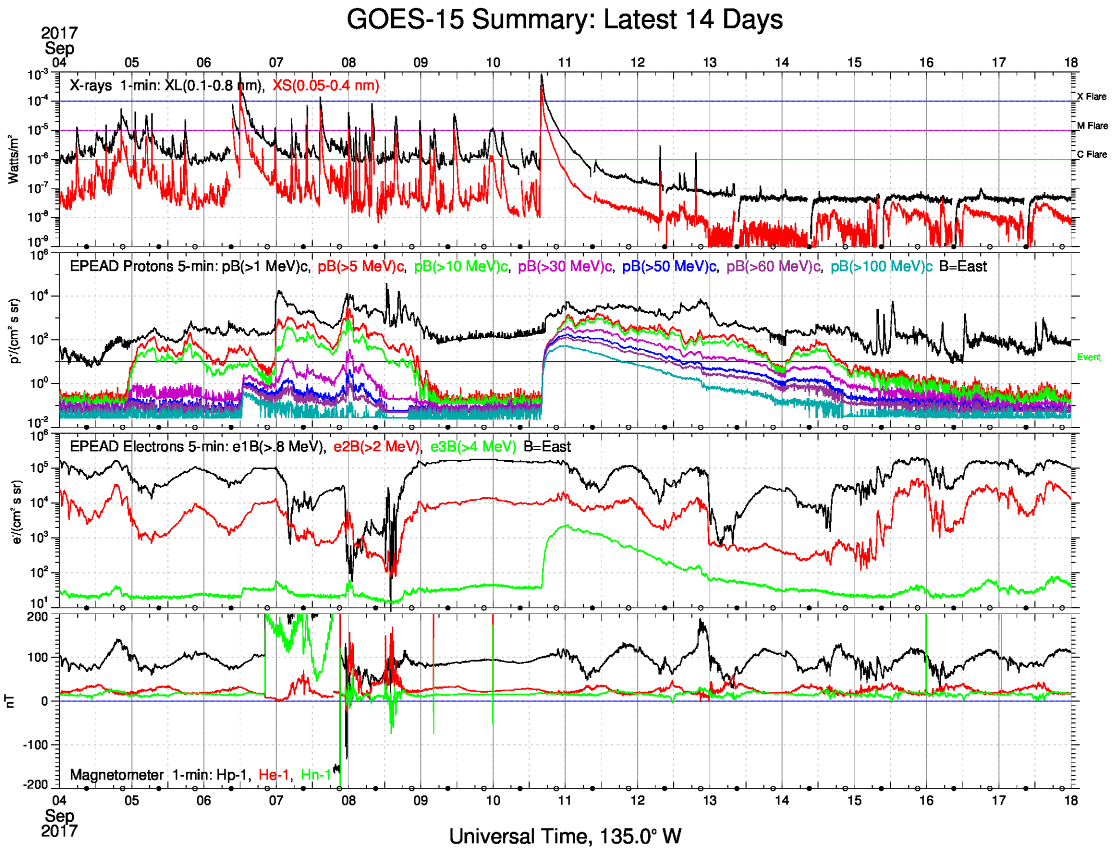


04 Sep 1200 UTC - 11 Sept 1200 UTC **123** Alert, Watch Warning and Summary Products issued. This was 5 more than issued the *entire month* before.



Region 12673





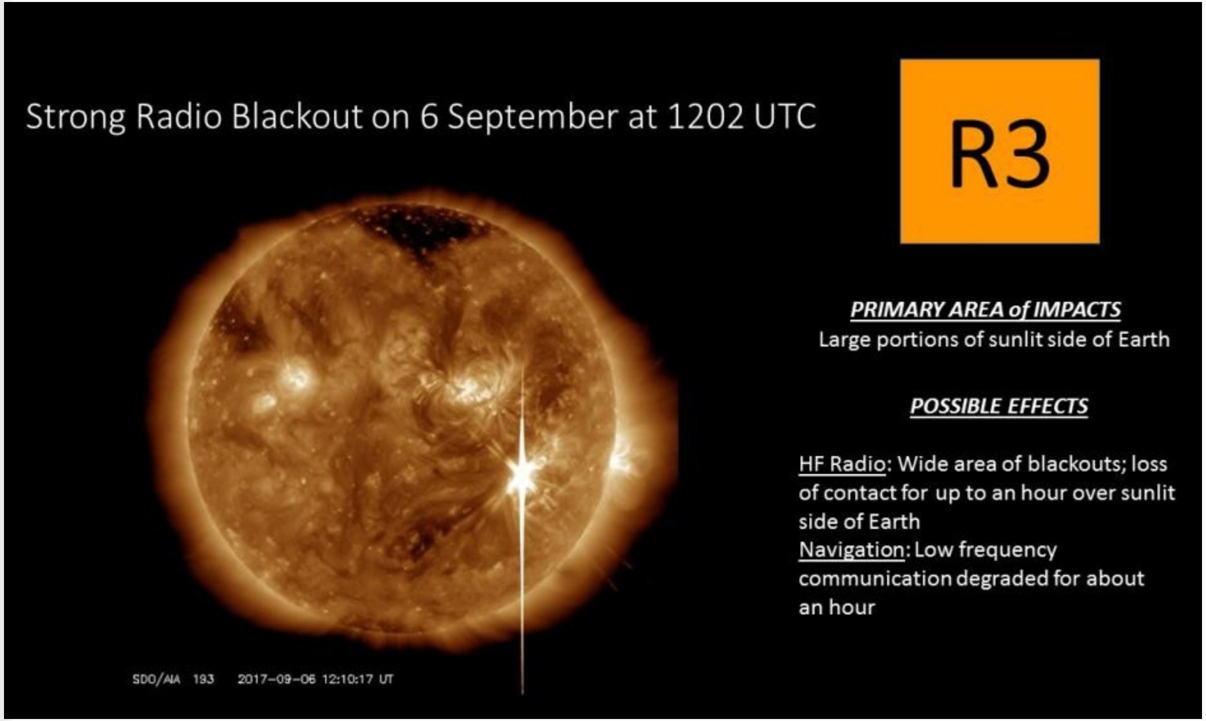
Solar Activity gets interesting in September!

The X9.3 flare son Sep 6 at 1202 UTC was the largest of the solar cycle, and the largest since Sep 7, 2005 (an X17) + S3

An X2.2 preceded the X9.3 flare on Sep 06 at 0910 UTC

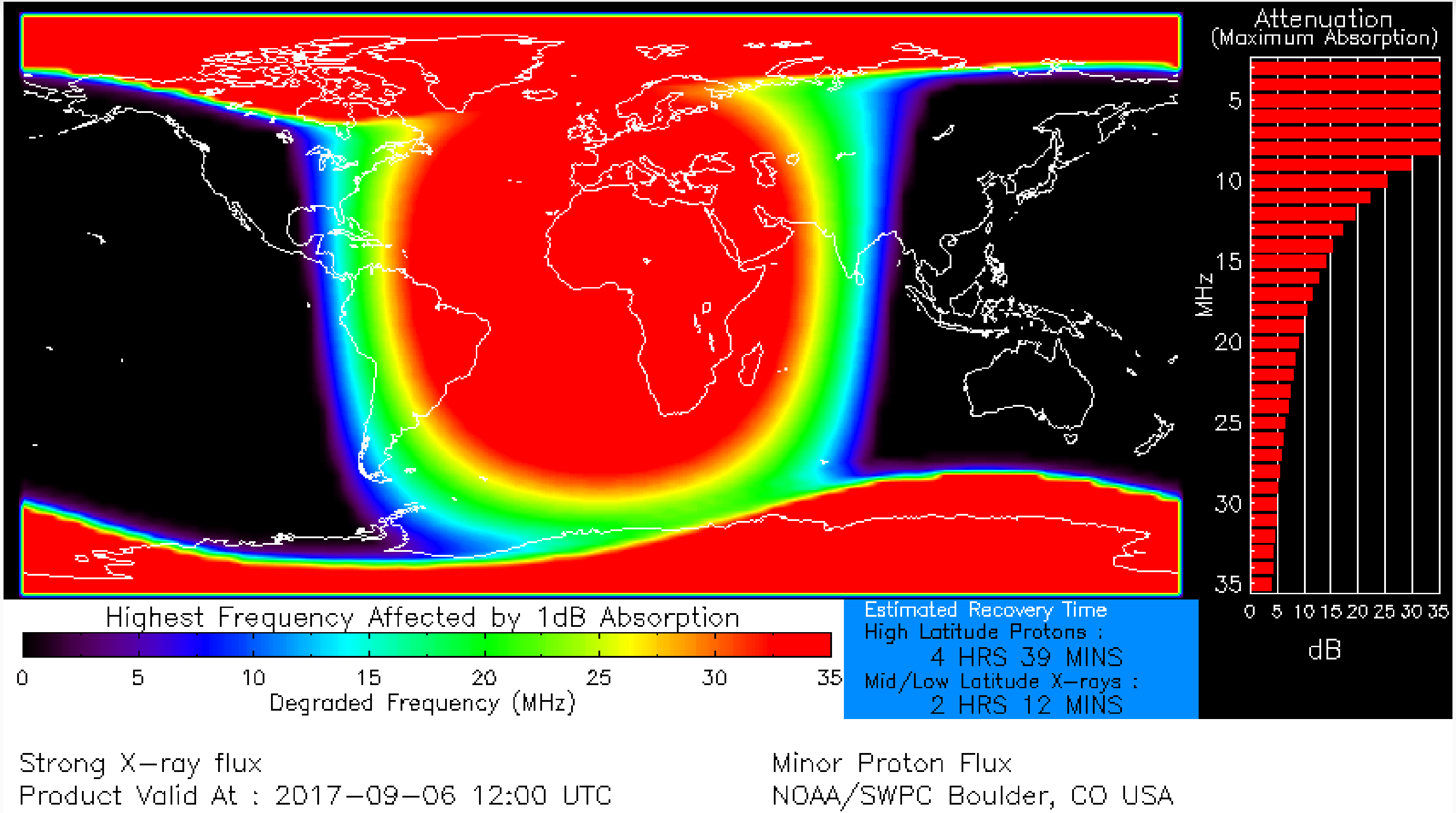
An X1.3 event followed on Sep 07 at 1436 UTC

An X8.2 event followed on Sep 10 at 1606 UTC + S3

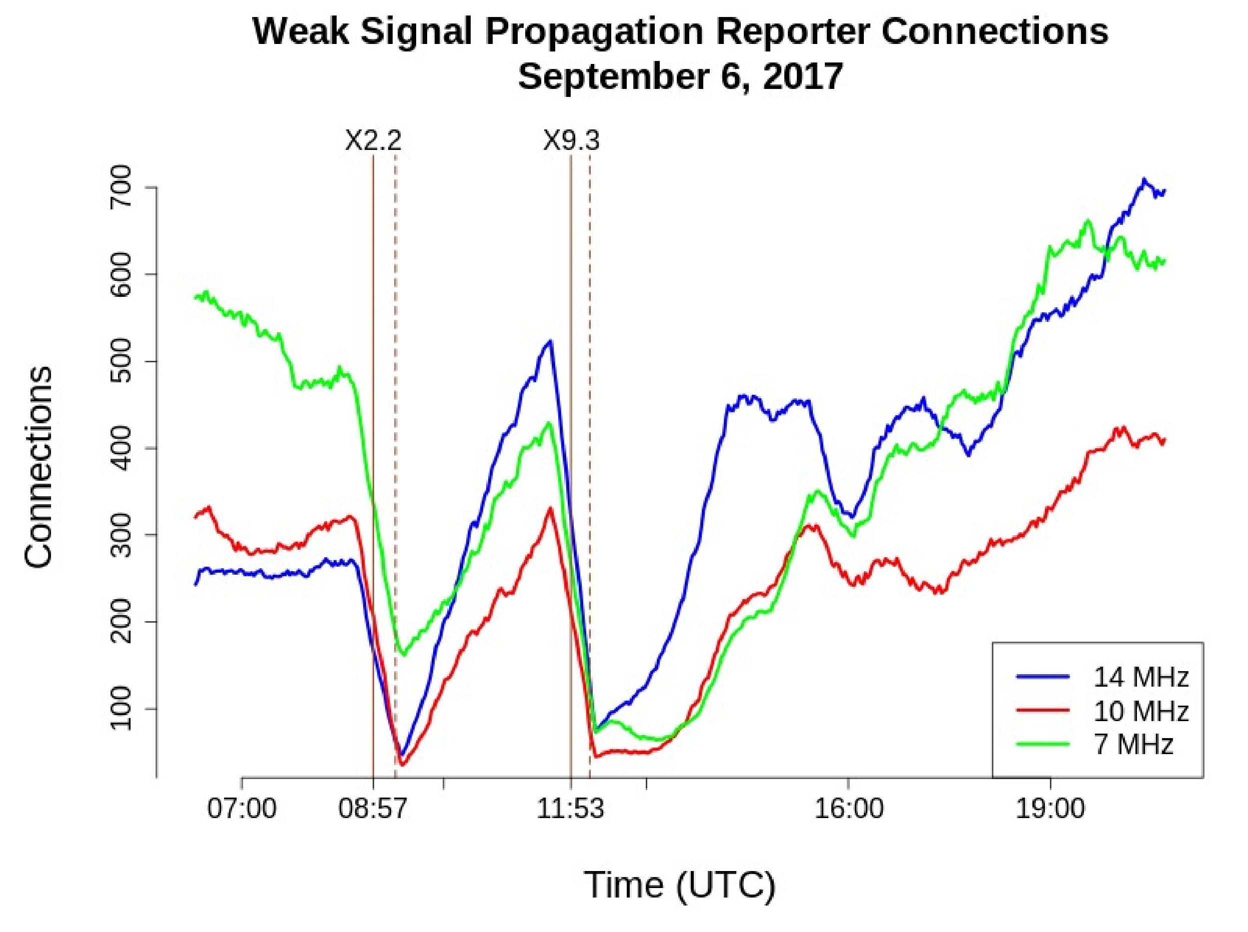


https://twitter.com/i/videos/tweet/905496088513269763?

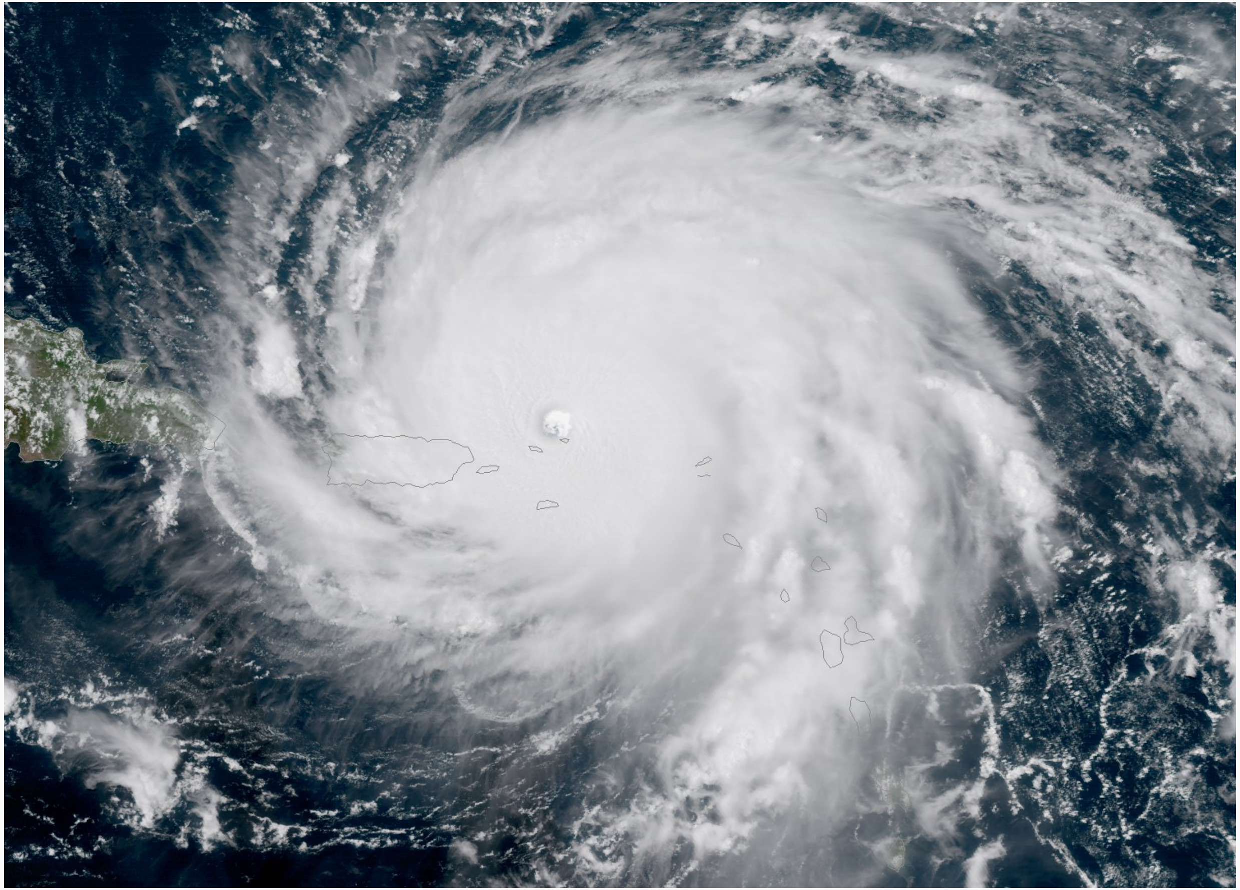
D-Region Absorption 06 Sep 2017



Impact on WSPR Network



Hurricane + Solar Flare = ?

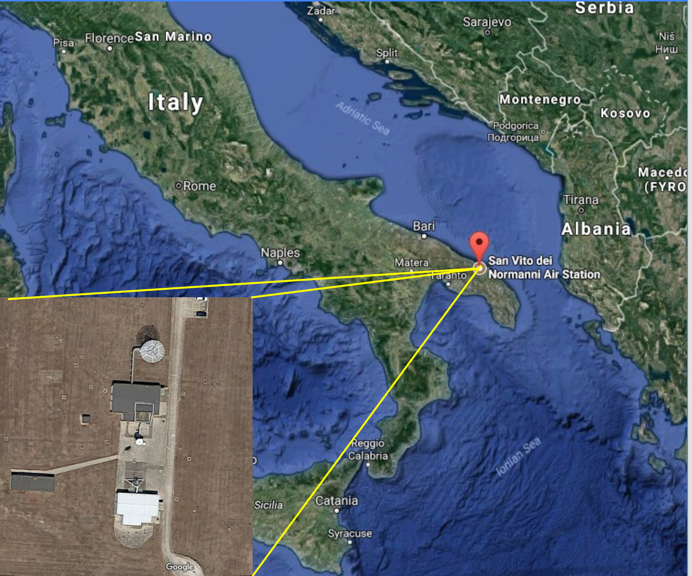


“...I’m not sure how long this blackout will last, but, **these flares could not happen at a worse time. We are looking at 3 hurricane threatening land and we cannot make contact with anyone on the 20 meter or 40 meter amateur bands…”**

Mother Nature is not playing well.

Solar Radio Burst Activity 06 Sep 2017

Solar Radio Burst reported by USAF optical/radio observatory at San Vito, Italy.




```
:Product: 20170906events.txt
:Created: 2017 Sep 09 0357 UT
:Date: 2017 09 06
# Prepared by the U.S. Dept. of Commerce, NOAA, Space Weather Prediction Center
# Please send comments and suggestions to SWPC.Webmaster@noaa.gov
#
# Missing data: ////
# Updated every 5 minutes.
#                         Edited Events for 2017 Sep 06
#
#Event    Begin    Max       End  Obs  Q  Type  Loc/Frq   Particulars       Reg#
#-------------------------------------------------------------------------------

7160       0000    ////      0433  PAL  C   RSP  025-180   VI/1

7340 +     1153   1202      1210  G15  5   XRA  1-8A      X9.3    5.7E-01   2673
7340 +     1154   1156      1432  SVI  G   RBR  2695      14000   CastelliU 2673
7340 +     1154   1156      1351  SVI  G   RBR  15400     8100    CastelliU 2673
7340 +     1155   1202      1232  SAG  G   RBR  410       6300    CastelliU 2673
7340 +     1155   1156      1356  SVI  G   RBR  8800      6500    CastelliU 2673
7340 +     1156   1157      1405  SVI  G   RBR  4995      5900    CastelliU 2673
7340 +     1156   1202      1424  SVI  G   RBR  1415      19000   CastelliU 2673
7340       1157   ////      1202  SVI  C   RSP  025-170   III/2             2673
7340 +     1158   1202      1232  SAG  G   RBR  610       9400    CastelliU 2673
7340 +     1201   ////      1515  SVI  C   RSP  025-180   IV/2              2673
7340 +     1202   1203      1411  SVI  G   RBR  245       3200    CastelliU 2673
7340       1202   ////      1208  SAG  C   RSP  025-061   VI/1              2673
7340       1202   ////      1221  SVI  C   RSP  025-081   II/2    1765      2673

7790      B1224   ////     A1630  SOH  4   CME  XUV,EUV,UV227-226/FS1429      2673
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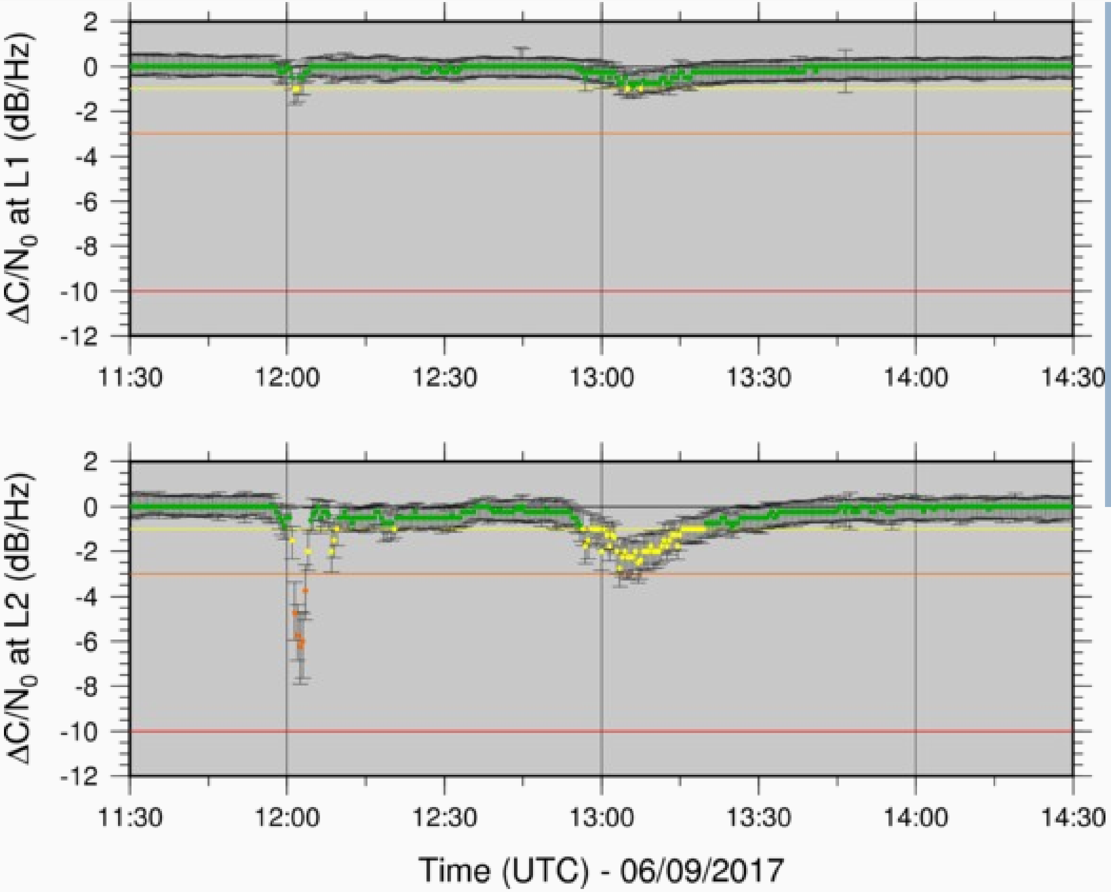
Summary of Radio Burst Impact to GPS - 06 September from ROB

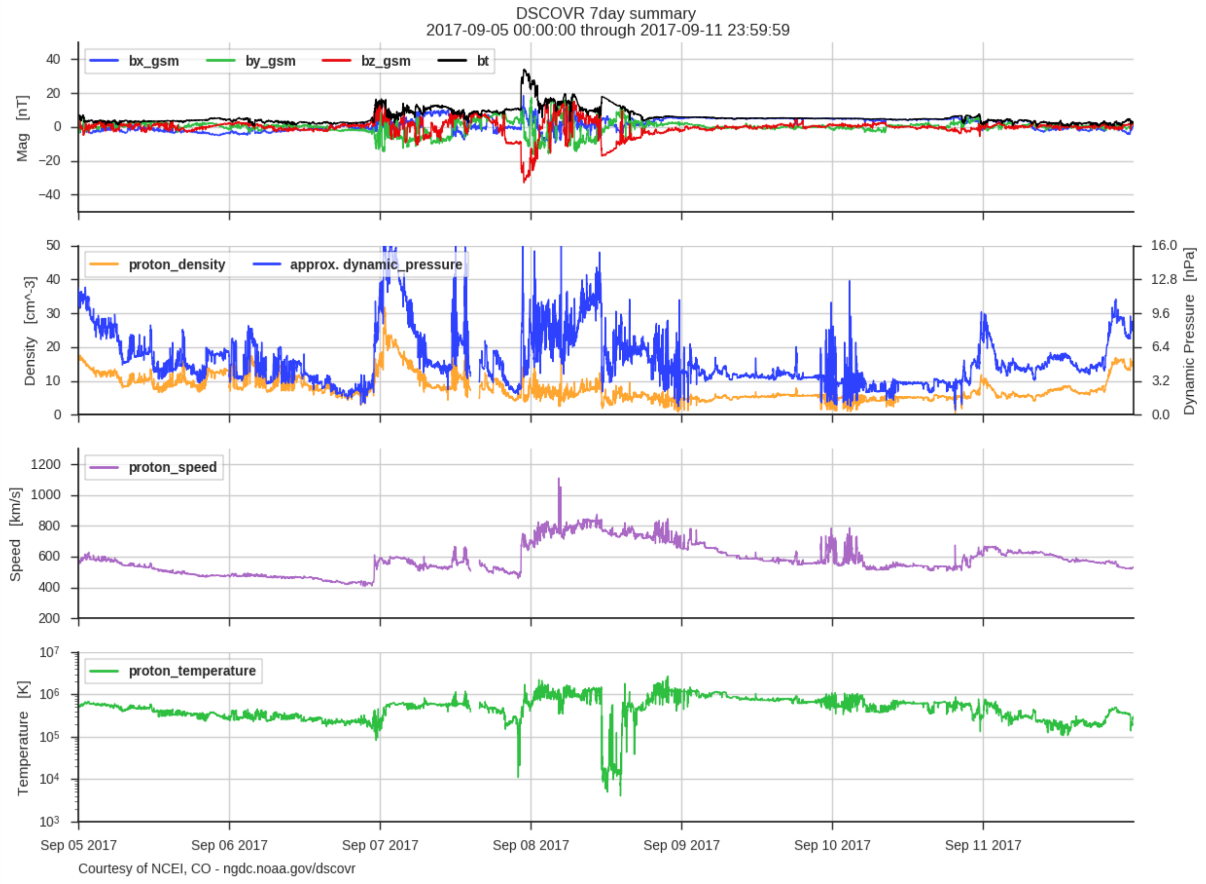


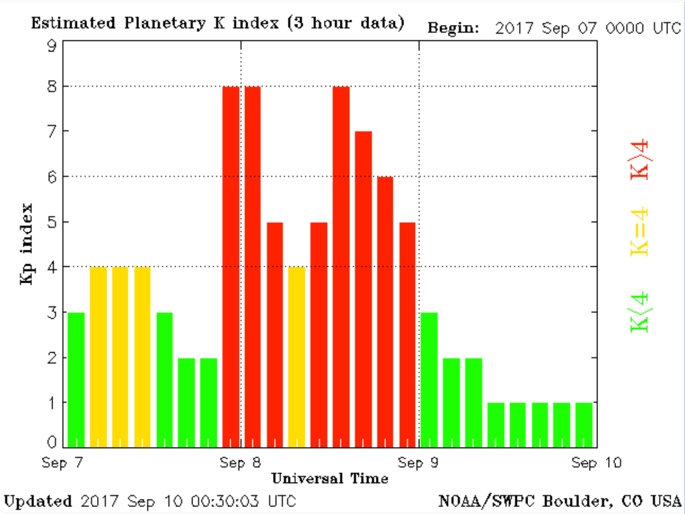
[Royal Observatory of Belgium GNSS Research Group]

IMPACT OF THE EVENT:

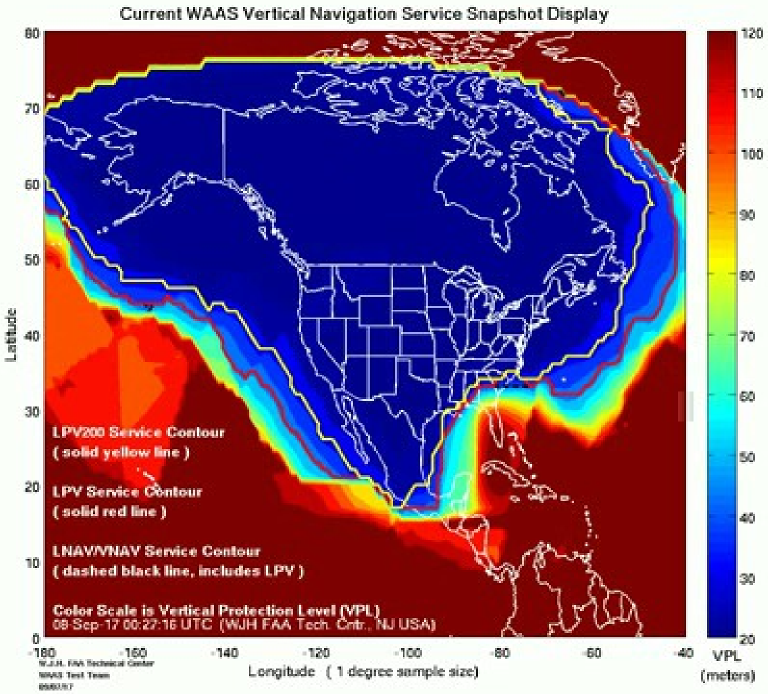
- On L1, two fades above 1dB/Hz were detected at 12h01 and 12h05.
- On L2, a first fade above 3dB/Hz which could potentially affect the GNSS application, occurred for 3 min with a maximum of -6.25±1.6dB/Hz at 12h02.
- It was followed by a second lower fade above 1dB/Hz at 13h03.

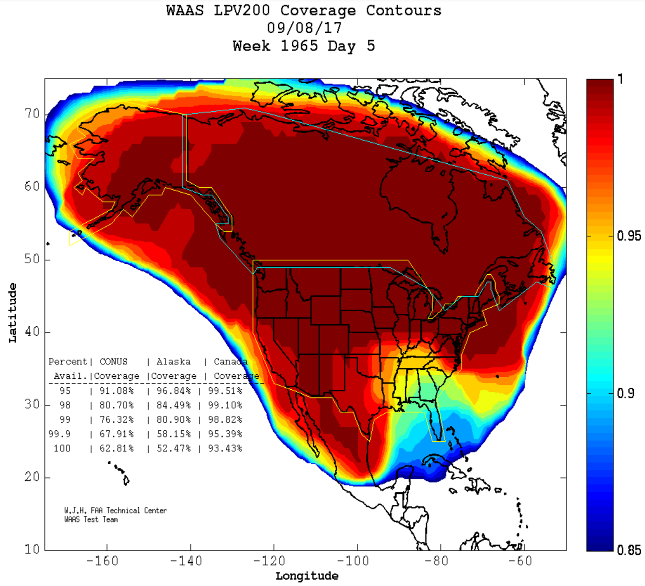
Solar Wind Environment 05-11 September, 2017





Localizer Performance with Vertical Guidance coverage 08 September 2017



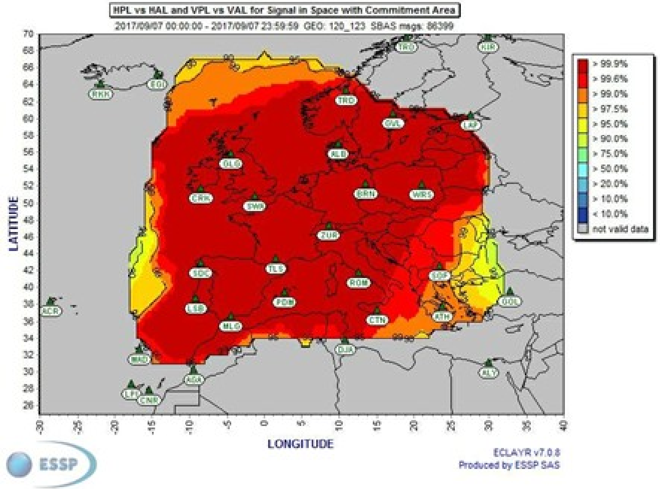


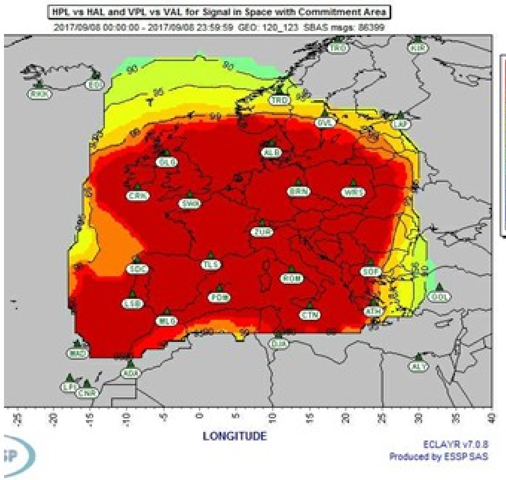
GPS Satellite Temporarily Unusable - suspected space weather impact

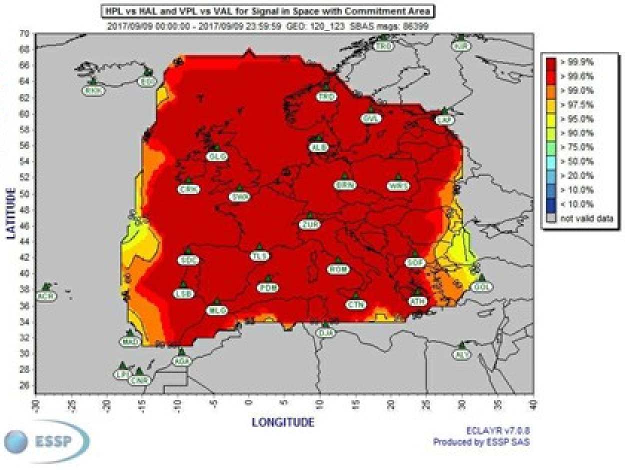
2017101 --------------------------
SVN48 (PRN07) UNUSABLE JDAY 255/1342 -
UNTIL FURTHER NOTICE
NOTICE ADVISORY TO NAVSTAR USERS (NANU)
2017101
SUBJ: SVN48 (PRN07) UNUSABLE JDAY
255/1342 - UNTIL FURTHER NOTICE
1. NANU TYPE: UNUSUFN
NANU NUMBER: 2017101
NANU DTG: 121355Z SEP 2017
REFERENCE NANU: N/A
REF NANU DTG: N/A
SVN: 48
PRN: 07
START JDAY: 255
START TIME ZULU: 1342
START CALENDAR DATE: 12 SEP 2017
STOP JDAY: UFN
STOP TIME ZULU: N/A
STOP CALENDAR DATE: N/A

2. CONDITION: GPS SATELLITE SVN48
(PRN07) WAS UNUSABLE ON JDAY 255
(12 SEP 2017) BEGINNING 1342 ZULU
UNTIL FURTHER NOTICE.

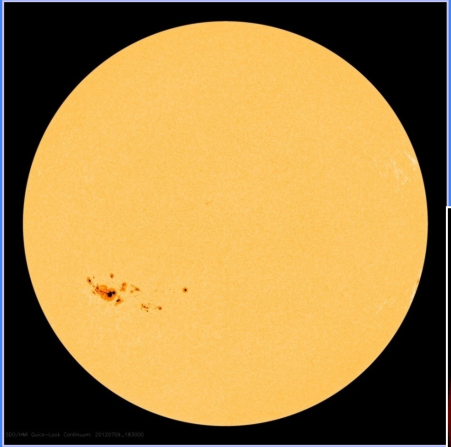
European Geostationary Navigation Overlay Service (EGNOS) performance



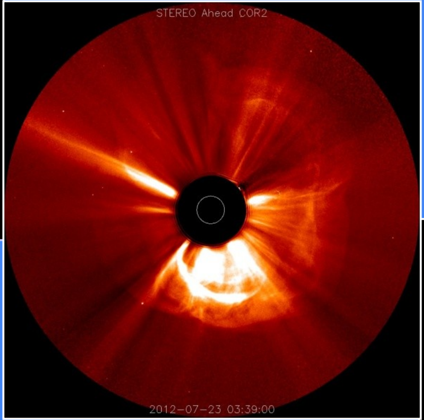


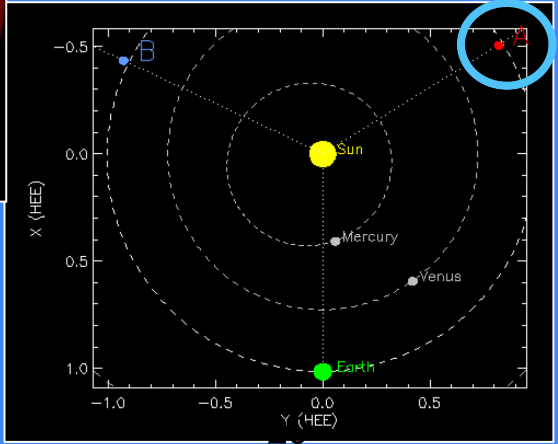


July 23, 2012

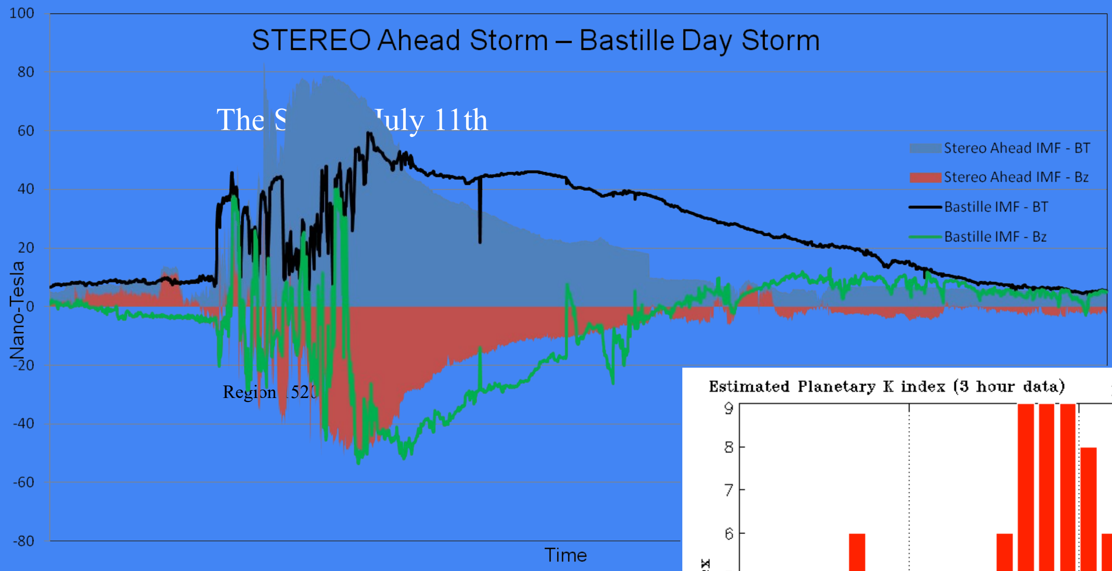


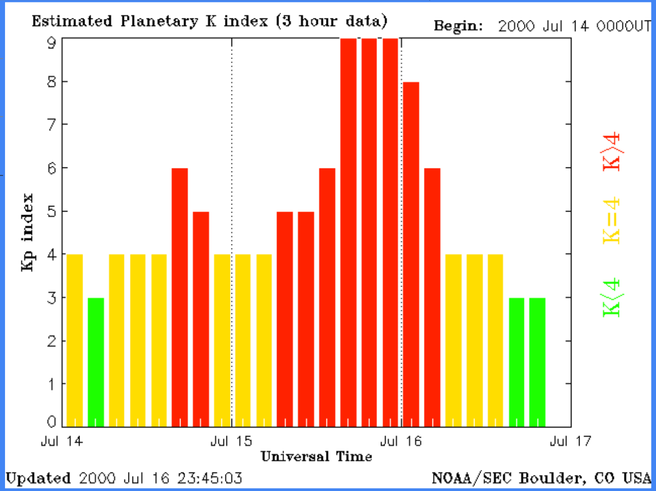
Region 1520





July 23, 2012 STEREO vs July 2000 Earth

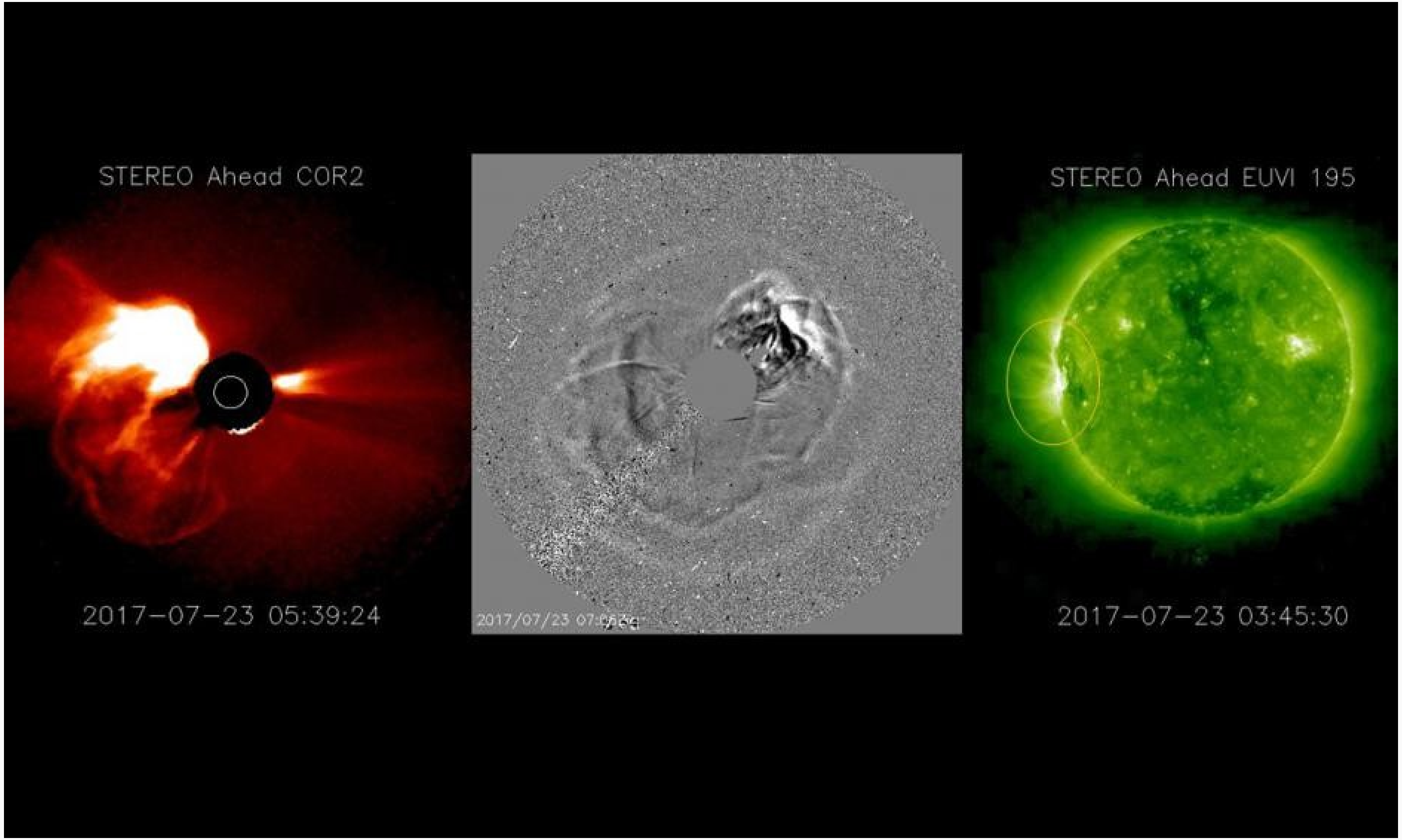




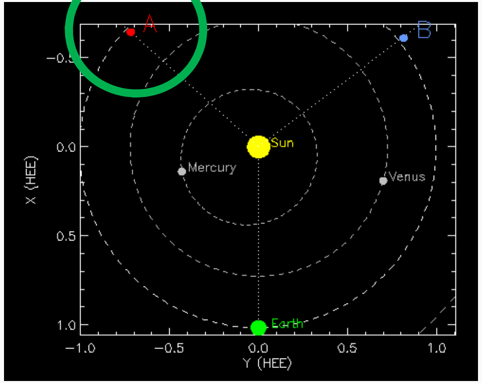
["If it had hit, we would still be picking up the pieces,"]

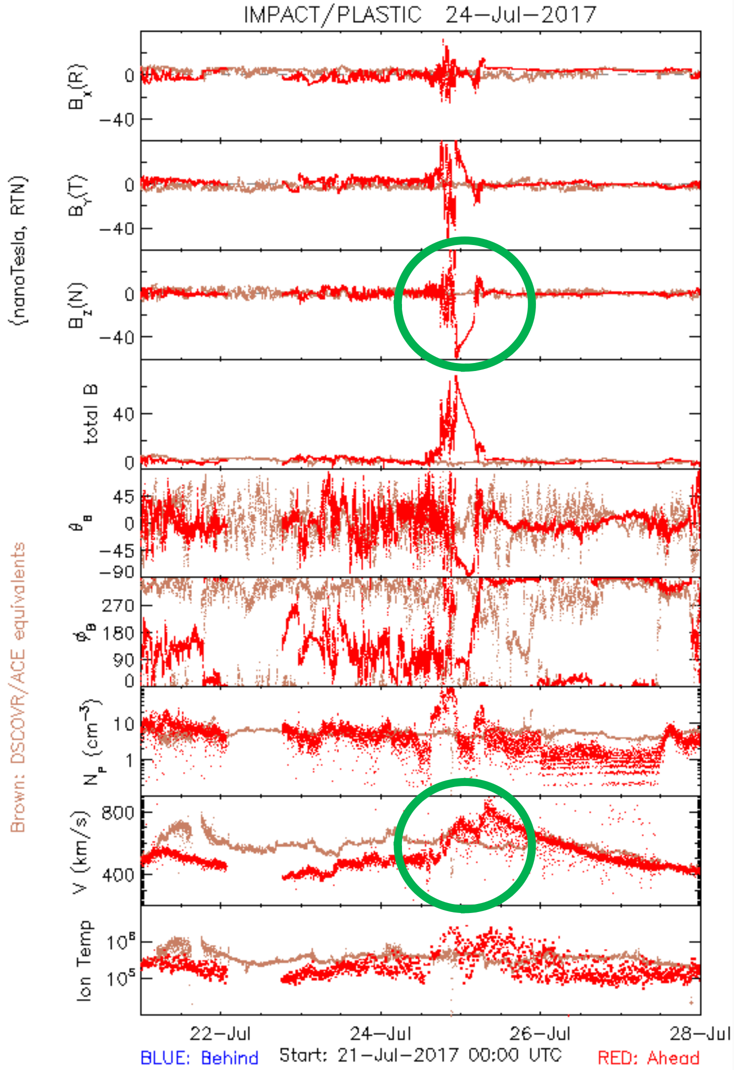
[Daniel Baker, University of Colorado].

July 23, 2017 Far Side CME



CME Impact STEREO-A 24-25 July 2017

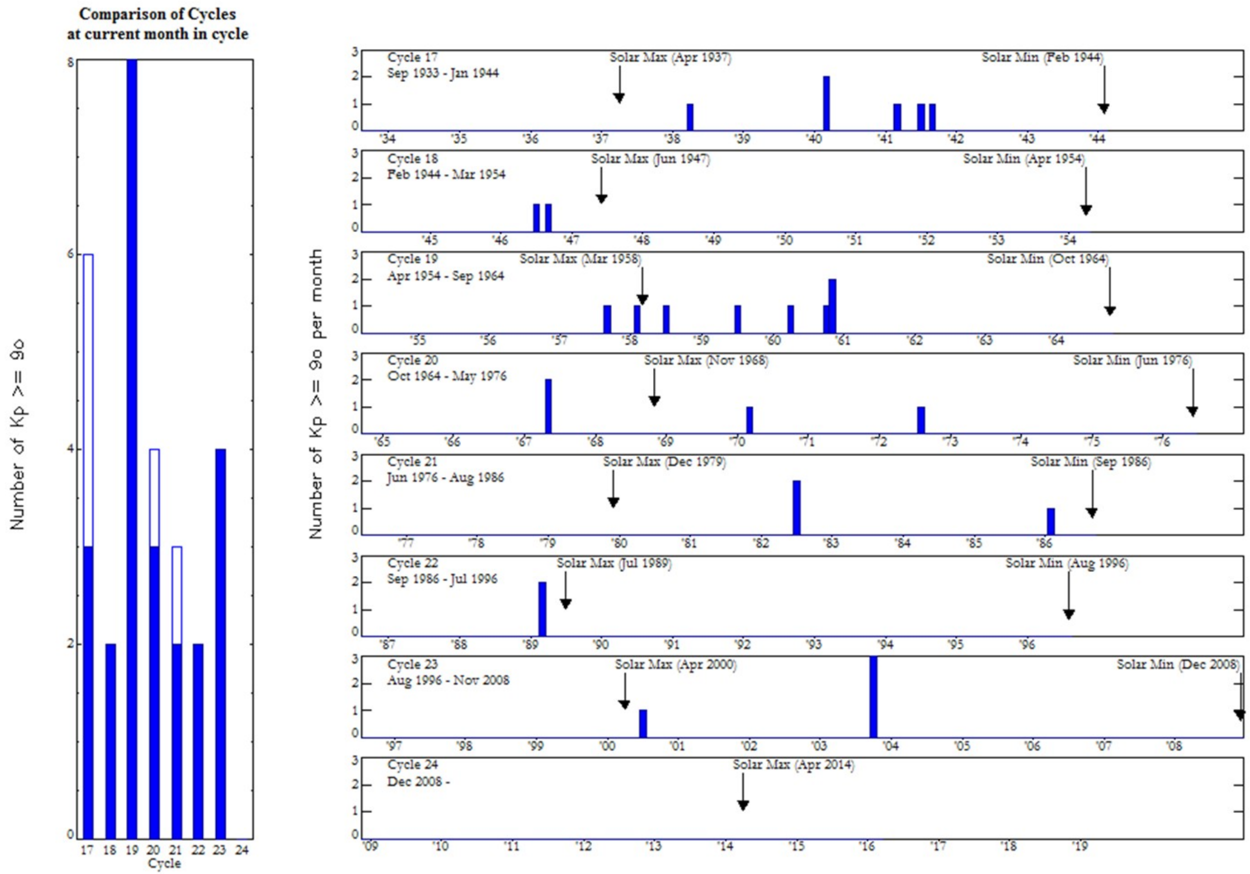




Periods with Kp >= 9o

March 2016

(Month 88)

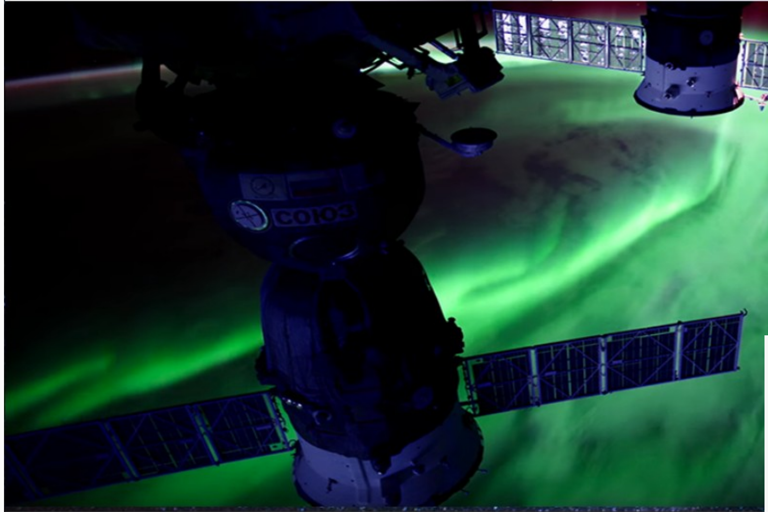


http://sworm.gov/ Space Weather Operations Research and Mitigation

SWORM

Space Weather Operations, Research and Mitigation Subcommittee

SPACE WEATHER | PUBLICATIONS | MEETINGS | ABOUT



The Space Weather Operations, Research, and Mitigation (SWORM)
coordinating body of the Committee on Environment, Natural Resourc
organized under the Office of Science and Technology Policy (OSTP), ac
Technology Council. The SWORM coordinates Federal Government depa
objectives specified in the National Space Weather Strategy and the act
Plan, both of which were released in Oc

The White House

Office of the Press Secretary

For Immediate Release October 13, 2016

Executive Order -- Coordinating Efforts to Prepare the Nation for Space Weather Events

EXECUTIVE ORDER

\- - - - - - -

COORDINATING EFFORTS TO PREPARE THE NATION FOR SPACE WEATHER EVENTS

By the authority vested in me as President by the Constitution and the laws of the United States of America, and to prepare the Nation for space weather

Home > Legislation > 116th Congress > S.881

Print Subscribe Share/Save Give Feedback

S.881 - Space Weather Research and Forecasting Act

116th Congress (2019-2020) | Get alerts

BILL Hide Overview ✖

Sponsor:	Sen. Peters, Gary C. [D-MI] (Introduced 03/26/2019)
Committees:	Senate - Commerce, Science, and Transportation
Committee Reports:	S. Rept. 116-171
Latest Action:	Senate - 12/11/2019 Placed on Senate Legislative Calendar under General Orders. Calendar No. 322. (All Actions)

Tracker:

Introduced | Passed Senate | Passed House | To President | Became Law

More on This Bill

CBO Cost Estimates [1]

Subject — Policy Area:

Science, Technology, Communications

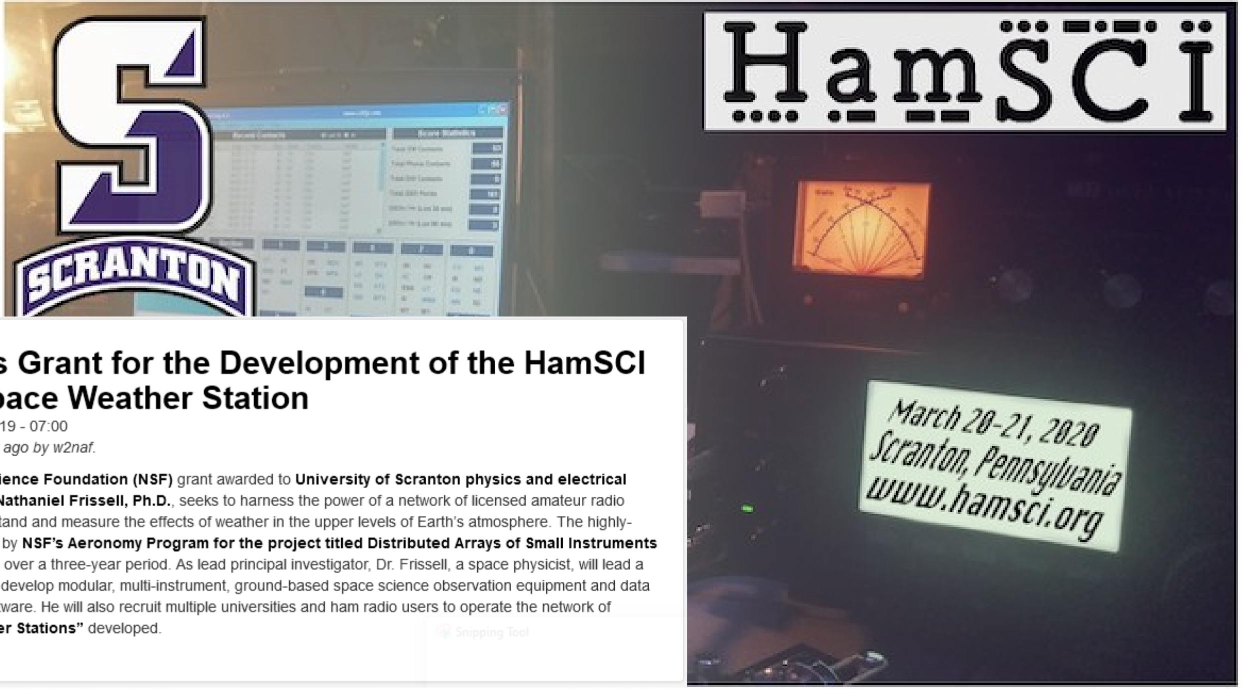
View subjects »

Summary (1) | Text (2) | Actions (4) | Titles (3) | Amendments (0) | Cosponsors (1) | Committees (1) | Related Bills (0)

Summary: S.881 — 116th Congress (2019-2020)

All Information (Except Text)

2020 HamSCI Workshop



THE UNIVERSITY OF SCRANTON
A JESUIT UNIVERSITY

NSF Awards Grant for the Development of the HamSCI Personal Space Weather Station

Thursday, November 7, 2019 - 07:00

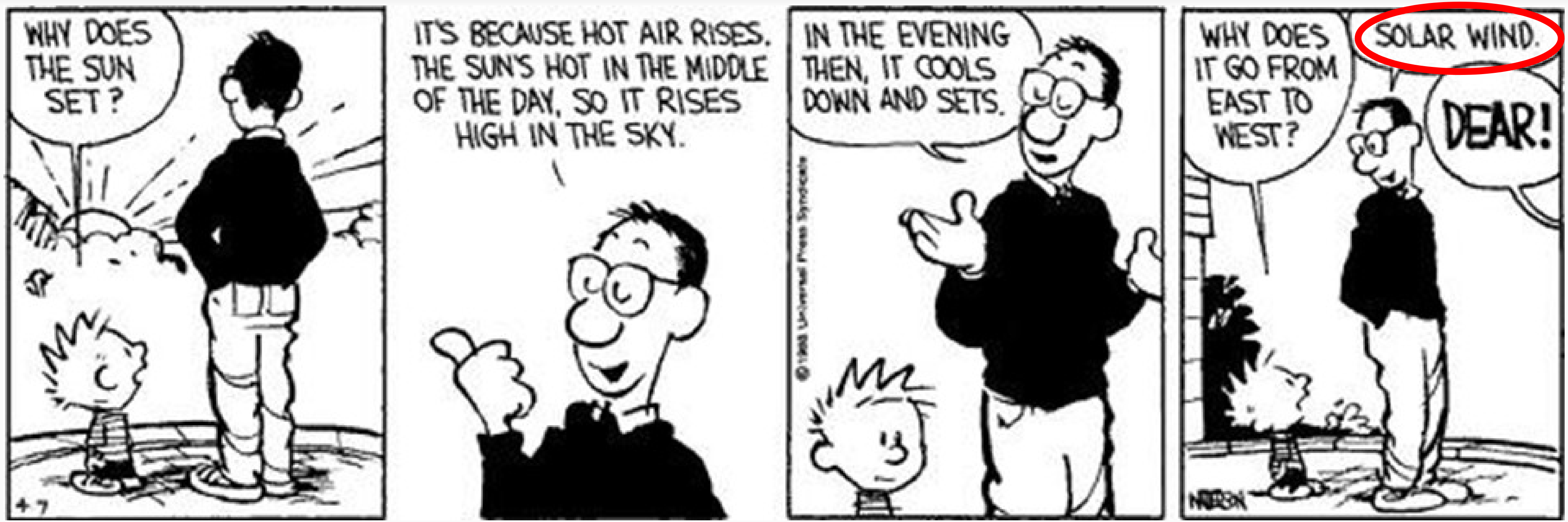
Submitted 1 month 1 week ago by w2naf.

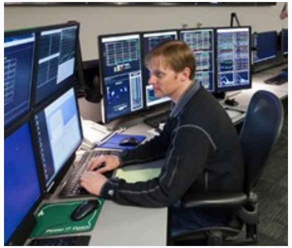
A $1.3 million **National Science Foundation (NSF)** grant awarded to **University of Scranton physics and electrical engineering professor Nathaniel Frissell, Ph.D.**, seeks to harness the power of a network of licensed amateur radio operators to better understand and measure the effects of weather in the upper levels of Earth's atmosphere. The highly-competitive grant awarded by **NSF's Aeronomy Program for the project titled Distributed Arrays of Small Instruments (DASI)** will be implemented over a three-year period. As lead principal investigator, Dr. Frissell, a space physicist, will lead a collaborative team that will develop modular, multi-instrument, ground-based space science observation equipment and data collection and analysis software. He will also recruit multiple universities and ham radio users to operate the network of **"Personal Space Weather Stations"** developed.

Read more

March 20-21, 2020 at The University of Scranton, Scranton, PA

Questions?

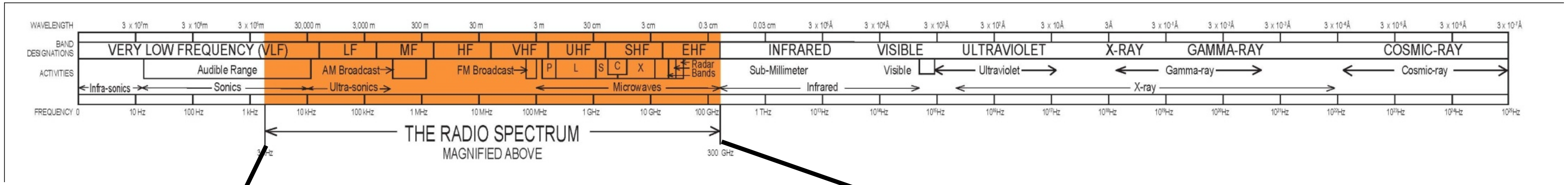

WHY DOES THE SUN SET?
IT'S BECAUSE HOT AIR RISES. THE SUN'S HOT IN THE MIDDLE OF THE DAY, SO IT RISES HIGH IN THE SKY.
IN THE EVENING THEN, IT COOLS DOWN AND SETS.
WHY DOES IT GO FROM EAST TO WEST?
SOLAR WIND.
DEAR!



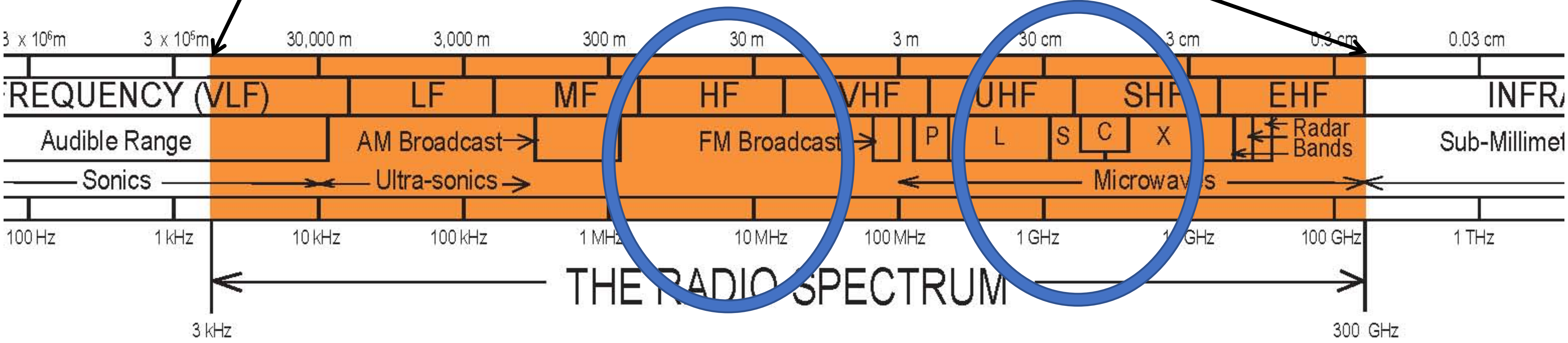
Learning Goals

- Describe a typical mid-latitude electron density profile (EDP)
- Anticipate EDP deviations for night/day; solar max/solar min
- Know the source(s) and losses of ionization in the ionosphere
- Estimate/Calculate the Maximum Usable Frequency from an EDP
- Recognize conditions for a Short Wave Fade (SWF) event

The Electromagnetic Wave Spectrum

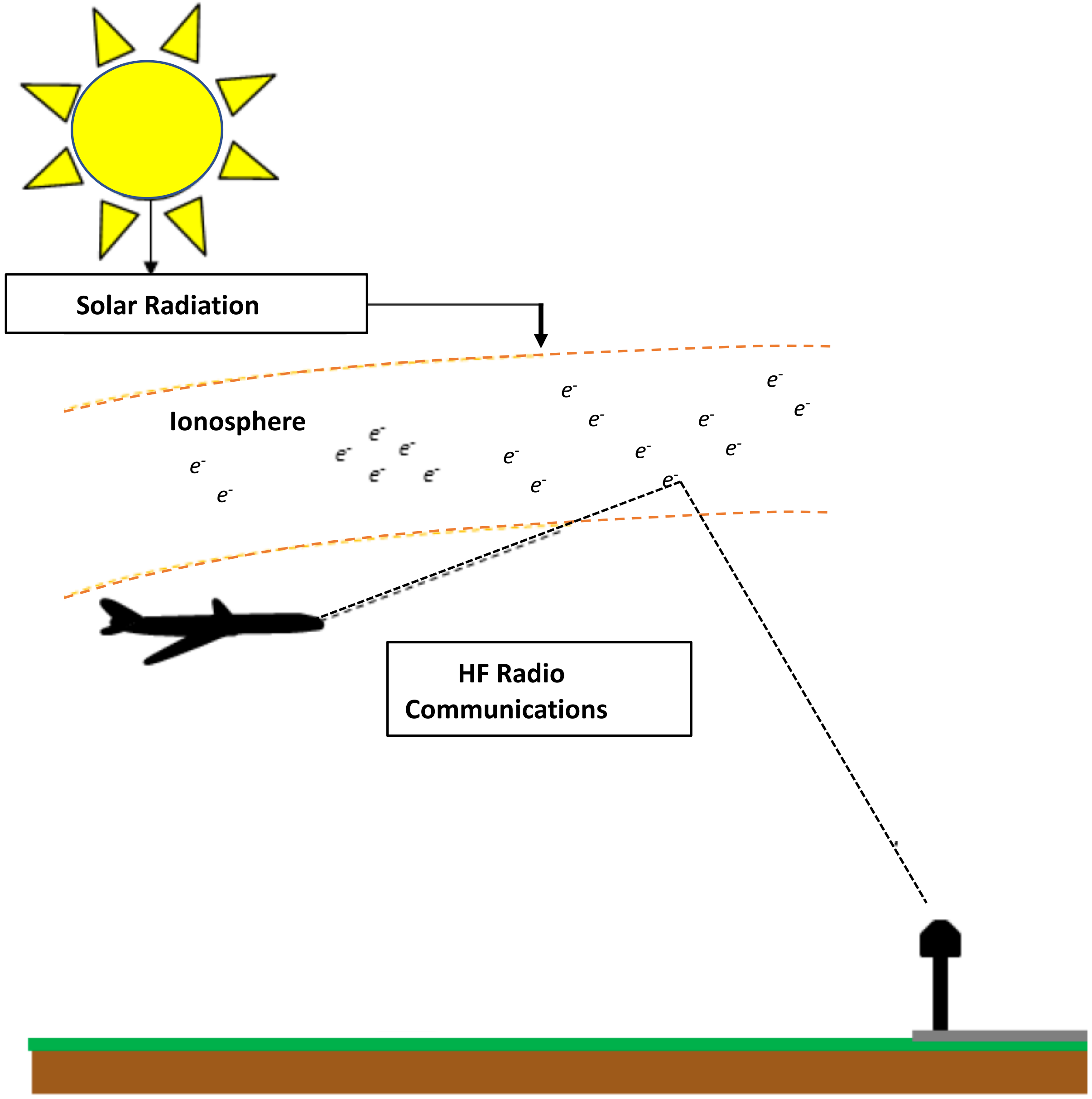


Radio Wave Spectrum



From: Dept of Commerce chart

Ionosphere: Radio Communication



After Abt Associates, 2017 for NOAA

Solar short wave radiation separates electrons from atoms in SAIR

- Produces the **ionosphere**
- Layers of ionization facilitate radio communication

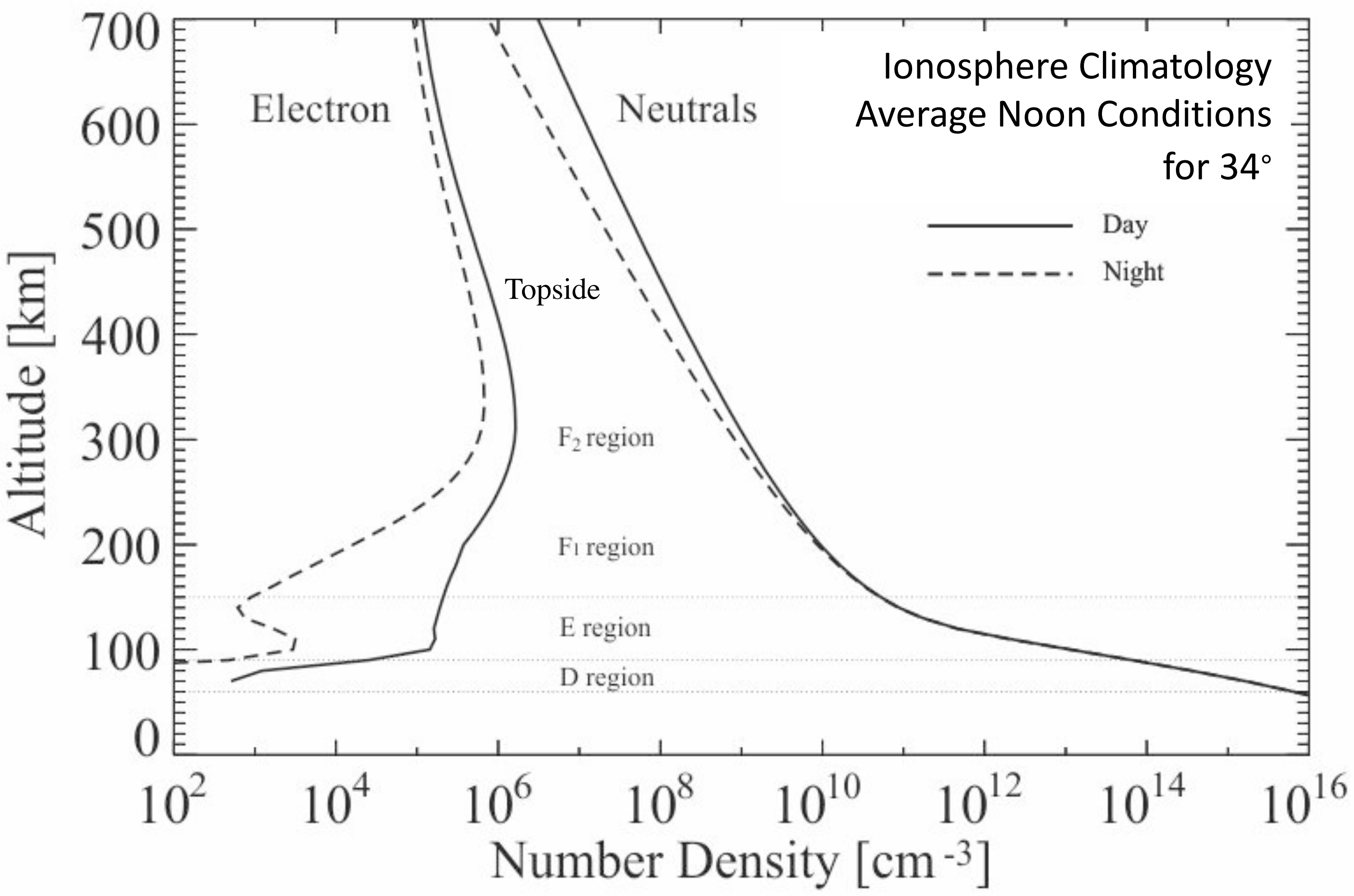
What could go wrong?

- Irregularities in ionization cause fade or block high frequency (HF) radio signals

Who cares?

Aviators
Navigators
Mariners
DoD Warriors
Emergency responders/planners
HAM radio operators
Anyone using HF as ‘backup’ comm mode

Electron Density Profile



Note use of metric, but non SI units

Neutral density: exponential decrease with alt

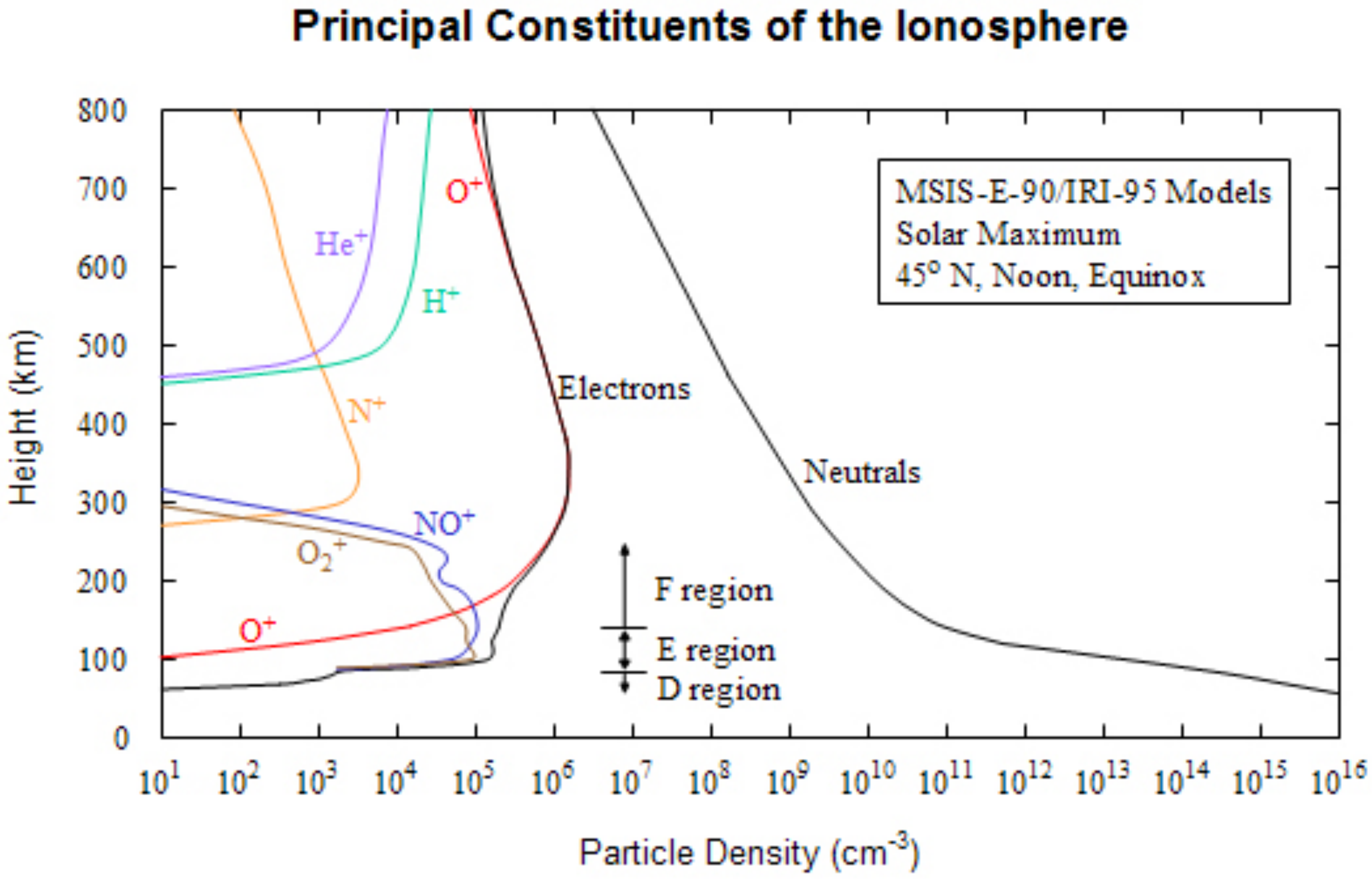
Vertical sounding (radar) reveals

- Region of weakly ionized **plasma**
- Unattached electrons constitute the ionosphere
  - 60-1000 km
  - Typically less than 0.1% of neutrals
  - Electron density profile (EDP)
- Gradients in electron density
  - Orders of magnitude change in altitude
  - **Layers of the ionosphere**
  - **D, E and F layers (regions)**

Gradients in electron density

- Refract (reflect) radio waves
- **Different densities reflect different wavelengths**
  - Reflect radio waves in 1-30 MHz range
  - High frequencies penetrate ionosphere
- Different densities
  - Day/Night (shown)
  - Seasonally/Solar Cycle/Storm time
  - Geographically

Ion and Electron Density Profile



Various instruments/techniques reveal

- Constituents of the ionosphere

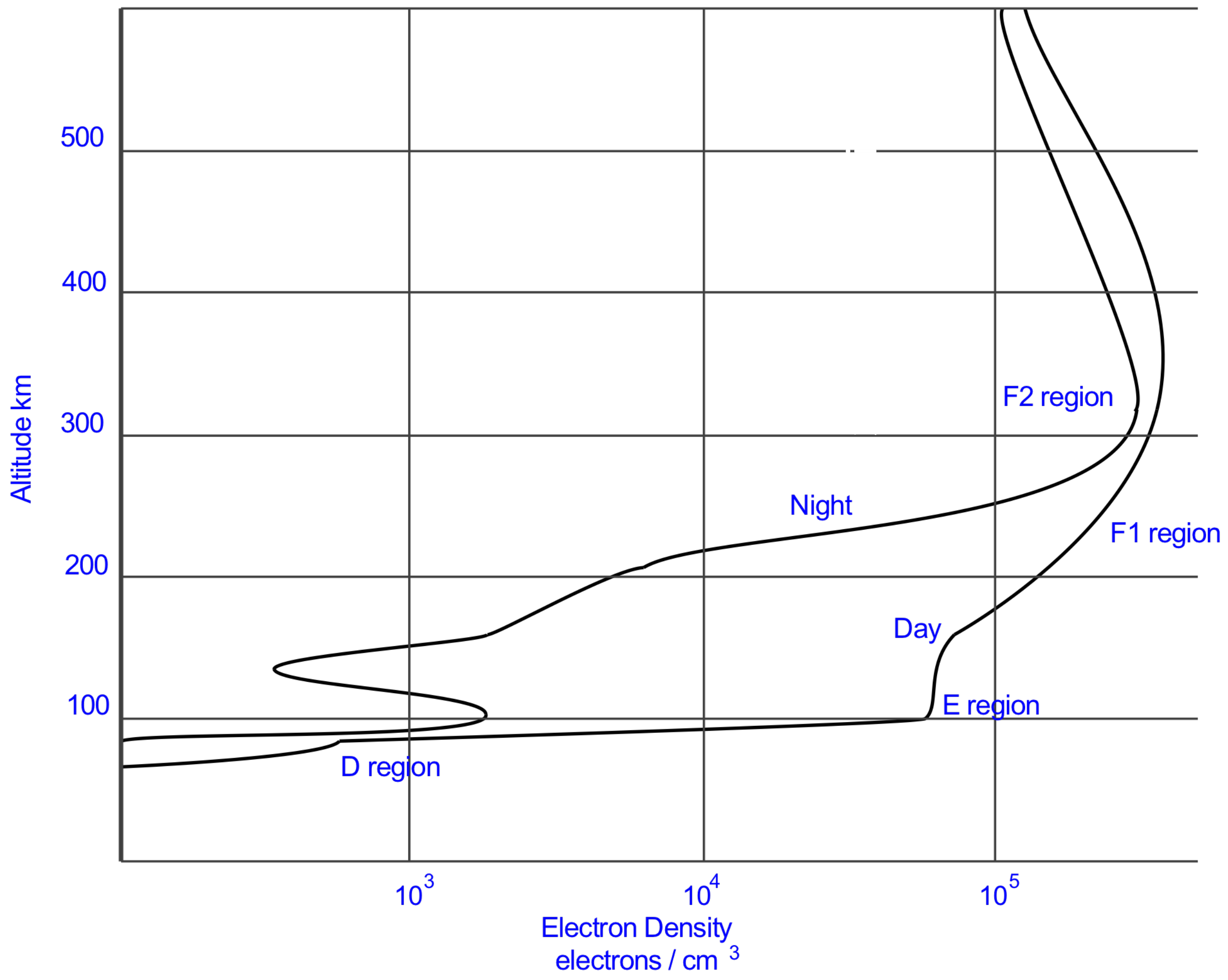
Lighter ions at the top

- Diffusion process: topside
- Chemistry and solar interactions: bottomside
  - Atomic O and O_2 above 100 km
    - **O+ dominates the profile**
  - Nitric Oxide below 100 km
    - Produce NO+

Solar Shortwave Radiation

- Different interactions with different species
  - Ionization cross section
- Different densities
  - Day/Night
  - Seasonally/Solar Cycle/Storm time
  - Geographically

Electron Density Profiles (EDP) and Solar Radiation (1)



Solar Shortwave Radiation

- **Different interactions with different species**
- **Upper atmosphere acts as wavelength filter**

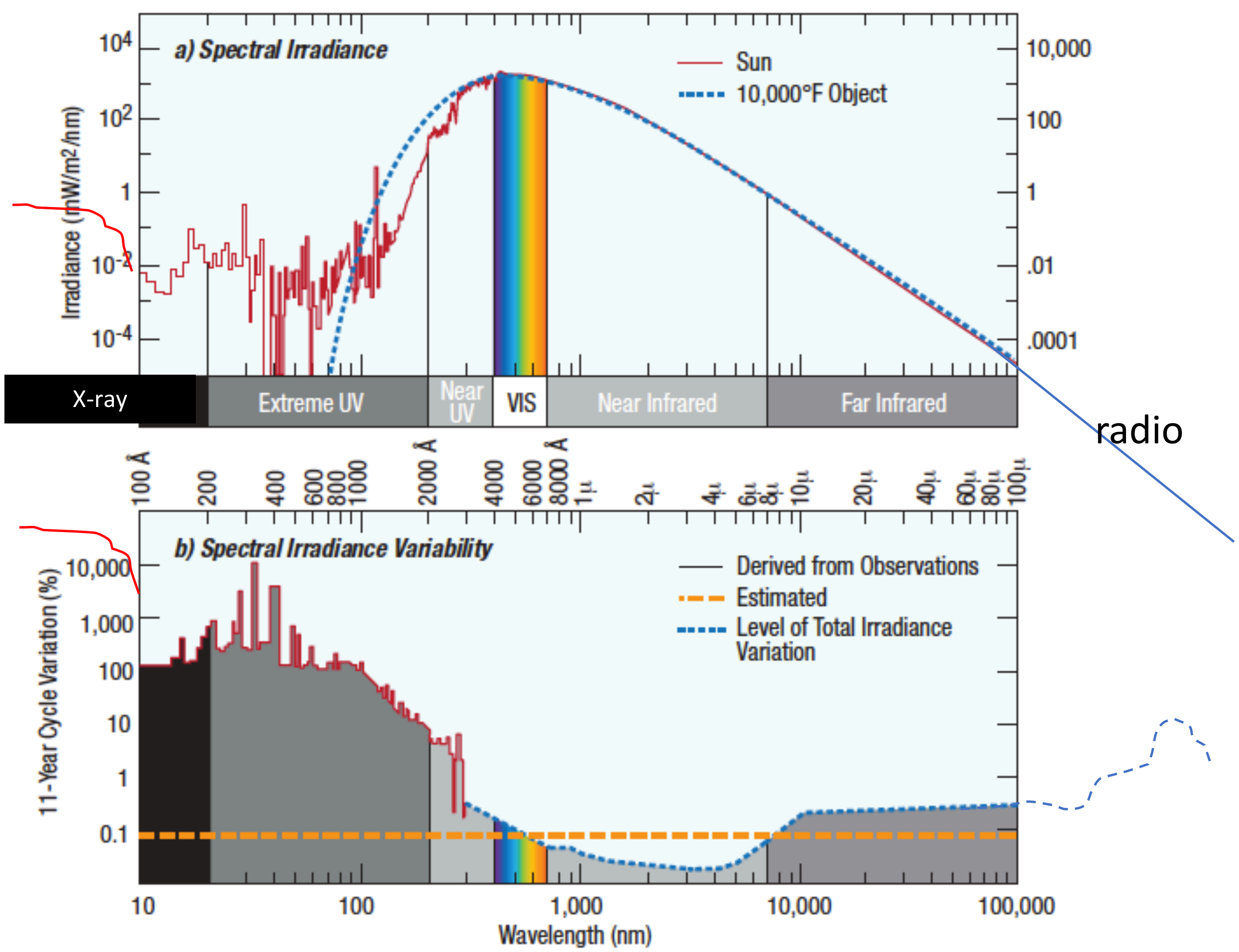
- **Daytime peak above 300 km**
  - Radiation separates ions and electrons
  - Broad peak
  - Other maxima lower
  - Typically 3-4 maxima (layers)
- **Nighttime peak is lower**
  - Many electrons and ions recombine
  - Narrower peak below 300 km
  - Lower peak ~ 100 km

- **Balance between production and loss**

- **D, E and F regions (or layers)**
  - 'E' for electron
  - F layer splits during day

Background graphic: https://www.electronics-notes.com/articles/antennas-propagation/ionospheric/ionospheric-layers-regions-d-e-f1-f2.php

Solar Photon Emissions: Ionospheric Climate and Weather



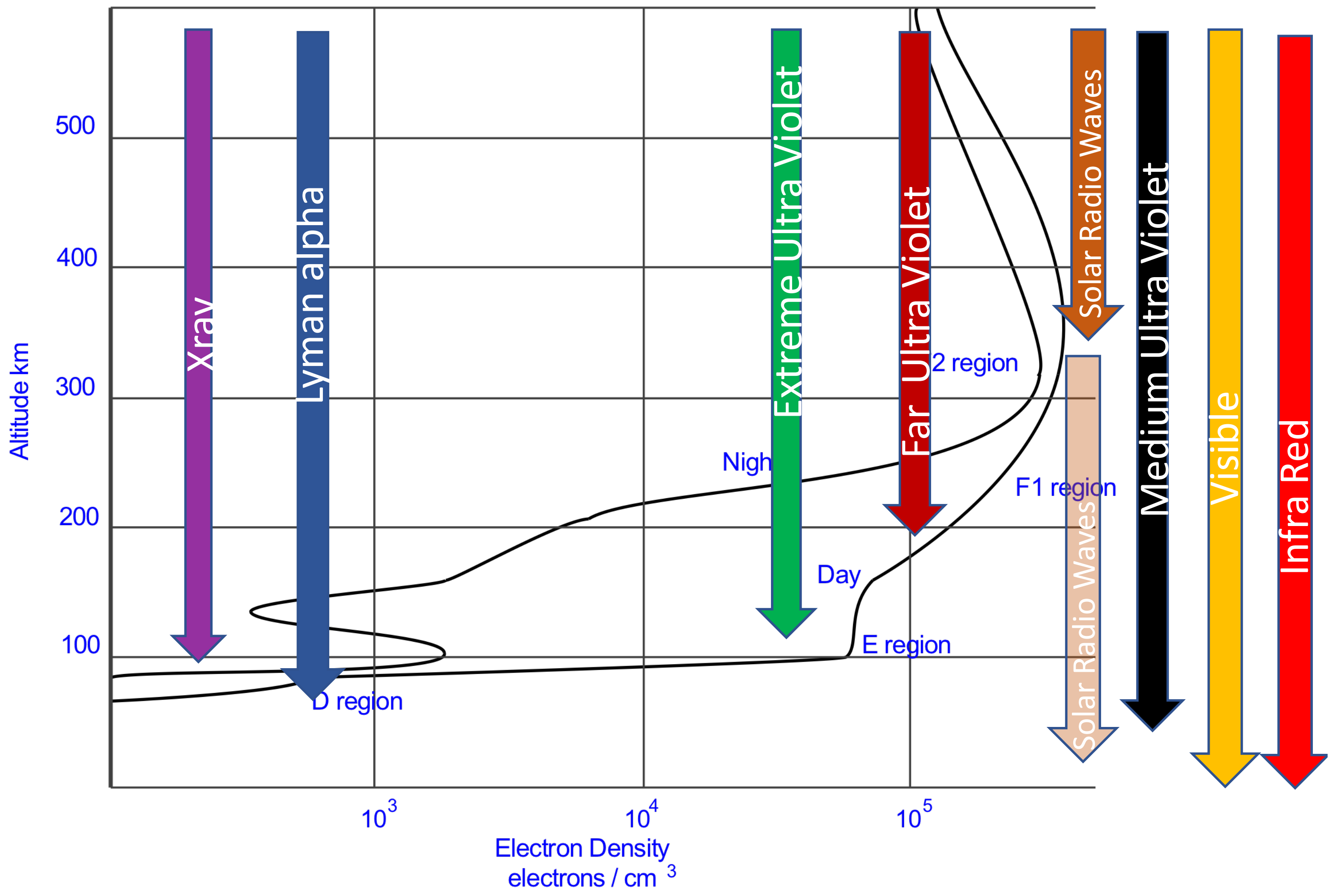
J. Eddy, pg 101

Solar Space Weather Effects

- The very short and very long wavelength portion of the electromagnetic spectrum play a large role in space weather.

- The short and long wavelength portions of the spectrum exhibit much more variability than the visible and infrared portion

Electron Density Profiles (EDP) and Solar Radiation (2)



Solar Shortwave Radiation

- **Different interactions with different species**
- **Upper atmosphere acts as filter**

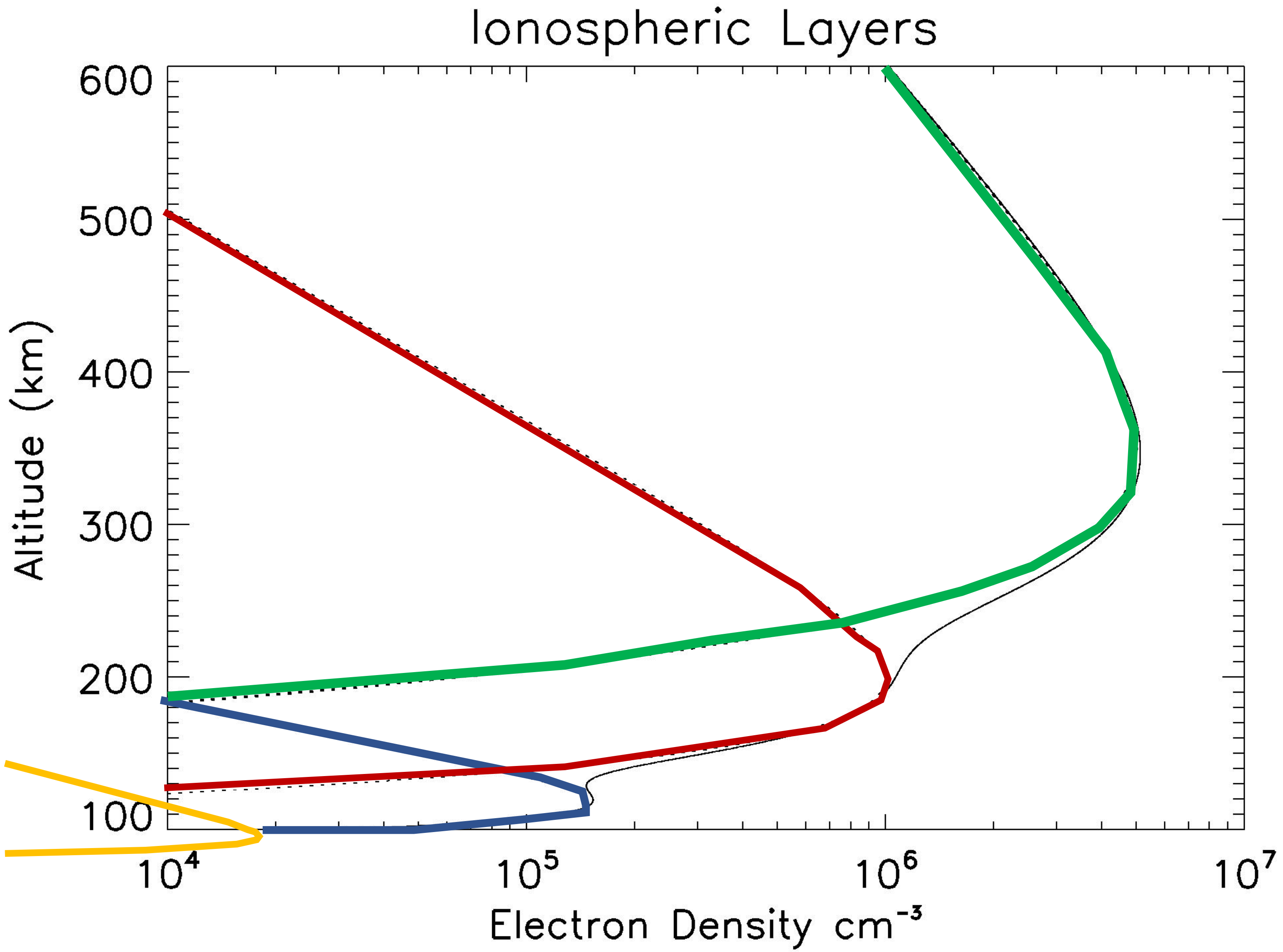
- **Ionization cross section**
  - Some species are good absorbers
  - Energy is used for ionization
  - Atomic oxygen & O_2 above 100 km
    - Produces lots of O+ and O_2+
  - Nitric Oxide below 100 km
    - Produce NO+
- **Free electrons interact with radio waves**
  - Also share their energy via heat
  - Attenuation of signal

- **Where do other solar wavelengths go?**

- **What about night time ionization?**

Background graphic: https://www.electronics-notes.com/articles/antennas-propagation/ionospheric/ionospheric-layers-regions-d-e-f1-f2.php

EDP as an Envelope of Ionosphere Layers

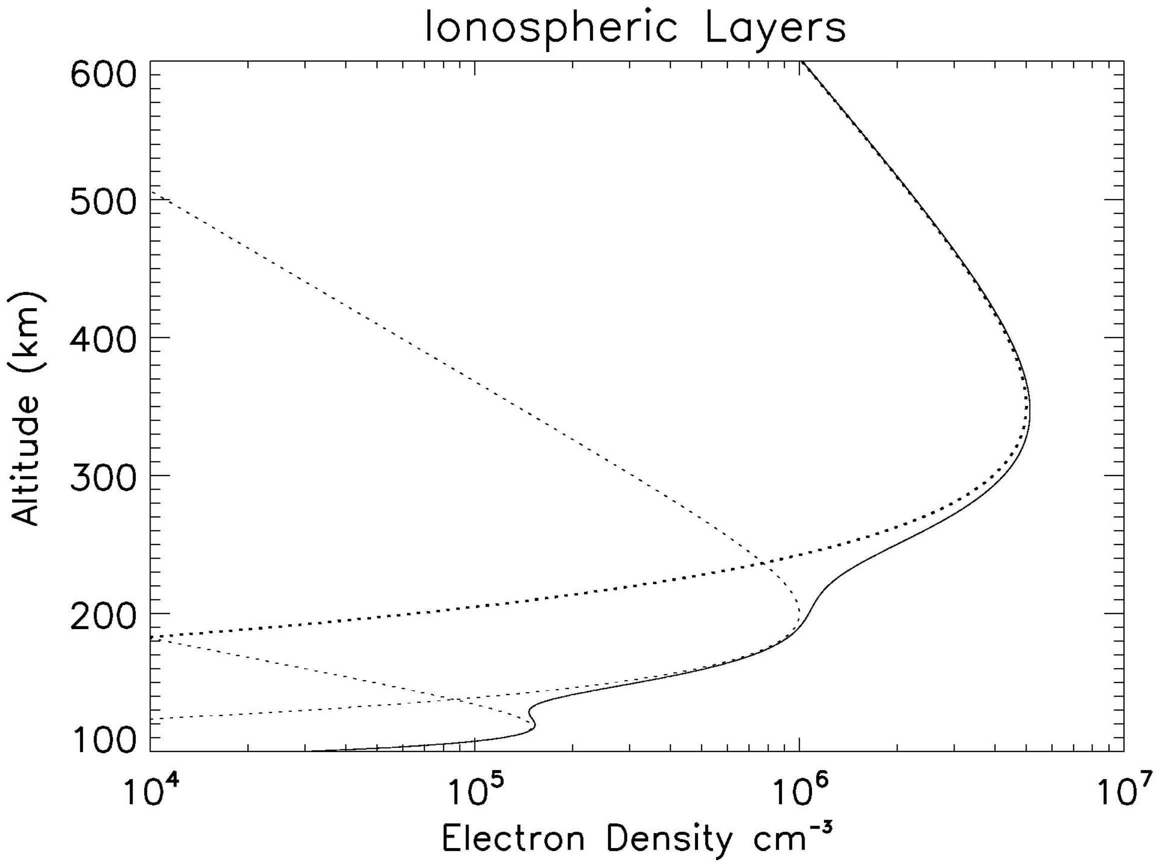


Wavebands produce layers

- Layers overlap
- Upper layers
    - thicker (deeper)
    - more ionization
    - Longer-lived

Balance in Ionospheric Layer Production

- Production of ions/free electrons is balanced by recombination



- F-region

Photo-ionization

$$O + h\nu \longrightarrow O^+ + e^-$$
$$N_2 + h\nu \longrightarrow {N_2}^+ + e^-$$
$$O_2 + h\nu \longrightarrow {O_2}^+ + e^-$$

Charge exchange

$$O^+ + N_2 \longrightarrow NO^+ + N$$
$$O^+ + O_2 \longrightarrow {O_2}^+ + O$$
$${N_2}^+ + O \longrightarrow NO^+ + N$$

Temperature dependent

Loss by Re-comb-ination

$$NO^+ + e^- \longrightarrow N + O$$
$${O_2}^+ + e^- \longrightarrow O + O$$
$${N_2}^+ + e^- \longrightarrow N + N$$

D Region Background

- D-region (about 60 to 90 km altitude)
  Production: daytime ionization of nitric oxide (NO) by solar Lyman alpha (121 nanometer wavelength) and of nitrogen and oxygen (N2, O2) by solar X-rays (less than 20 nm). Molecular ions react with water vapor to produce water cluster ions.
  Loss: electrons recombine rapidly with water cluster ions and also attach to molecules to make negative ions (but rapidly detach again in daylight).
  Balance: layer disappears at night (within several minutes) as production essentially ceases and electrons undergo rapid recombination and attachment.

E Region Background

- E-region (about 90 to 140 km altitude)
  Production: daytime ionization of molecular oxygen (O_2) by extreme ultraviolet solar radiation (90-103 nm), ionization of meteoric vapors.
  Loss: electrons recombine with molecular ions (O_2^+ and NO^+).
  Balance: layer persists, although diminishes, during night due to slower recombination (than in D-region) and presence of atomic metallic ions such as Na^+ (sodium) and Fe^+ (iron). Electrons recombine with atomic ions (such as Na^+ or O^+) very inefficiently.

  E region behaves as a Chapman layer.

  At the E region heights sporadic thin layers can be formed that can have electron densities well above the background values.

F Region Background

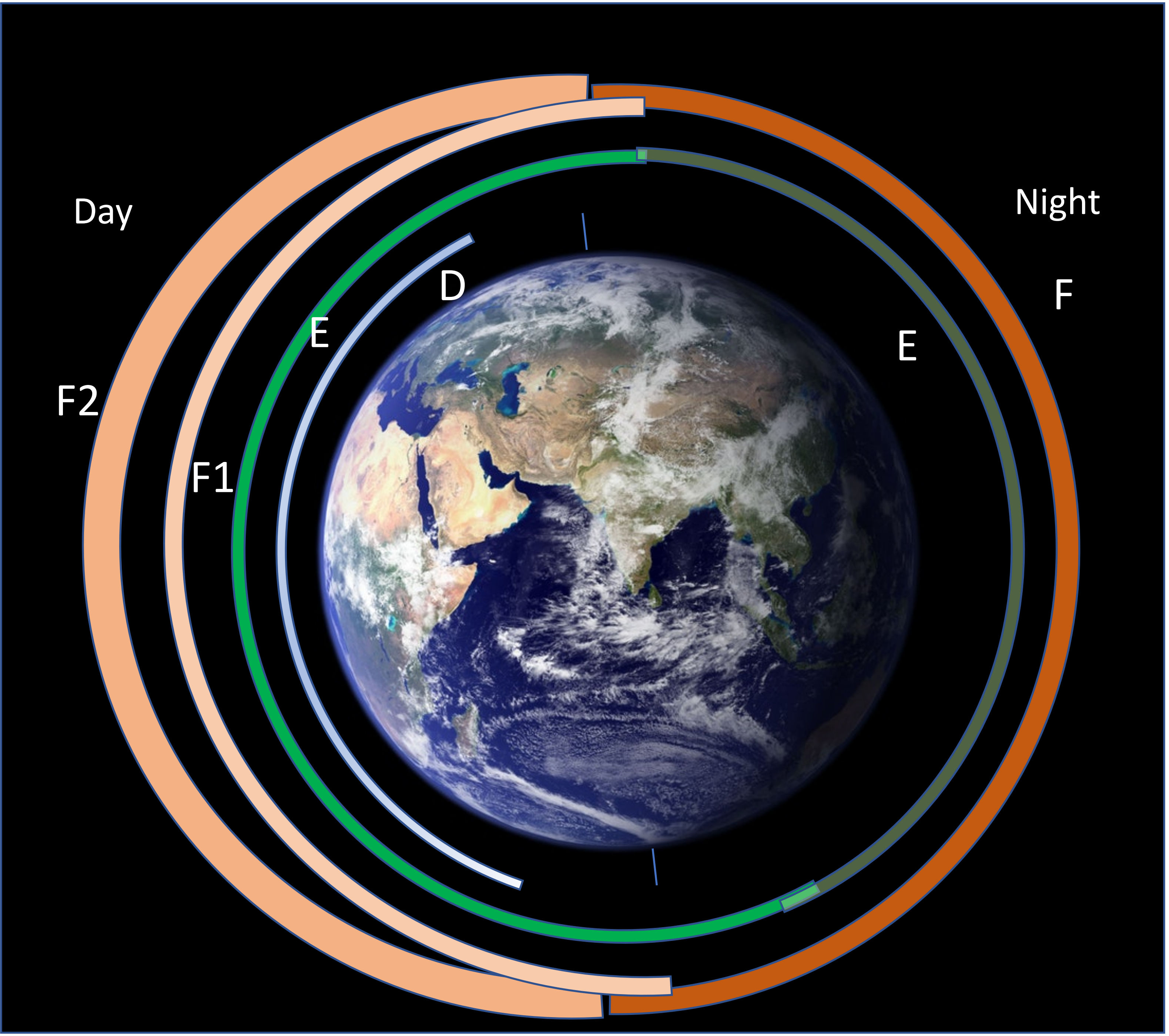
- F-region (above 140 km altitude)
  Production: daytime ionization of atomic O by extreme ultraviolet (EUV) solar radiation (20 - 90 nm). O+ converted to NO+ by molecular nitrogen (N2)

- F1-layer (about 140 to 200 km altitude)
  Loss: controlled by recombination of NO+ ions with electrons.
  Balance: layer diminishes at night as electrons recombine with NO+.

  F1 layer behaves as a Chapman layer

- F2-layer (peak about 300 to 400 km altitude)
  Loss: controlled by O+ reaction with molecular nitrogen (N2), electrons recombine quickly with ion product (NO+) as it is created.
  Balance: layer persists through night (becoming simply the F-region) since the small supply of N2 leads to slow conversion of O+ to NO+ and hence only a small reduction in the number of electron.

  Transport processes become important in the F2 and upper F regions, including ambipolar diffusion and wind-induced drifts along B, and and electrodynamic drifts across B.



Idealized View of Ionosphere Layers

Layer characteristics change from day to night:

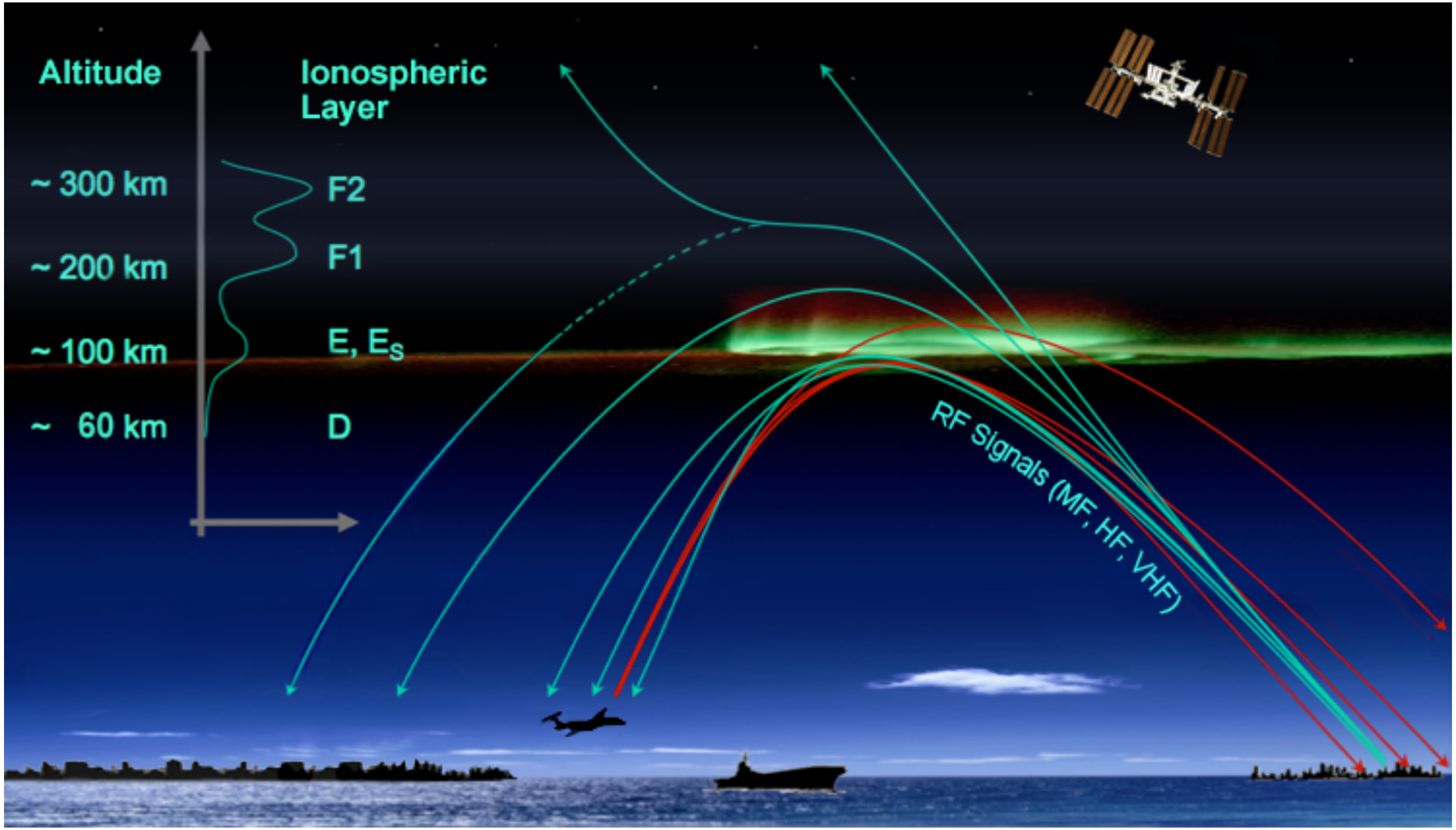
- D region disappears
- E region weakens/becomes sporadic
- F region combines

Fun Fact/Question

Which region gets a mention in the musical "Cats"?

Not to scale

HF Radio Communication and the Ionosphere



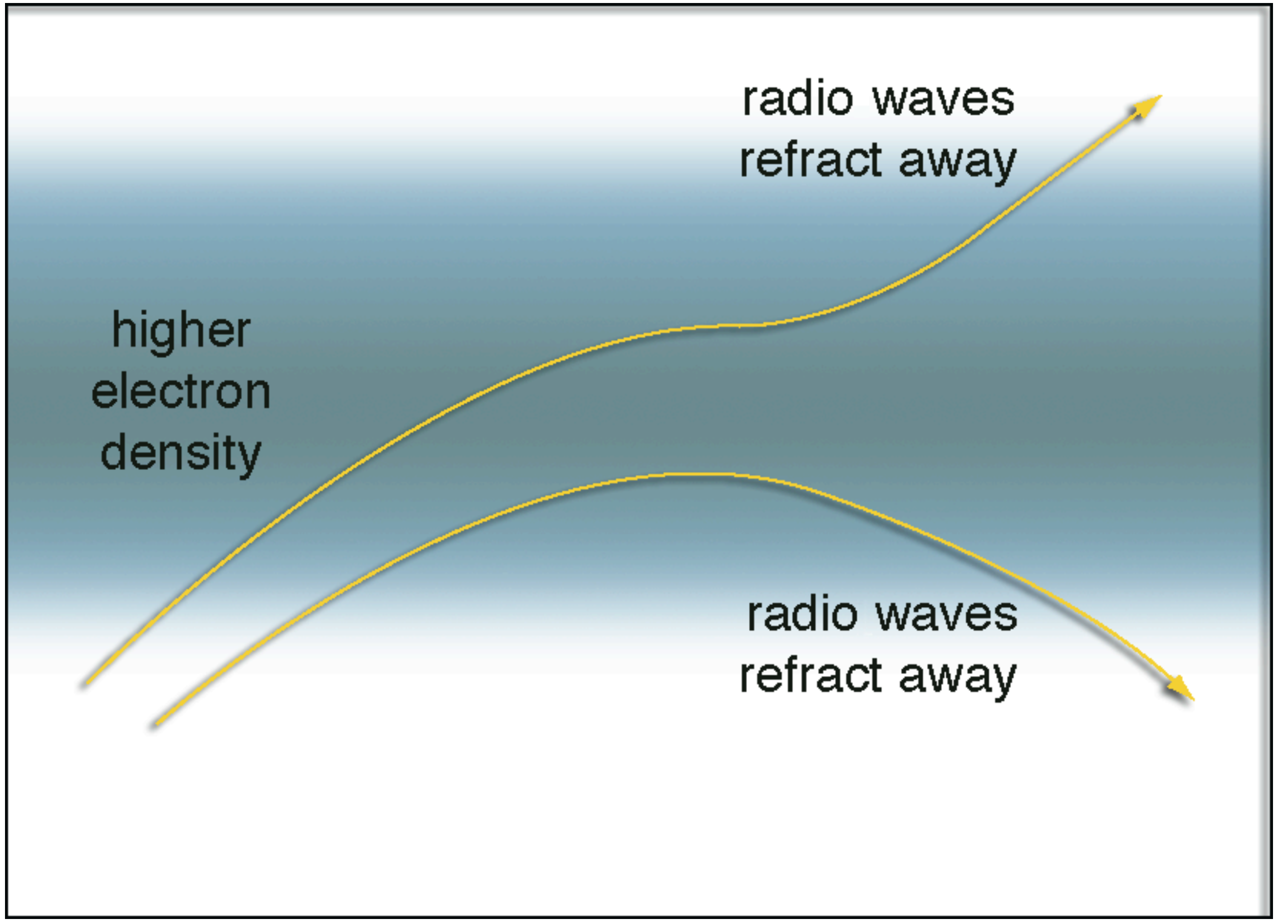
Solar radiation & auroral particles produce regions (layers) of ionization in Earth's upper atmosphere:

- Sustained radio communication relies on the "good behavior" of the ionosphere
- Irregular variations disturb/inhibit communication
- More on particles later

*Marconi-1901
*Heaviside & Kennelly 1902

http://www.astrosurf.com/luxorion/qsl-hf-tutorial-nm7m8.htm

Radio Communication and the Ionosphere: Reflectivity



Gradients in electron density

Layers of enhanced electron density

- **Ionosphere layers or regions**

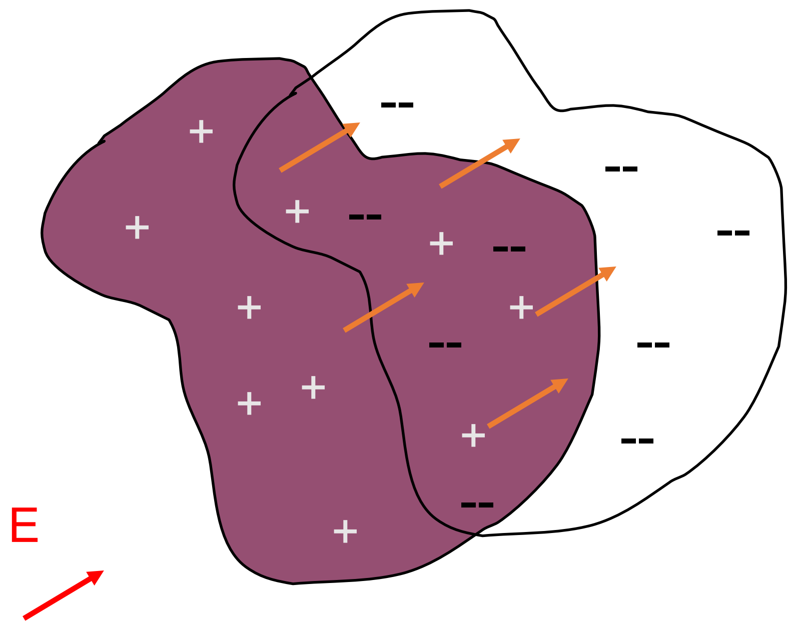
Gradients in electron density

- Higher electron density guides waves away from peak density
- Refract (reflect) radio waves

Different densities reflect different wavelengths

- MHz range reflect/refract
- High frequencies penetrate but bend

Plasma frequency



$$f_p = \sqrt{\frac{n_e e^2}{2\pi m_e \varepsilon_0}} \approx 9 n_e^{1/2} kHz$$

n_e = Electron Density   e = Charge on electron

m = Mass of an electron ε_0 = Permittivity of free space

If the electrons in a plasma are perturbed be passing radio wave

- Assuming the ions are much more massive, thus stationary
- Electrons oscillate about their equilibrium position
  - Simple Harmonic Motion
  - At frequency known as the **plasma frequency**.

Electromagnetic waves in a plasma

Group velocity

$$v_{gp} = c\sqrt{1-\left(\frac{f_p}{f_{wave}}\right)^2} \le c$$

= the speed of light
Speed information can travel in medium

An electromagnetic wave can only propagate through a plasma if its frequency is greater than the local plasma frequency;

- then a wave packet or signal travels at the group velocity

The total delay in a signal is proportional to the column number density of path – the Total Electron Content or TEC

Reflection of radio waves

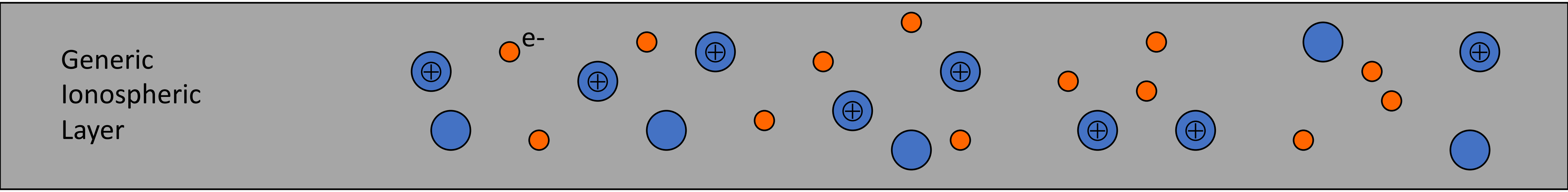
$$f_{wave} = f_p = \sqrt{\frac{n_e e^2}{2\pi m_e \varepsilon_0}} \sim 9 n_e^{1/2} kHz$$

$$v_{gp} = c\sqrt{1 - \left(f_p / f_{wave} \right)^2} \leq c$$

If an electromagnetic wave propagates into a plasma with increasing plasma density, its

- group velocity will get progressively slower as the plasma frequency increases to near the wave frequency.
- The wave will reflect at the point where the wave frequency equals the plasma frequency, i.e. where

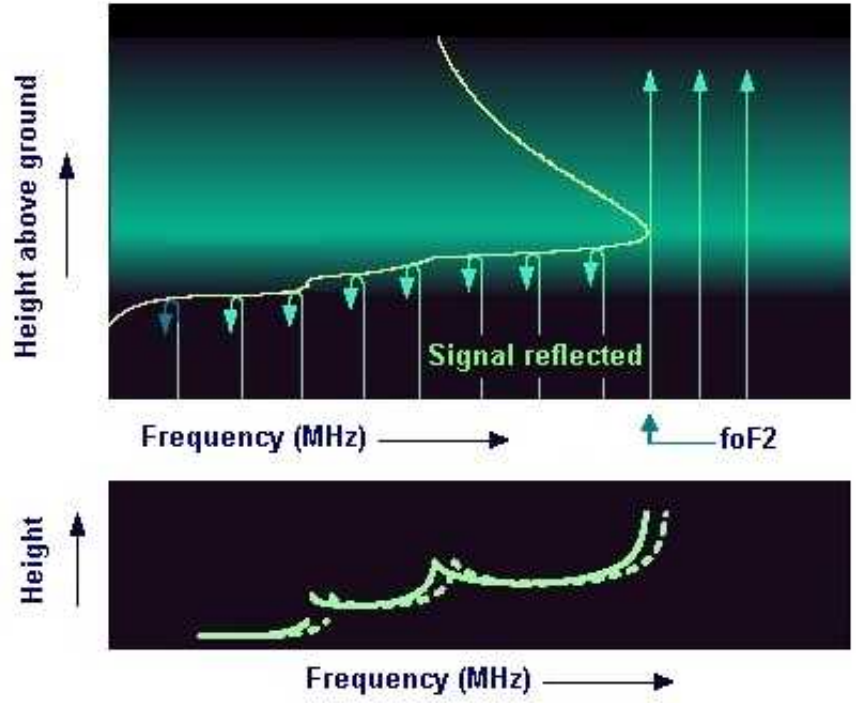
Frequency Calculation



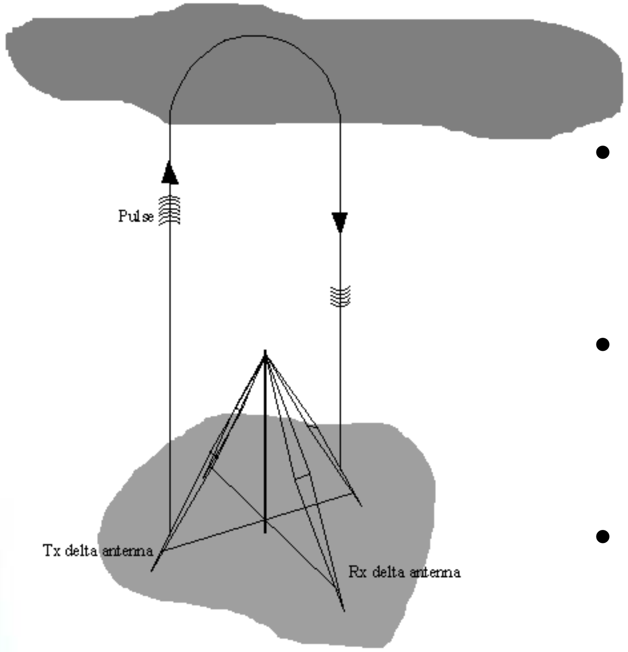
$$f_p = \sqrt{\frac{n_e e^2}{2\pi m_e \varepsilon_0}} \approx 9 n_e^{1/2} kHz$$

So if $n_e = 10^6\ \mathrm{cm}^{-3}$, $f_p =$

Radio Communication and Ionospheric ‘Sounding’



10 MHz



- As radio waves pass, electrons oscillate in simple harmonic motion
- Electrons being the lightest are most responsive
- Use radar to ’sound’ the ionosphere with varying radio wavelengths
  - With just the right (critical) wavelength the radio wave escapes
  - Below critical frequency the signal ‘returns’
  - Above critical frequency the signal passes through

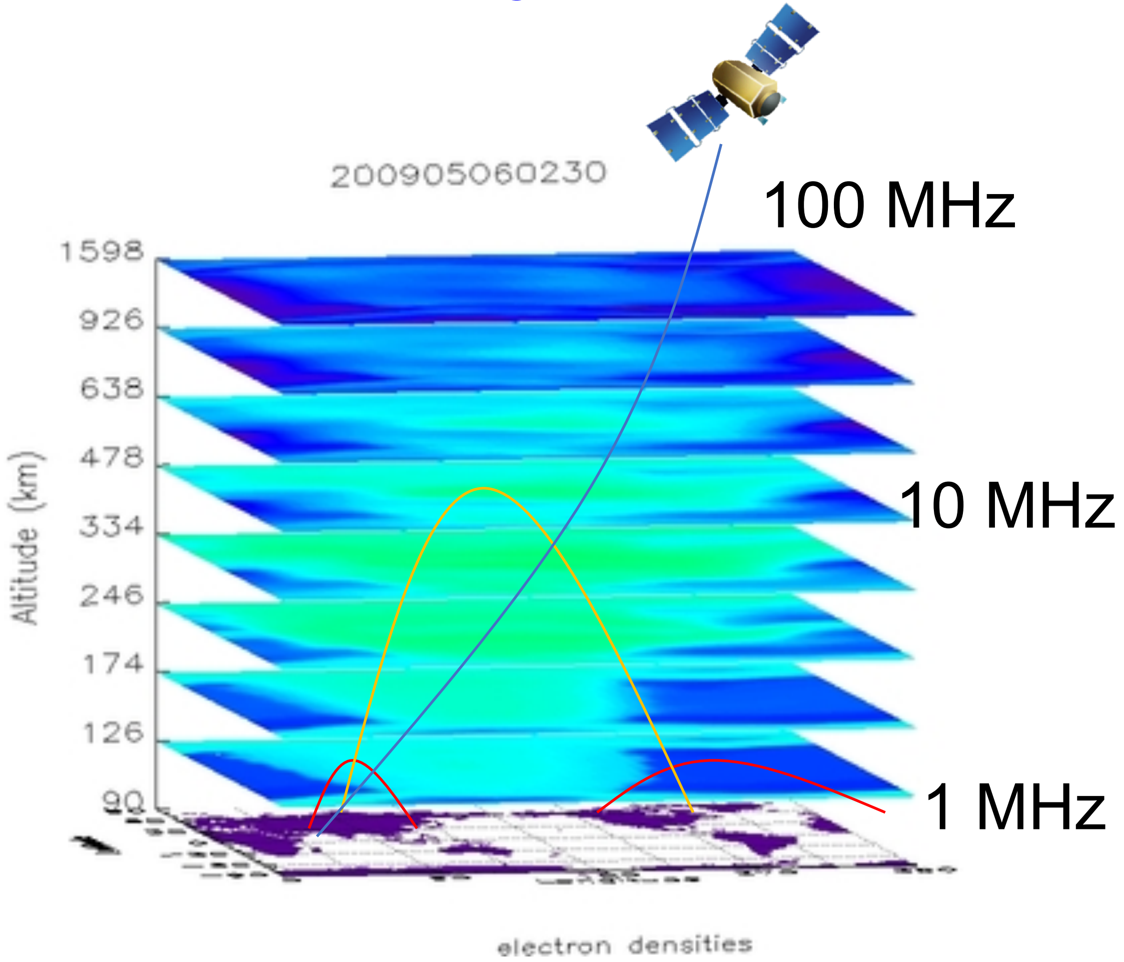
http://www.astrosurf.com/luxorion/Radio/ionogram-reflection.jpg

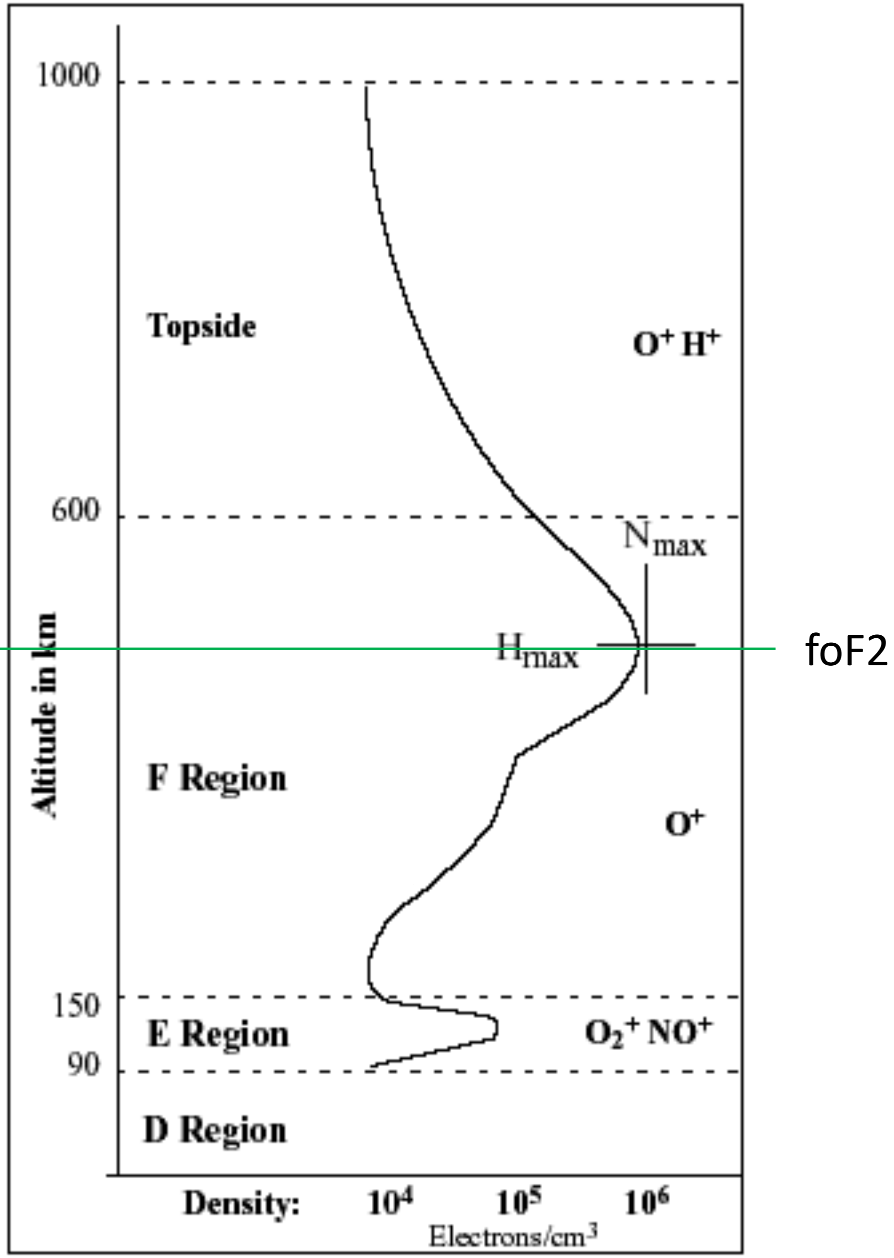
Time-out-to-think #1

Your ionosonde returns a good signal at 900 kHz during the day. You are likely getting returns from the

1. D region.
2. E region.
3. F1 region.
4. F2 region.
5. Topside ionosphere

Summary:
Electron Density Profiles and Solar Radiation



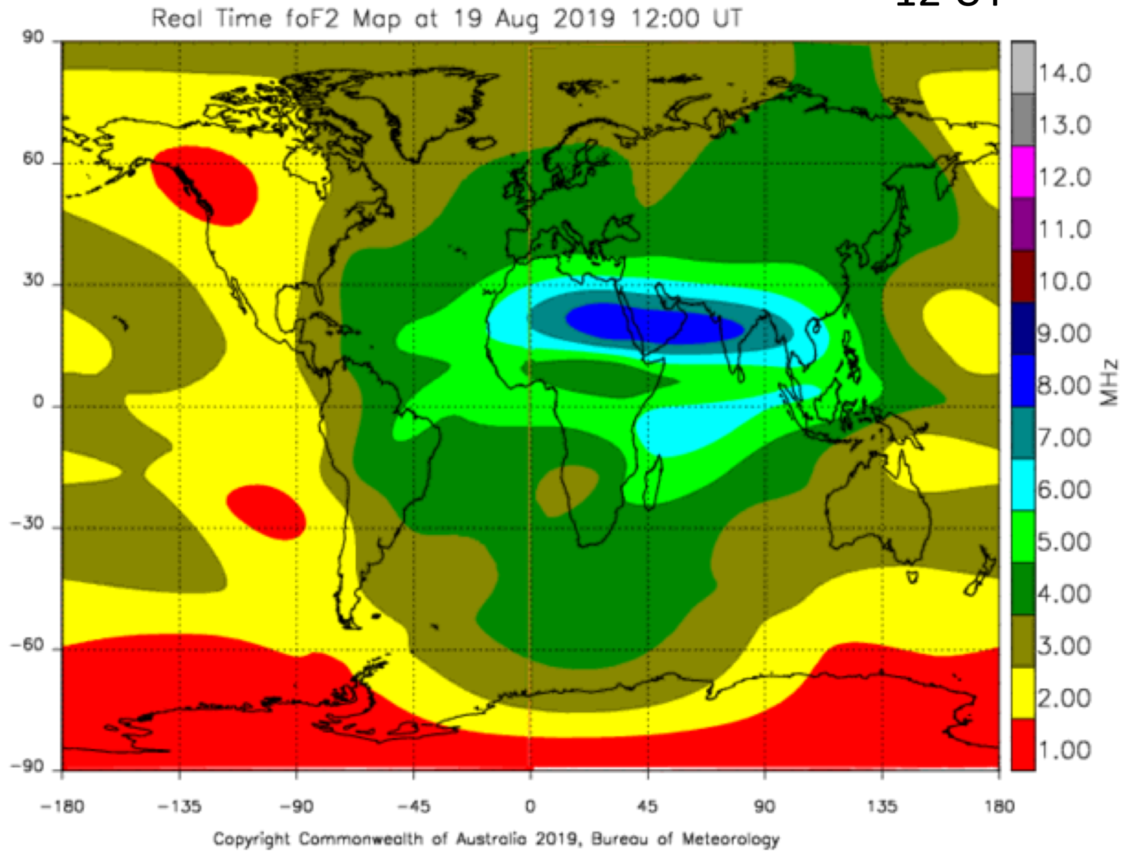


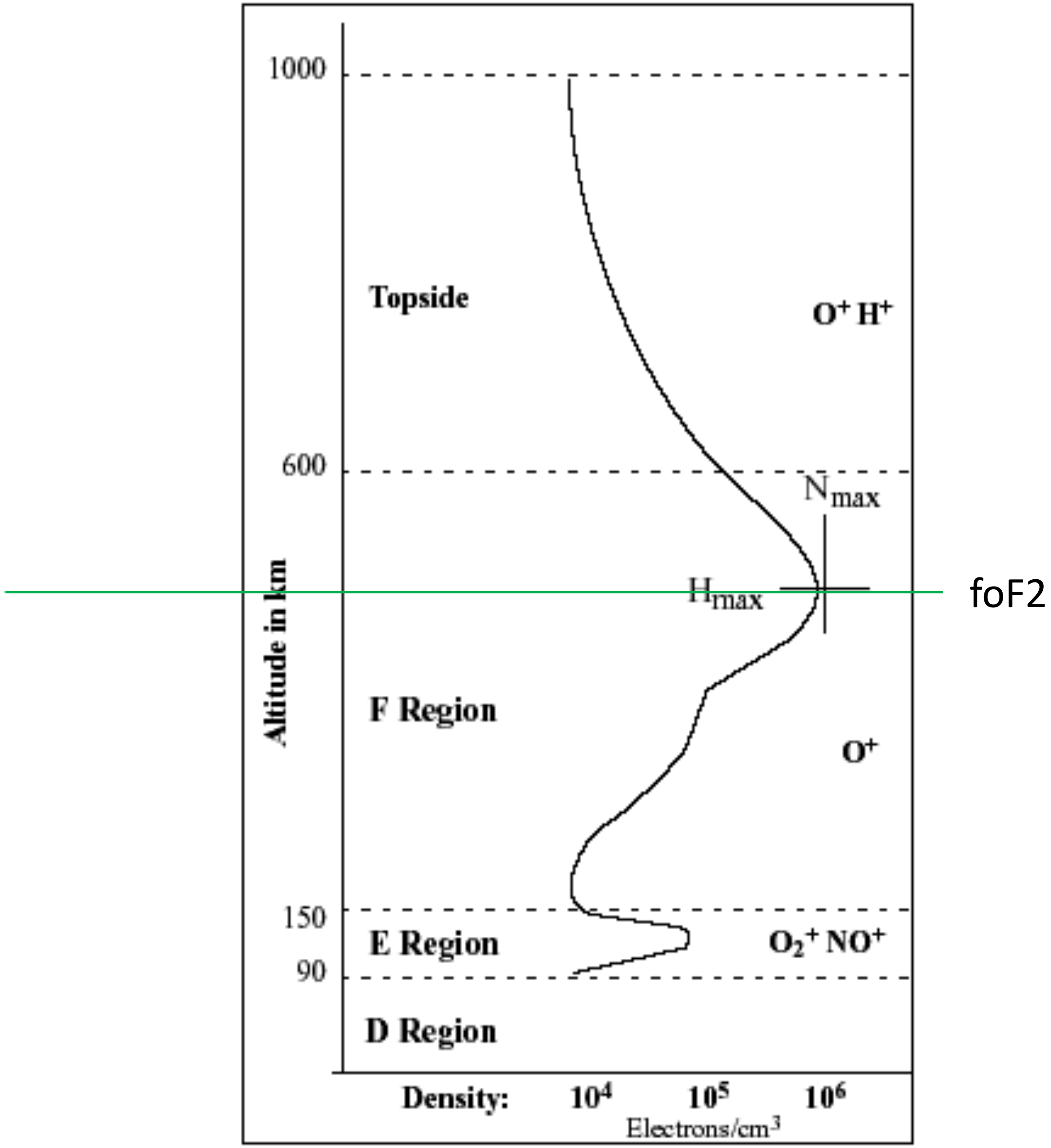
Height/slice view of HF radio propagation

- Height variations in electron density produced by solar short wave radiation control/modulate propagation of HF radio waves

Wordwide Critical Frequency Map

12 UT



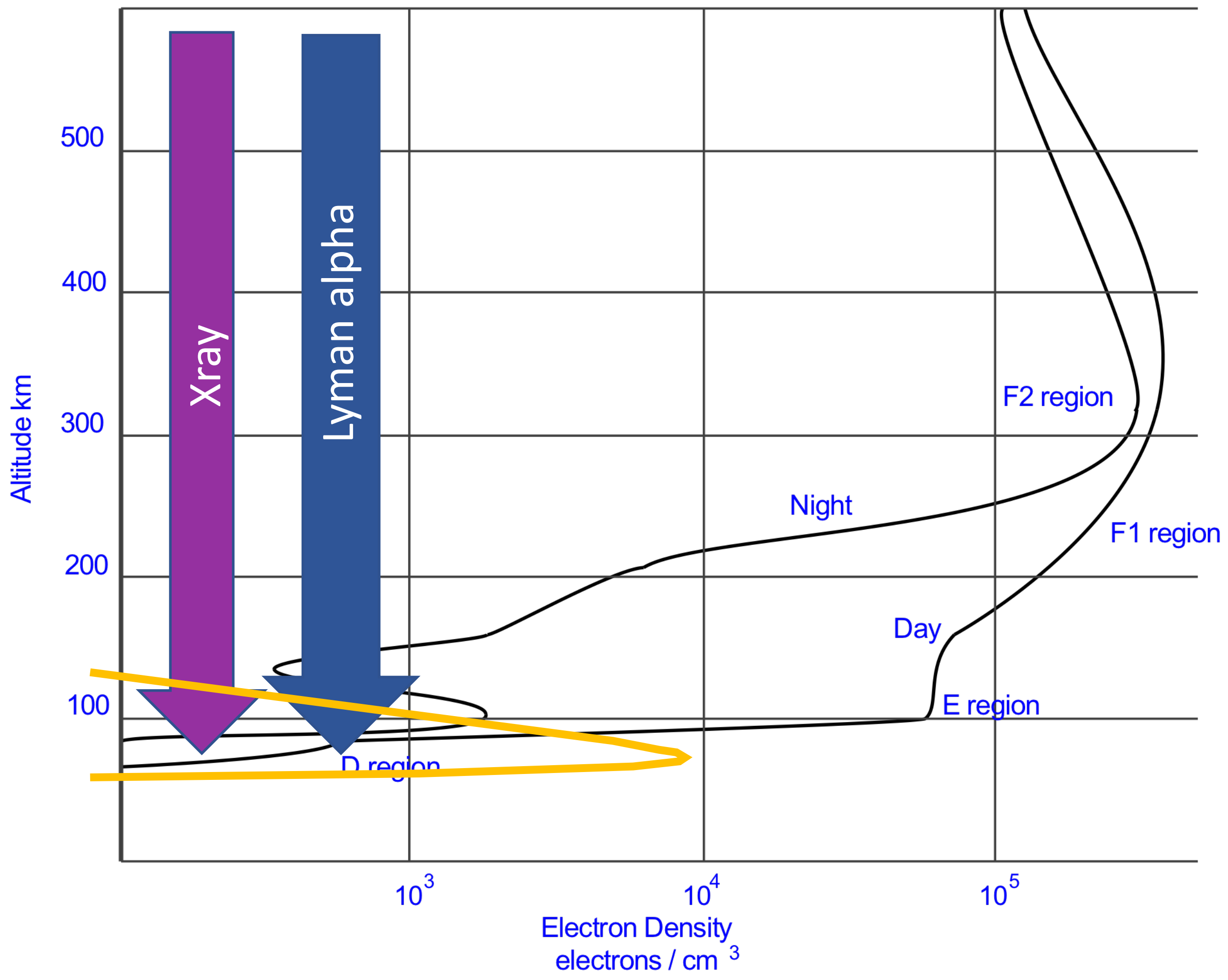


- Assess the critical frequency and plot it
  map maximum reflectable high frequency anywhere

- Peak and min values are where?

https://www.sws.bom.gov.au/HF_Systems/6/5

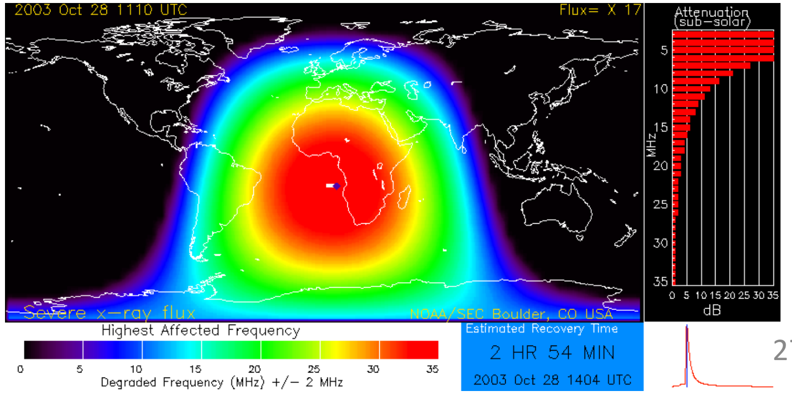
Shortwave Fade   Solar Flare-D Region Enhancement



Excess Solar Flare Shortwave Radiation

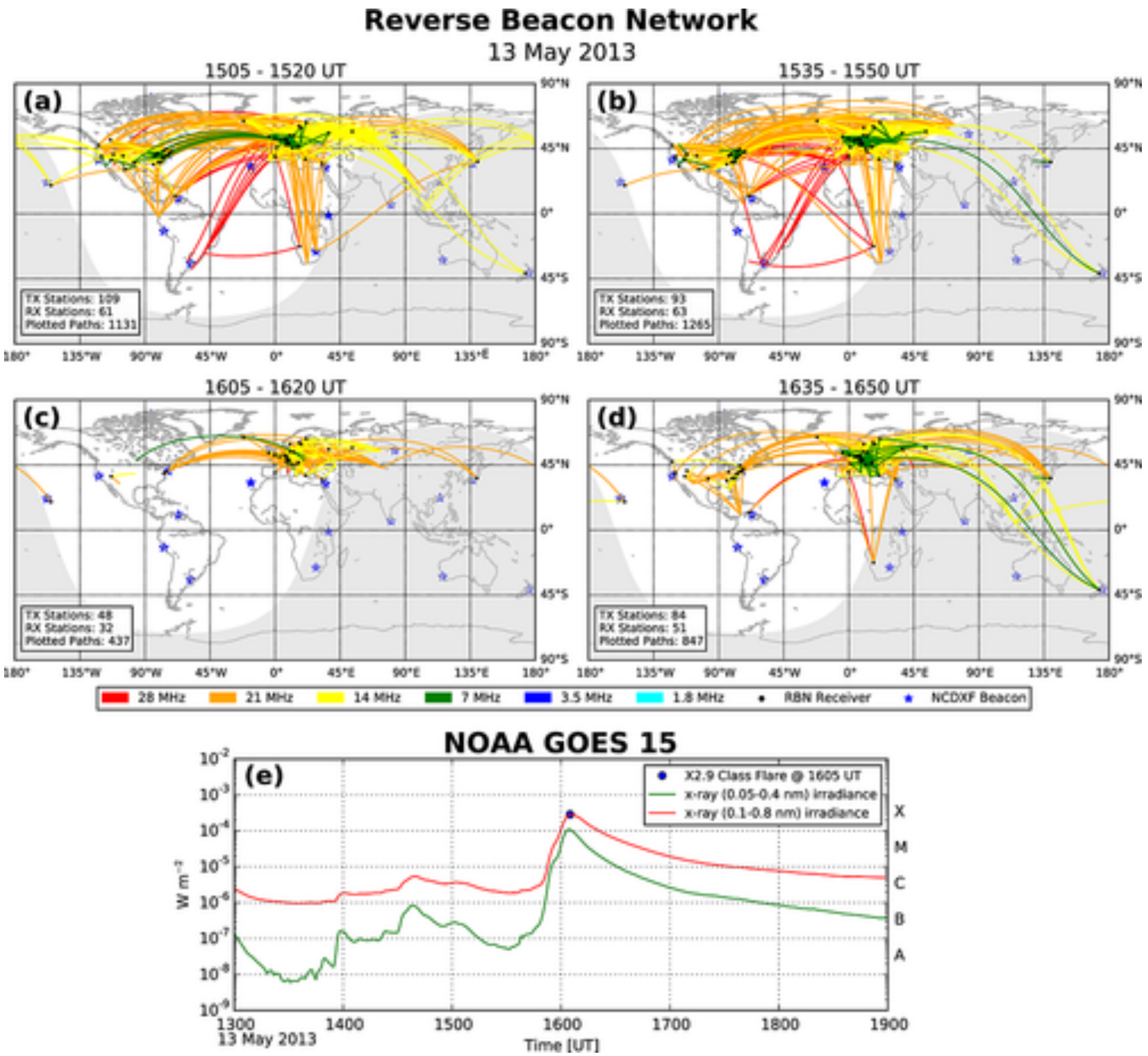
- **X-rays & Lyman-alpha (Far UV)**

- Radiation enhances the D layer
- Electrons in the D interact with incident radio waves and then collide with neutrals due to the higher density
- Propagation of the the radio wave is inhibited by the extra D layer electrons and their collisions
- 5-30 MHz radio waves are absorbed/attenuated 1-2 Hr



Background graphic: https://www.electronics-notes.com/articles/antennas-propagation/ionospheric/ionospheric-layers-regions-d-e-f1-f2.php

Shortwave Fade Example

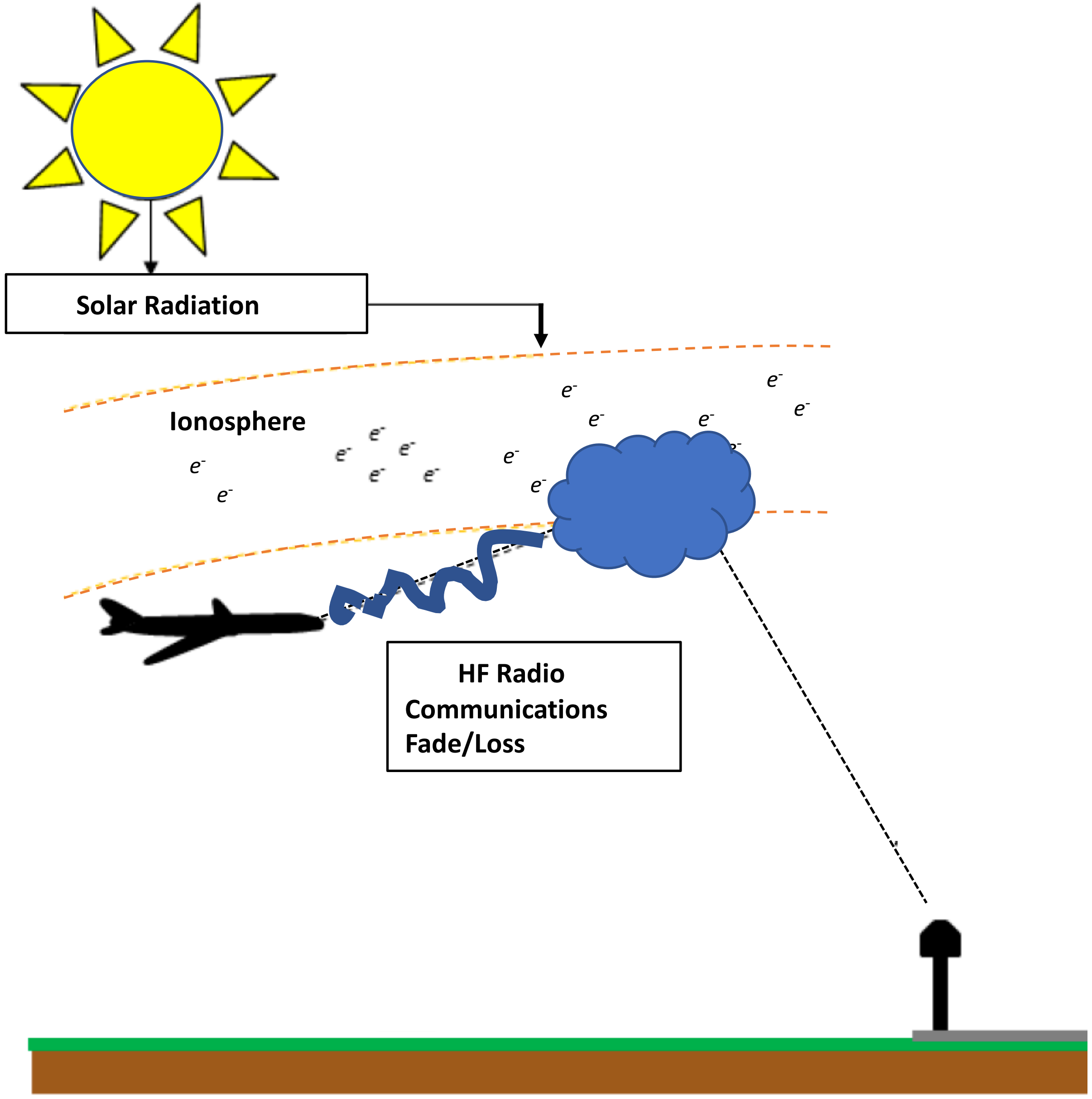


13 May 2013

- X2.9 Flare
- Complete loss of mid-day low-latitude HAM HF circuits
- Significant loss of mid and high latitude HF circuits
- Recovery time exceeded 1 hr

Space Weather, Volume: 12, Issue: 12, Pages: 651-656, First published: 22 October 2014, DOI: (10.1002/2014SW001132)

Ionosphere: Radio Communication/SWF



After Abt Associates, 2017 for NOAA

Solar short wave radiation separates electrons from atoms in SAIR

- Produces the **ionosphere**
- Excess electron/ionization in D region

What could go wrong?

- Excess electrons respond to HF radio waves, but collide with neutrals before wave can propagate
- **HF are attenuated and signal is lost/garbled**

What's the fix?

- Use higher frequency comm
- …but useable frequency may be so high that it becomes trans-ionospheric

Who cares?

ICAO
Anyone using HF as 'backup' comm mode

Time-out-to-think #2

The communications system you are using has the capability of tuning frequency in response to possible ionospheric changes. At solar maximum, how will you need to tune your system? The average reflecting frequency of the F-region will _________________ relative to the average reflecting frequency of the F-region at solar minimum.

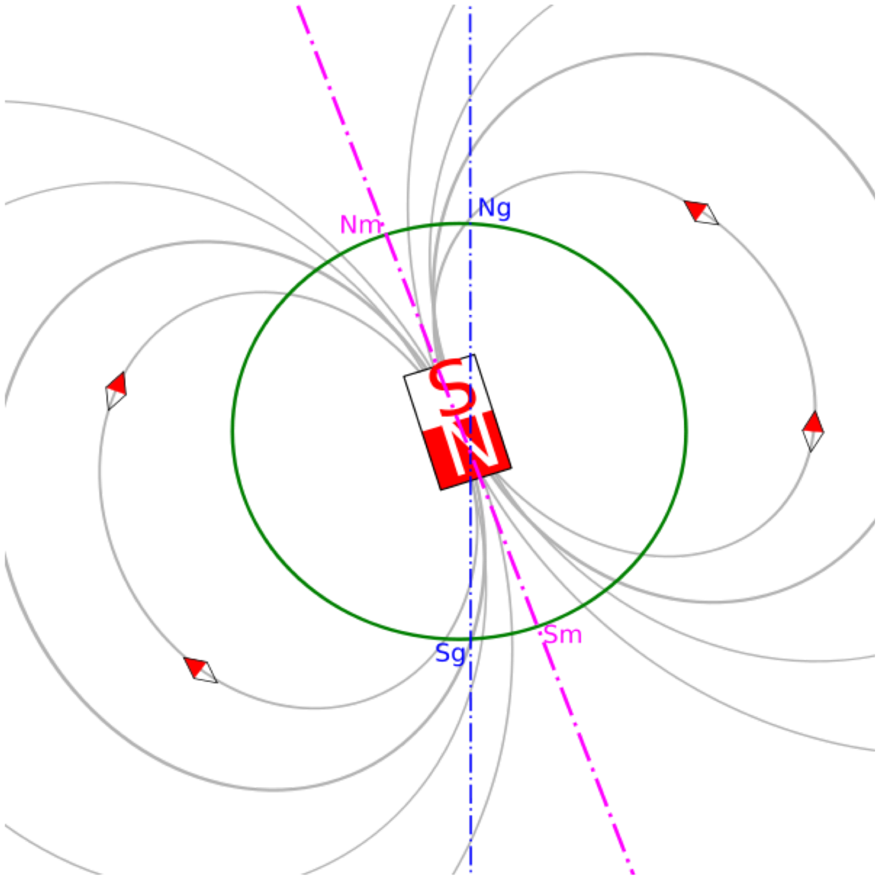
1. Remain the same.
2. Increase.
3. Decrease.
4. Increase or decrease depending on latitude.
5. Increase or decrease depending on local time.

Learning Goals

- Recognize typical organizational domains of the ionosphere
- Distinguish between polar cap absorption and auroral absorption
  - PCA and AA
  - Causes, locations, agents and effects
- Explain how a RIOMETER provides information on PCA and AA severity
- Explain the circumstances under which SWF and PCA can be simultaneous
- Explain the circumstances under which PCA and AA can be simultaneous
- Know the association between enhanced PCA and geomagnetic storms
- Know the association between enhanced AA and geomagnetic storms

Large Scale Structure/Morphology of Ionosphere

- Organized by
  - Latitude
  - Earth's Magnetic Field
  - Day/Night/Terminator Regions
  - Season
  - Longitude

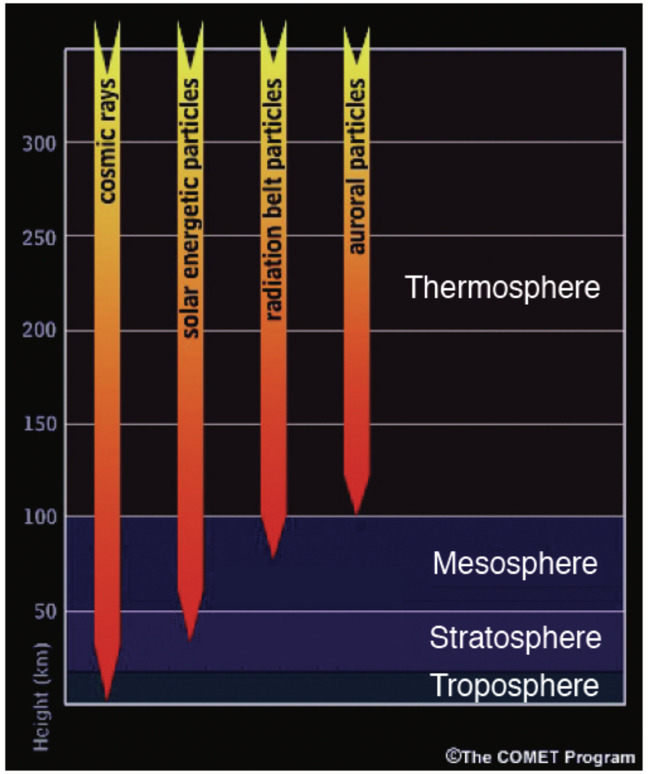


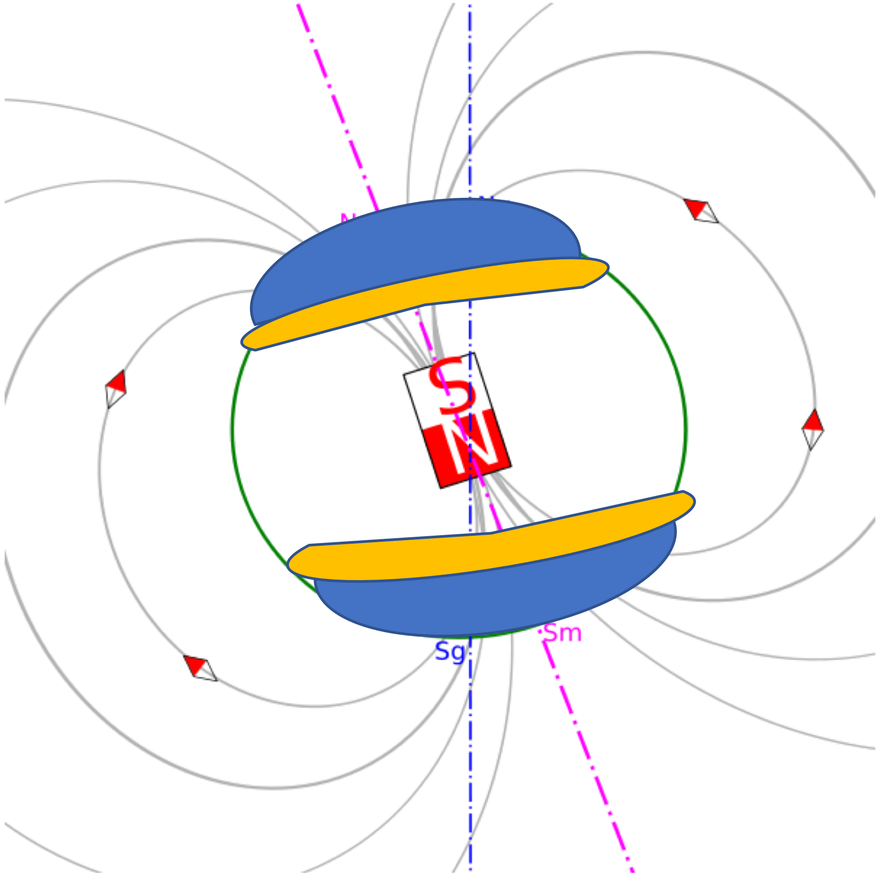
Earth + Magnetic Field

Large Scale Structure/Morphology of Ionosphere

Signal Absorption

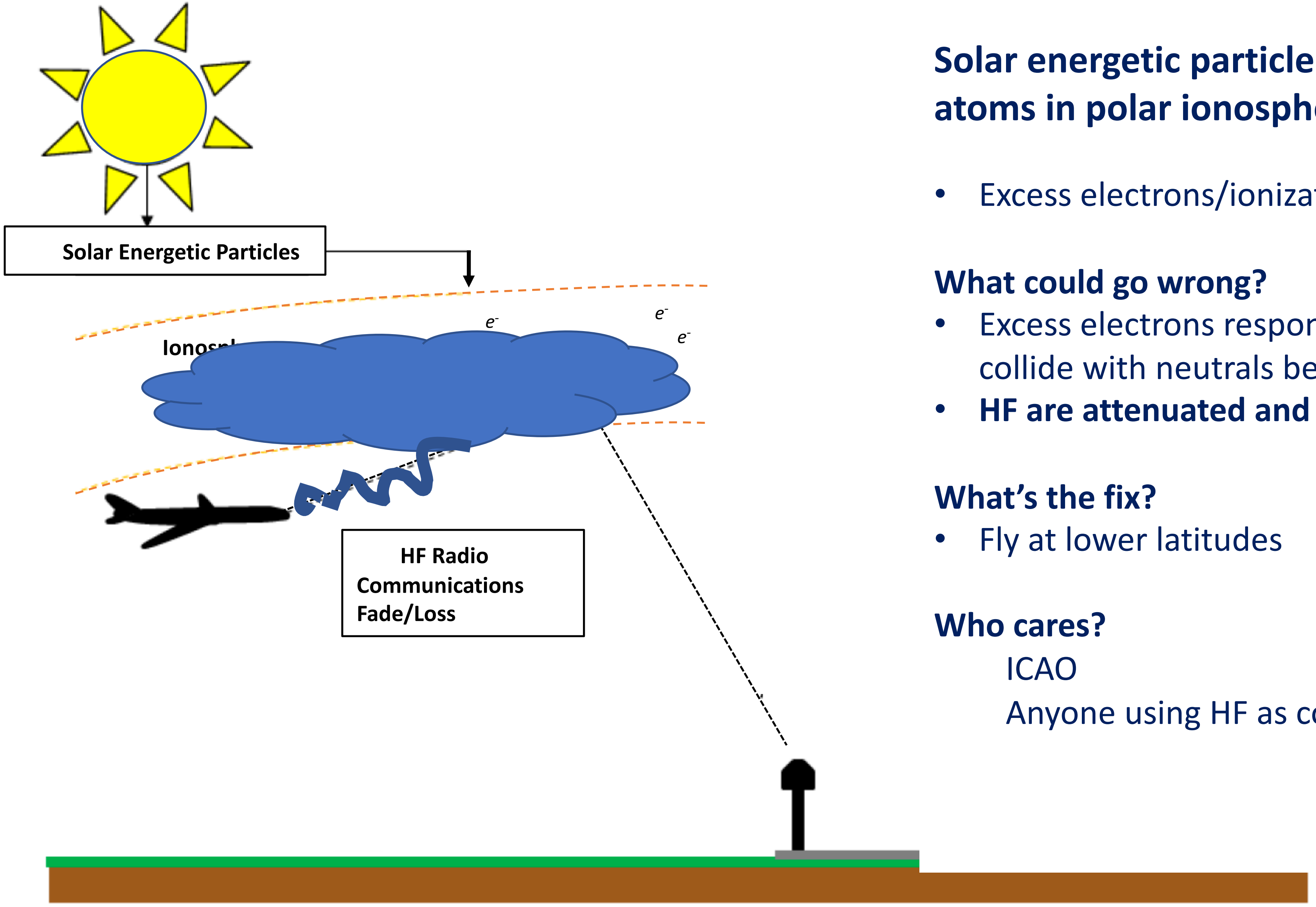
- High Latitudes
- Earth's Magnetic Field
- Day/Night/Terminator Regions
- Energetic Particles





Earth + Magnetic Field

Ionosphere: Radio Comm/Polar Cap Absorption



After Abt Associates, 2017 for NOAA

Solar energetic particles separate electrons from atoms in polar ionosphere

- Excess electrons/ionization in D region

What could go wrong?
- Excess electrons respond to HF radio waves, but collide with neutrals before wave can propagate
- **HF are attenuated and signal is lost/garbled**

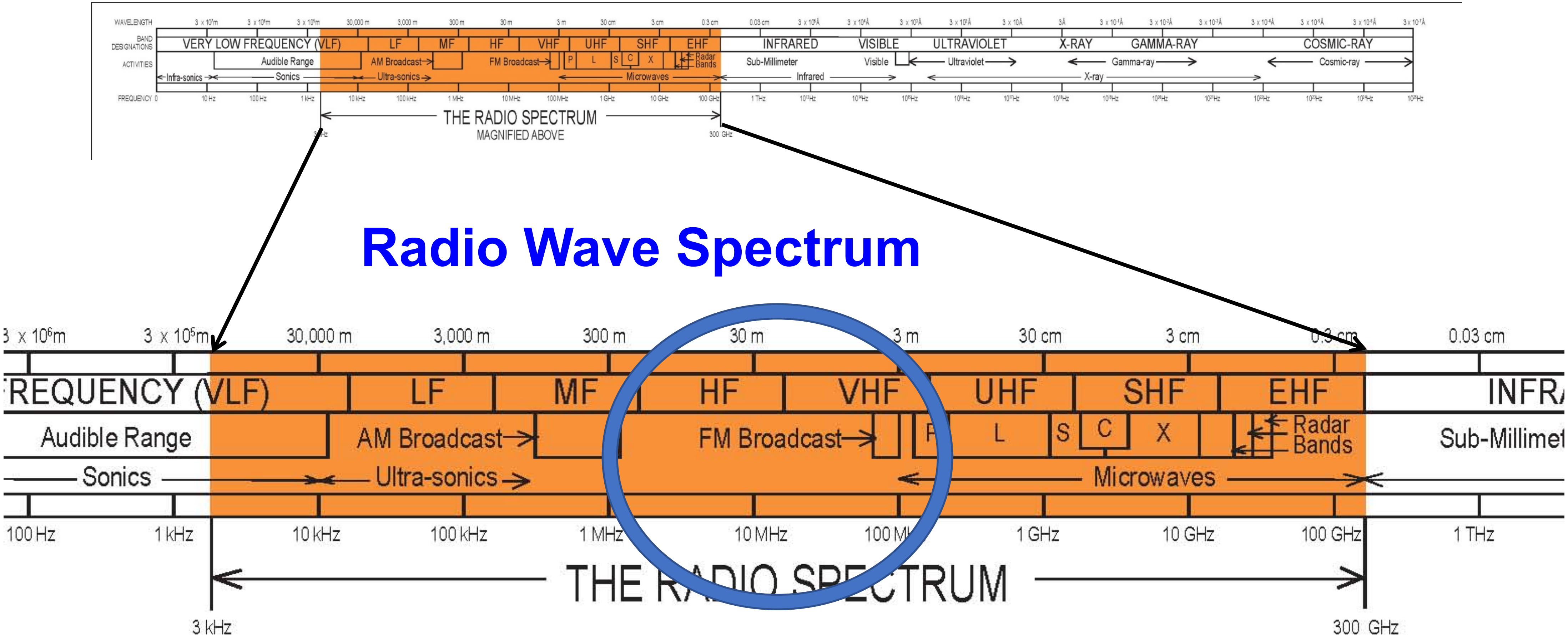
What's the fix?
- Fly at lower latitudes

Who cares?

ICAO

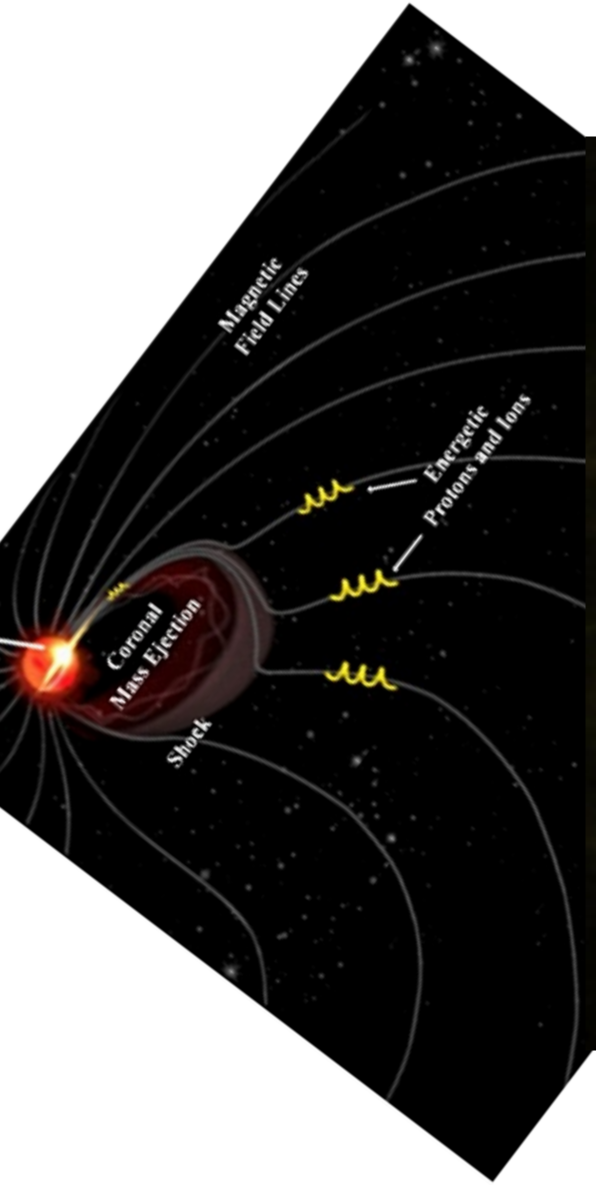
Anyone using HF as comm mode

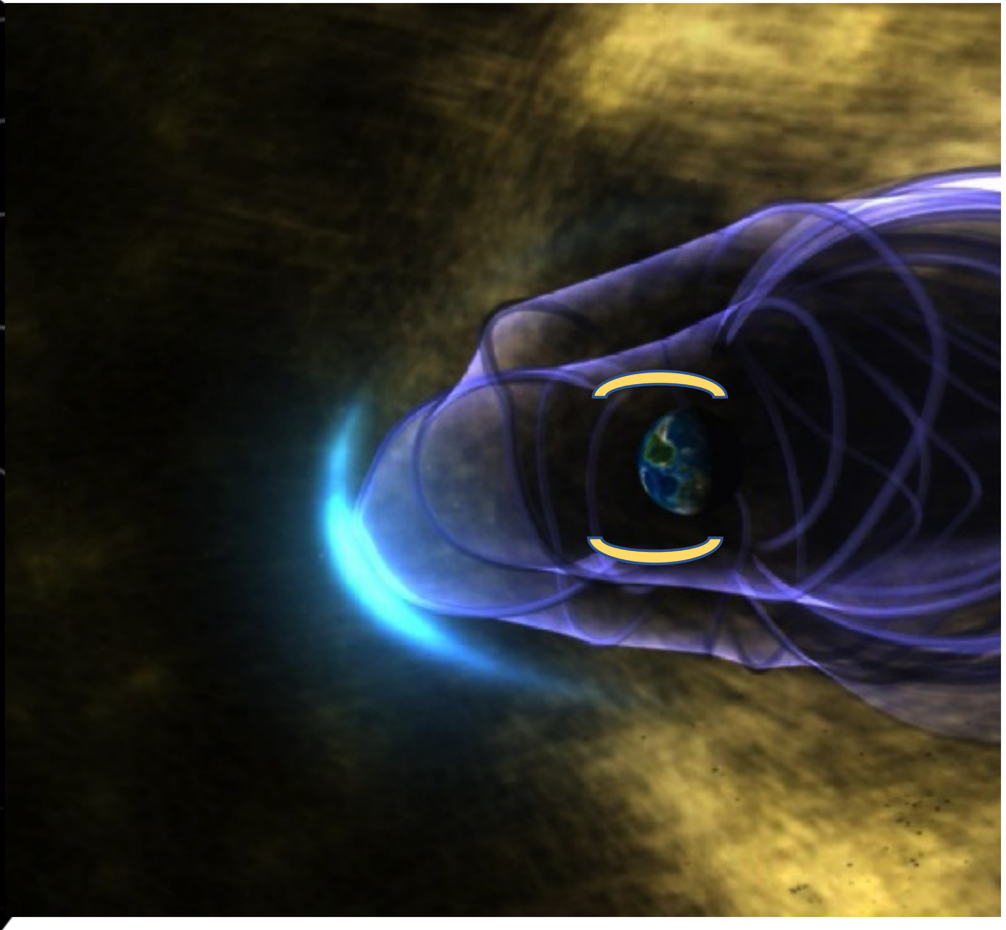
Polar Cap Absorption Effects



From: Dept of Commerce chart

Recipe for Polar Cap Absorption Events





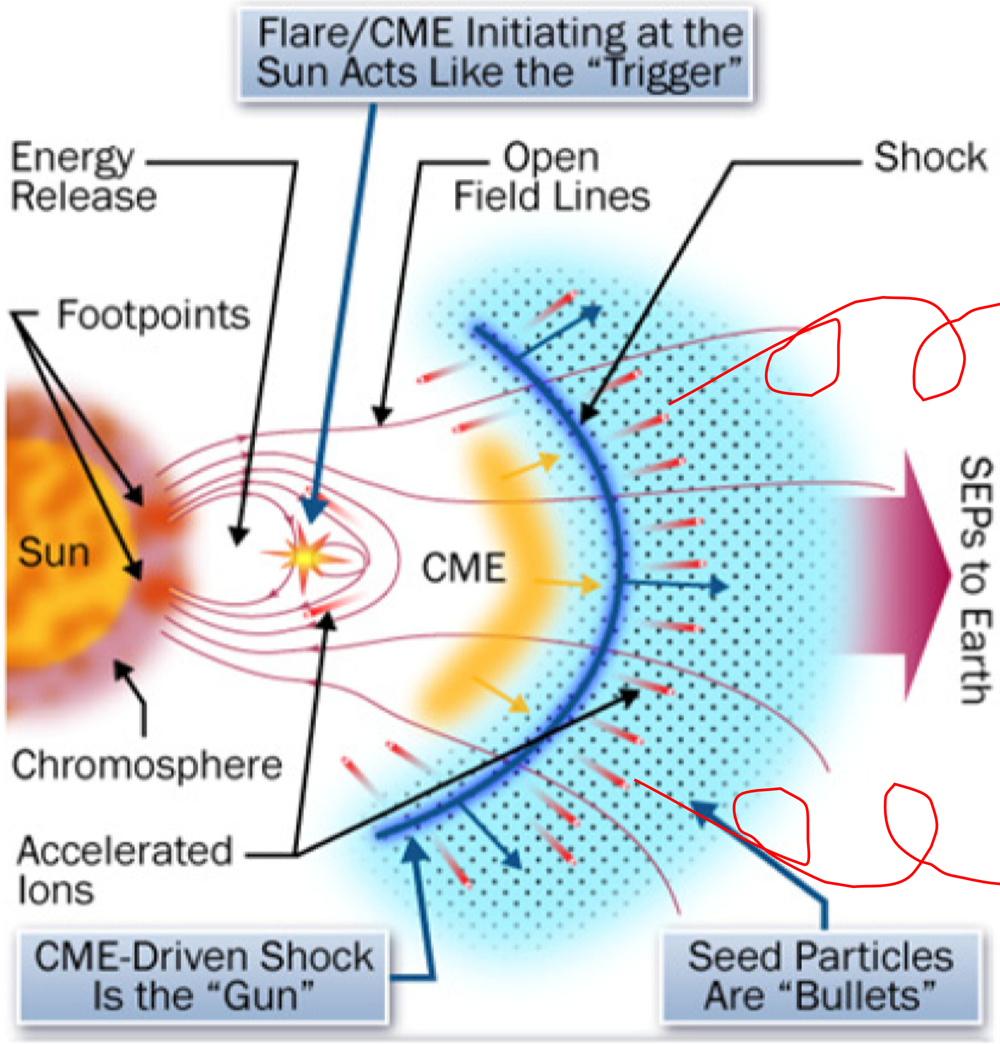
- SEPs from a CME (>10 MeV)
- Good magnetic connection to Earth
- **Open polar field lines at Earth**
- Polar Ionosphere

(Image: © Walt Feimer (HTSI)/NASA/Goddard Space Flight Center Conceptual Image Lab)

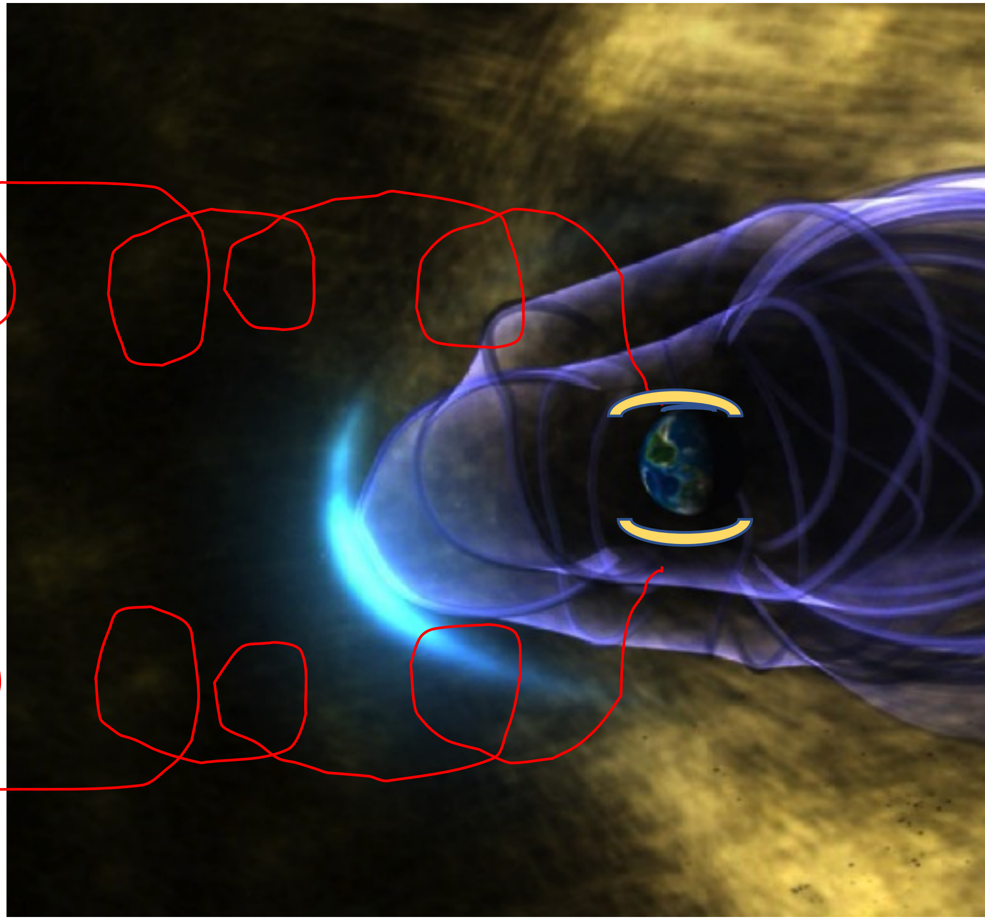
http://spaceweather.uma.es/solarstorms.html

Recipe for Polar Cap Absorption Events

- Prior CME
- **Open polar field lines at Earth**
- **Polar Ionosphere**

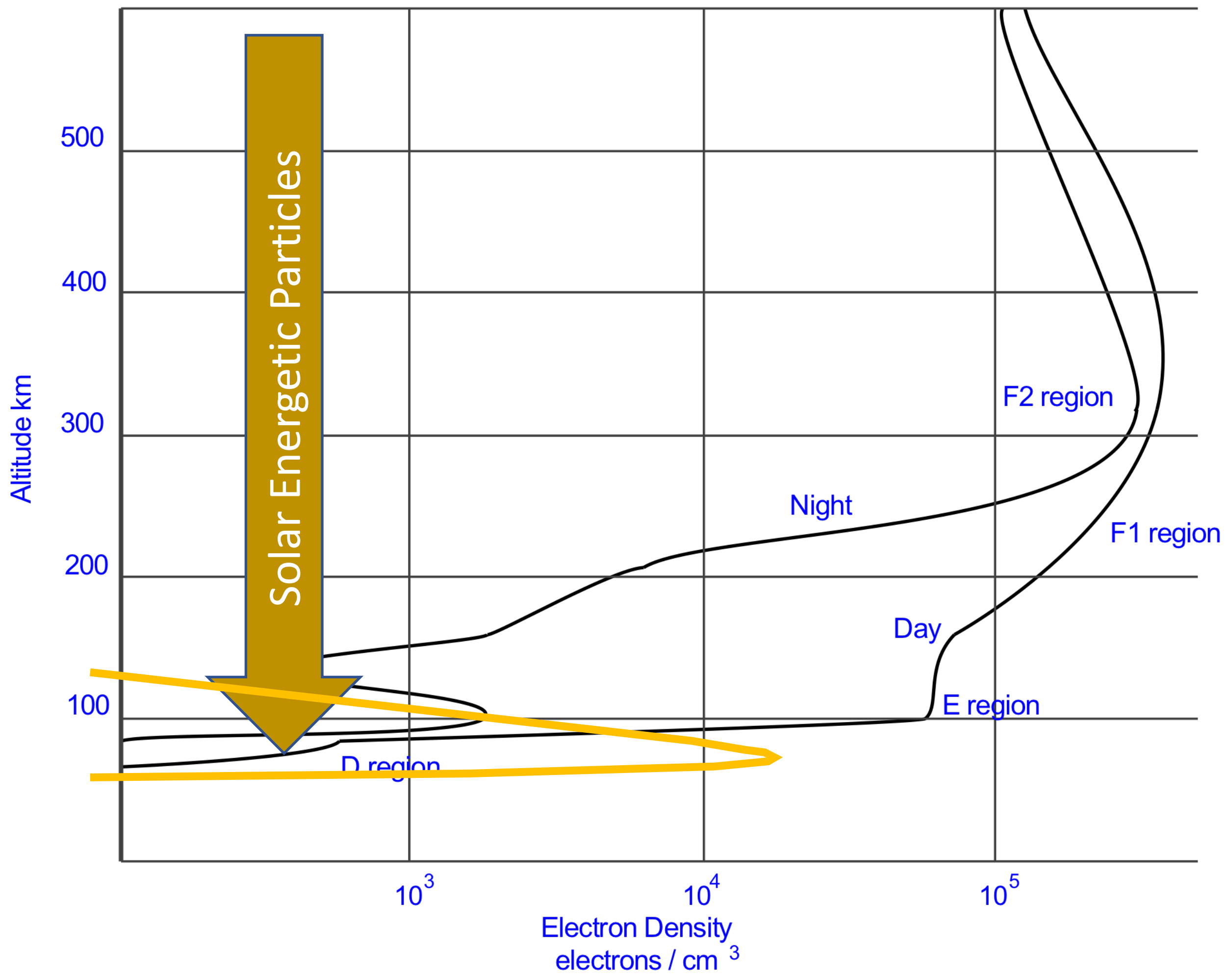


https://www.osapublishing.org/ao/fulltext.cfm?uri=ao-54-31-F222&id=326843



(Image: © Walt Feimer (HTSI)/NASA/Goddard Space Flight Center Conceptual Image Lab)

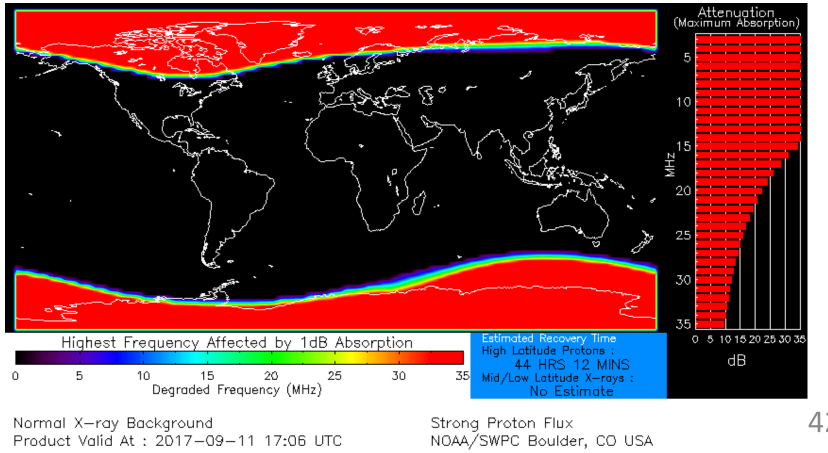
Polar Cap Absorption - D Region Enhancement



Excess High Energy Solar Ion Flux

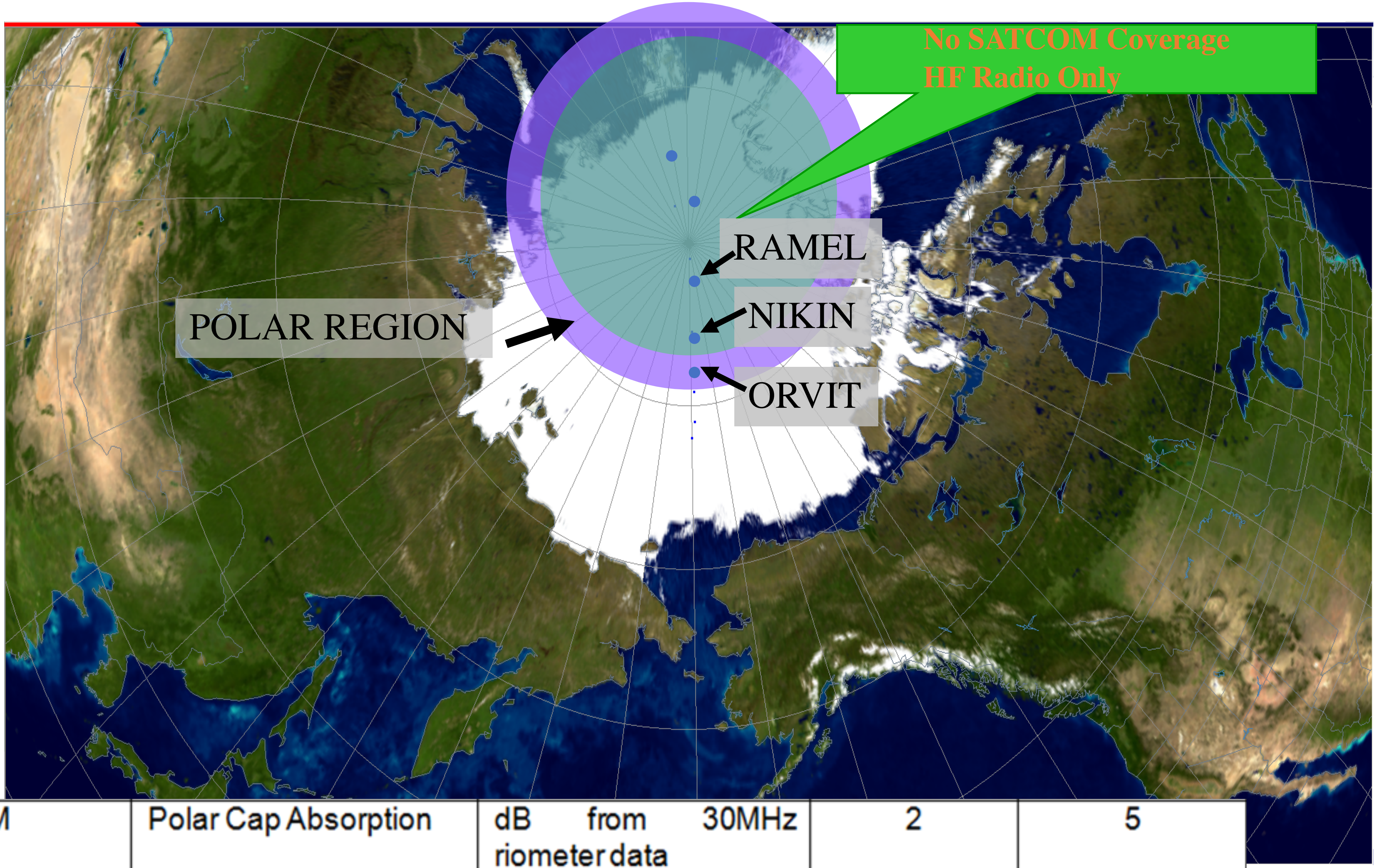
- **Ions with Energy > 10 MeV**

  - Massive high energy particle do most ionization close to end of their path
  - Particles ionize neutrals; enhance D layer
  - Propagation of the the radio wave is inhibited by the extra D layer electrons and their collisions
  - V/U/HF radio waves are absorbed/attenuated Hours-Days



Background graphic: https://www.electronics-notes.com/articles/antennas-propagation/ionospheric/ionospheric-layers-regions-d-e-f1-f2.php

During Polar Cap Absorption Event no HF



- No HF to cover lack of SATCOM Above 82 Deg;

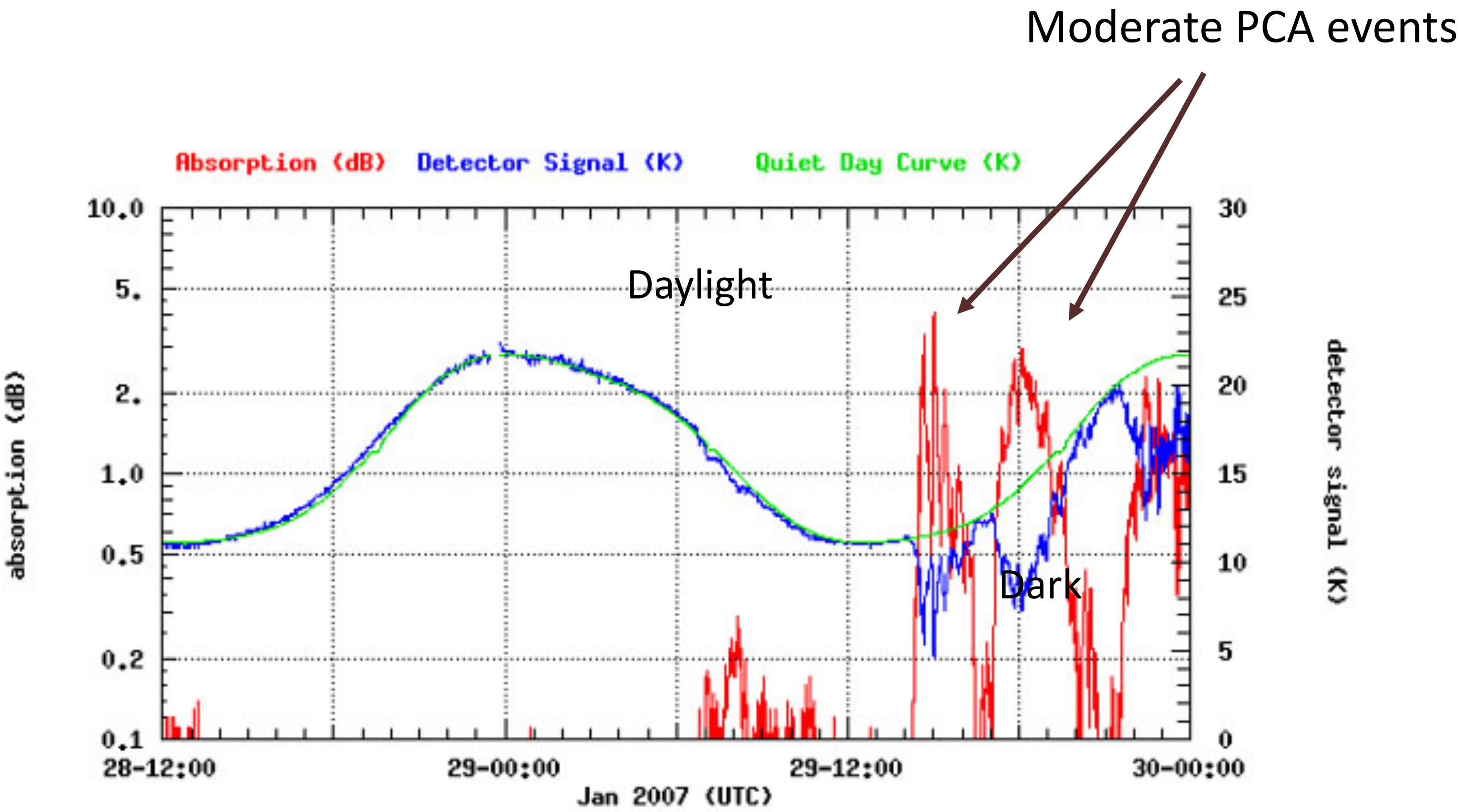
HF COM	Polar Cap Absorption	dB from 30MHz riometer data	2	5

Riometer and Polar Cap Absorption Event

- A riometer is a ground-based radio receiver tuned to 20-60MHz.
  - Monitors the flux of cosmic radio waves travelling through the ionosphere.
  - As radio waves traverse the ionosphere they cause free electrons to oscillation
  - If the electrons then collide with neutral atoms the waves begin to lose energy (they are attenuated).
  - High fluxes of SEPs create so many free electrons that cosmic radio waves are fully attenuated (as are other HF/VHF/UHF signals)
  - From the ground, this appears as a reduction in signal strength.
  - The degree of attenuation, measured in dB, indicates the strength of the PCA
    - **2 dB attenuation @ 30 Mhz = moderate event**
    - **5 dB attenuation @ 30 Mhz = severe event**

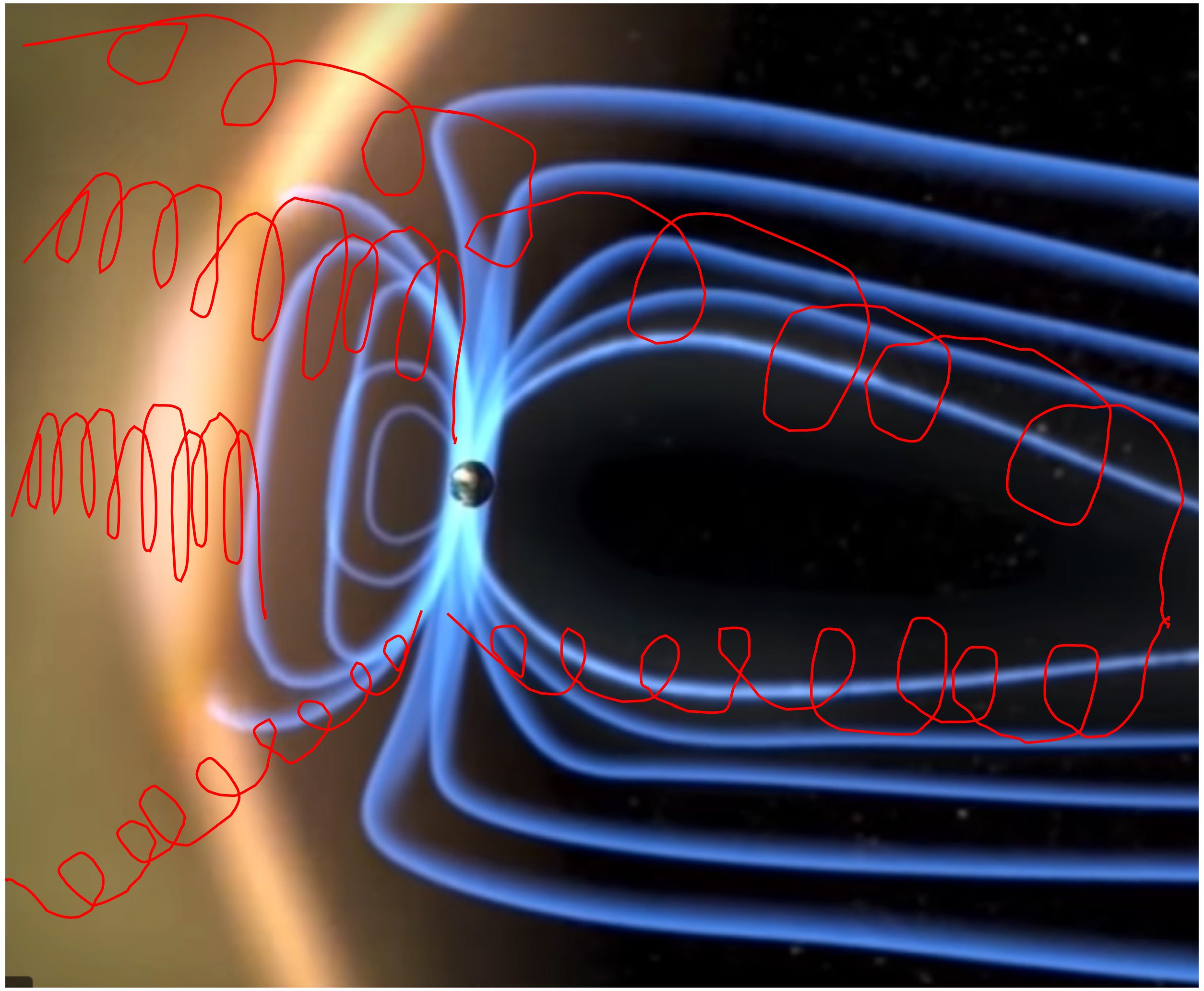
http://aurora.phys.ucalgary.ca/norstar/rio/doc/CANOPUS_Riometer_Baselining.pdf

Relative Ionospheric Opacity Meter (Riometer)



http://www.haarp.alaska.edu/haarp/Rio.html (archive: https://web.archive.org/

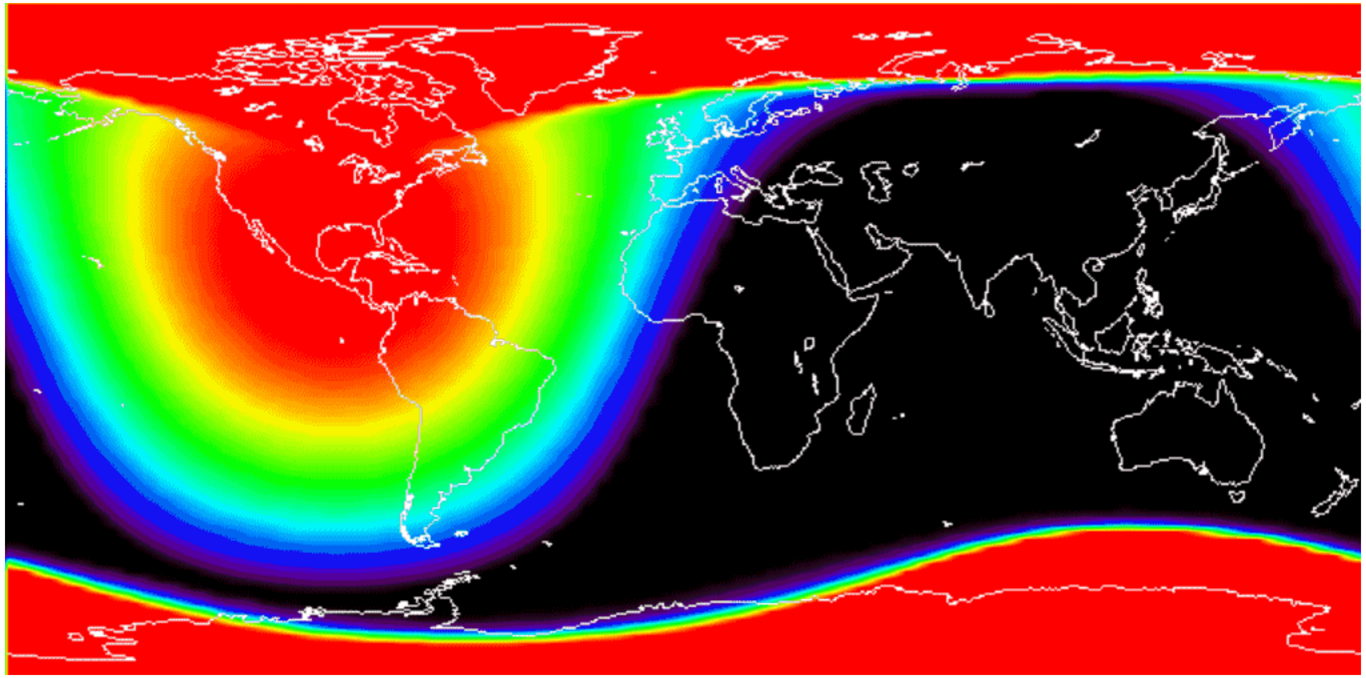
Polar Cap Absorption/SEP Considerations



- During geomagnetic storms the open polar cap may be vary large
  - PCA event extends to lower latitudes
- Solar Energetic Particles may get trapped in magnetotail
  - Enter polar cap via a rather circuitous path
- Sunlit/Dark Asymmetries
  - More absorption in sunlight
  - Riometers in polar regions may report differing values: lit/unlit
- Some SEP events are ’beamed’
  - One pole may be more affected than the other

Time-out-to-think #3

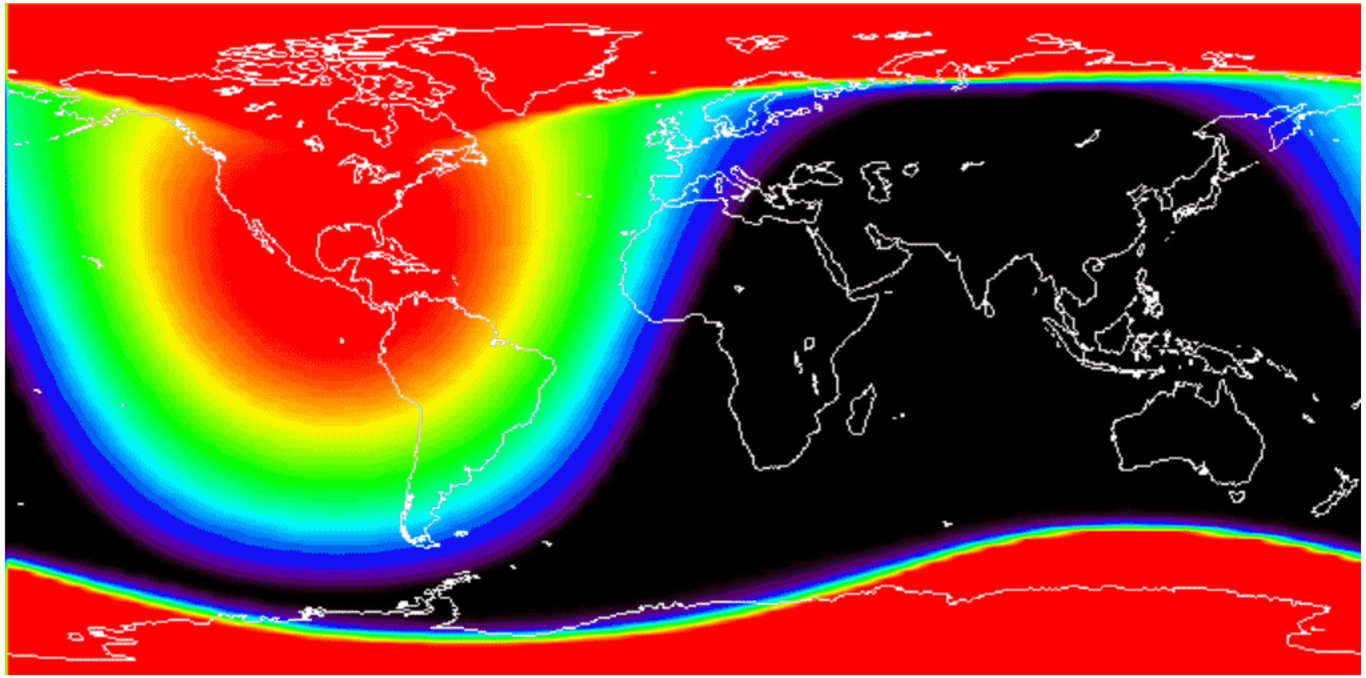
What is the most likely sequence of events to produce this result



1. Flare CME SEP
2. SEP CME Flare
3. Flare CME SEP Flare
4. Flare CME SEP CME
5. All simultaneous

Time-out-to-think #4

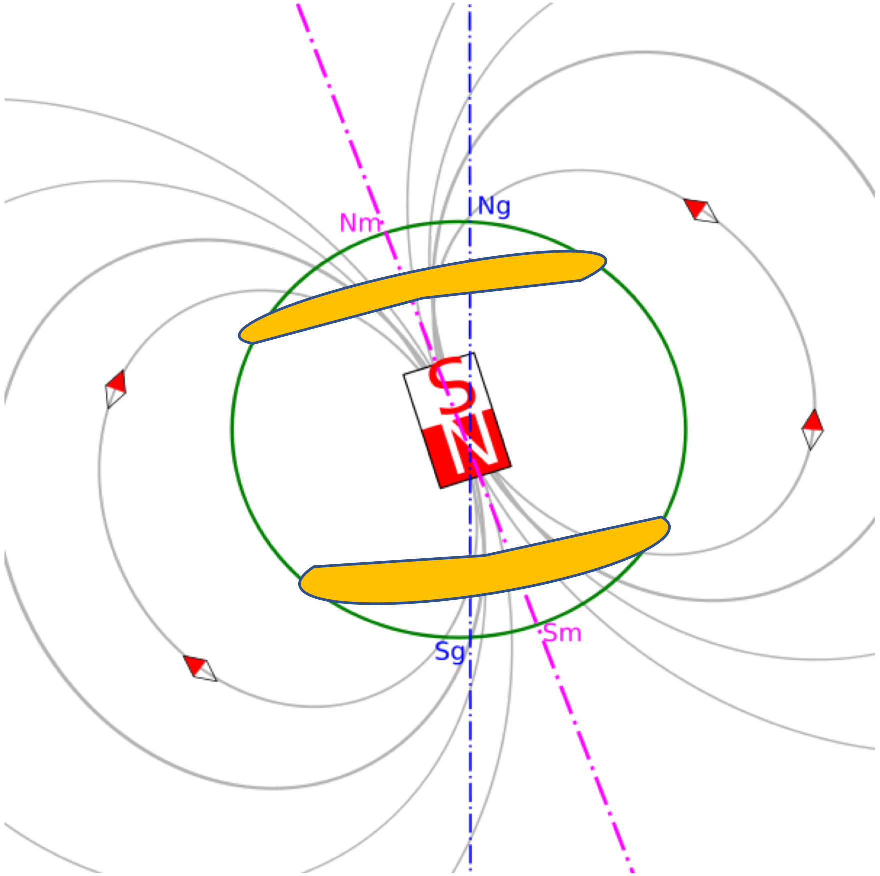
During what season did this event likely occur



1. NH Winter
2. NH Spring
3. NH Summer
4. NH Autumn
5. All have equal probability

Large Scale Structure/Morphology of Ionosphere

Auroral Absorption

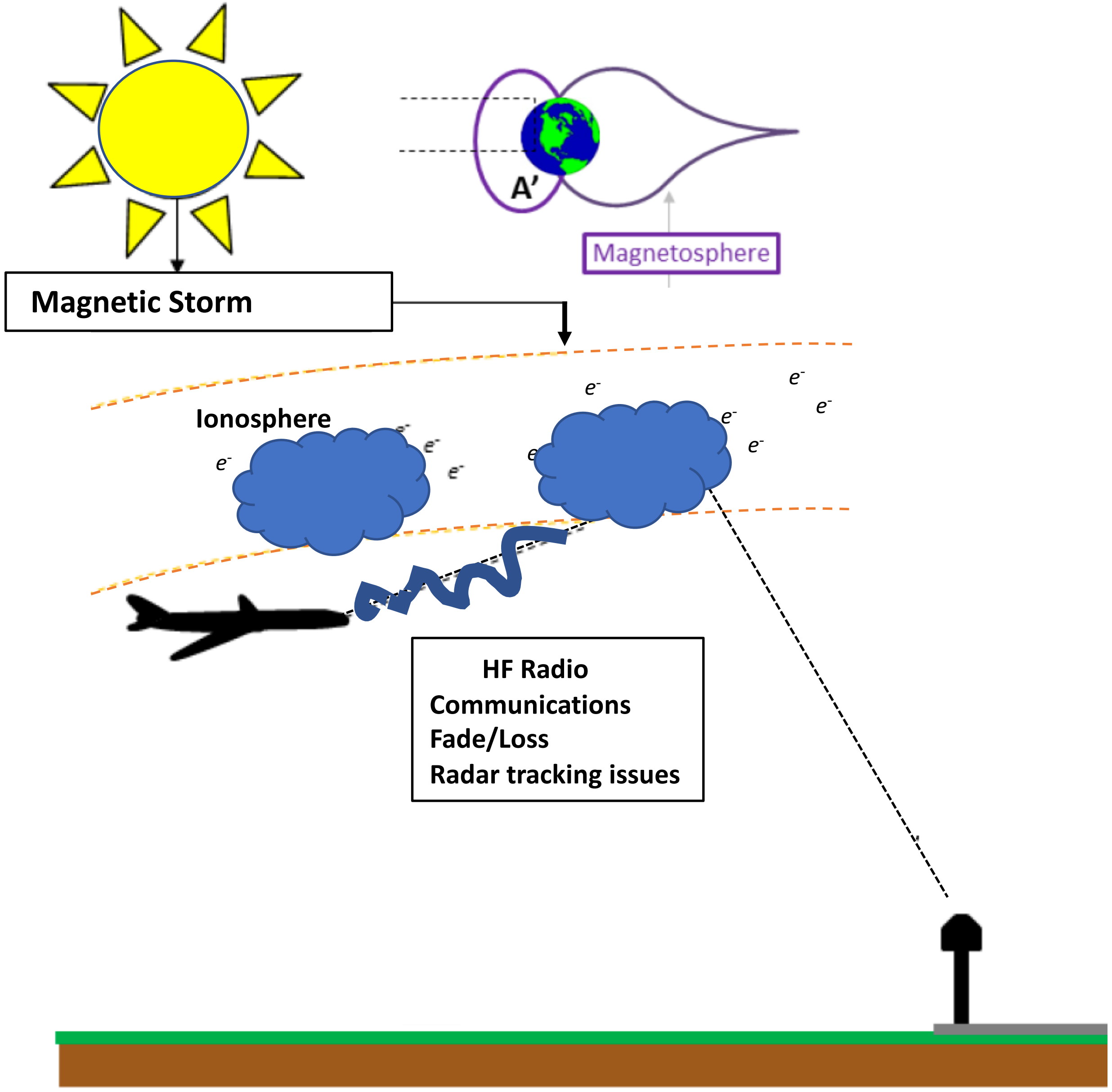


Earth + Magnetic Field

- High (auroral)Latitudes
- Near midnight and post dawn

- Particles from Magnetotail
  - Guided by Earth's Magnetic Field
  - Produce deep patchy ionization in auroral zones
  - Radio wave reflection is spotty
  - Deep ionization (D & E regions) produce fades in HF

Ionosphere: Radio Comm and Radar/Auroral Absorption



After Abt Associates, 2017 for NOAA

Magnetosphere accelerates electrons that flow into auroral ionosphere

- Excess electrons/ionization in D & E region

What could go wrong?

- Excess electrons respond to HF radio waves, but collide with neutrals before wave can propagate
- **HF are attenuated and signal is lost/garbled**
- **Radar transmissions suffer interference**

What's the fix?

- Wait it out

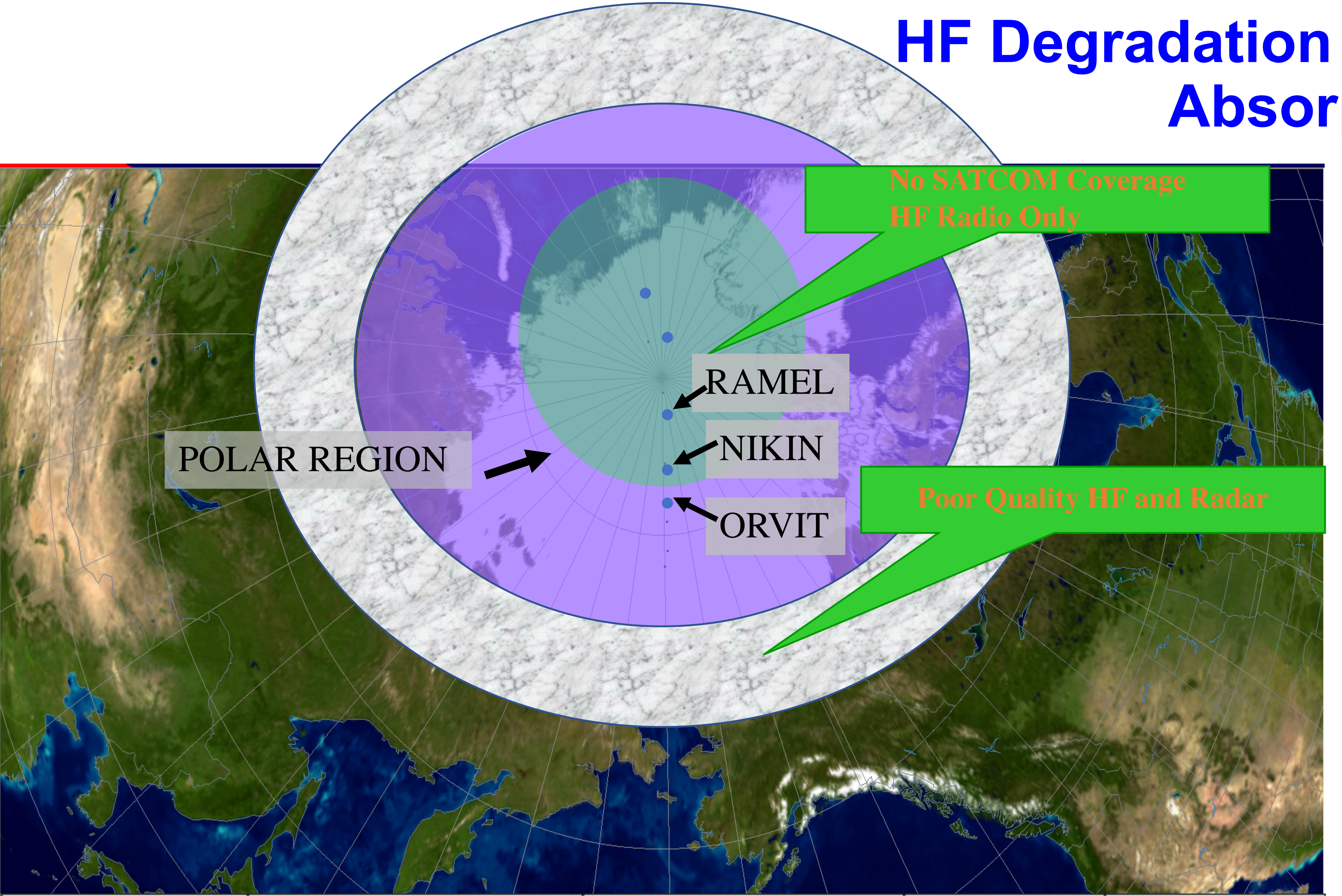
Who cares?

ICAO

Anyone using HF as comm mode or high latitude radars

HF COM

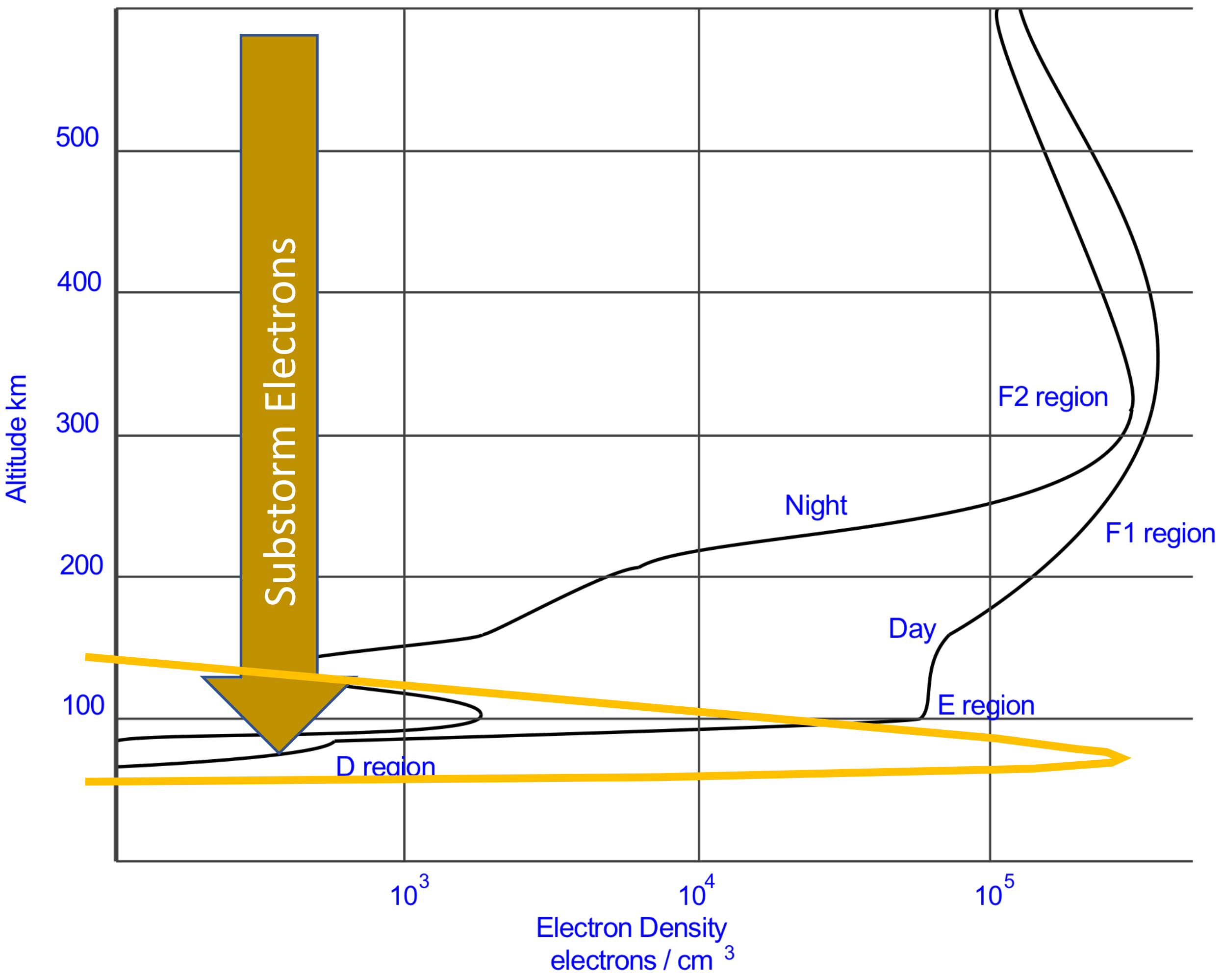
HF Degradation Due to Auroral Absorption



HF COM	Auroral Absorption	Kp	8	9

- Auroral Regions expands equatorward during geomagnetic activity; High Kp
- Auroral Regions and ionospheric layers becomes irregular during high Kp
- Large portion of high latitude region with poor quality HF Comm and very poor radar coverage.
- Tends to occur near midnight

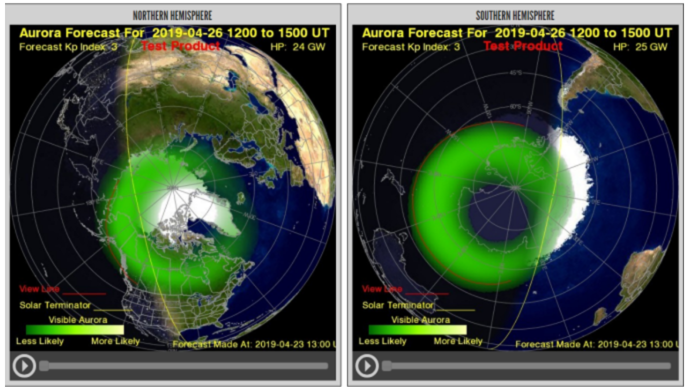
Auroral Absorption - D & E Region Enhancement



Excess Substorm Medium Energy Electron Flux

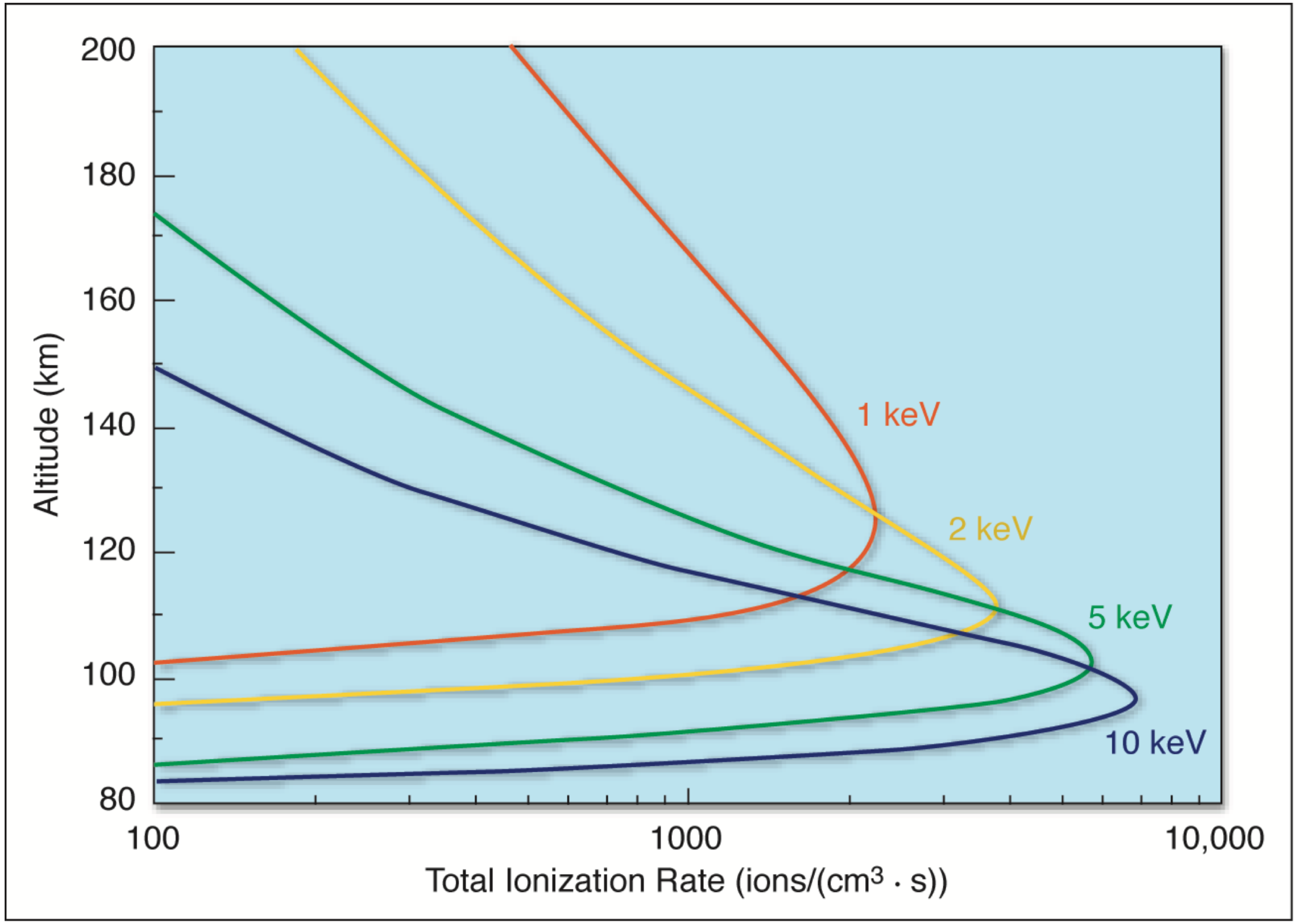
- **Electrons with Energy > 10-50 KeV**

- Do most ionization close to end of their path
- Particles ionize neutrals;
  - enhance D & E layer
- Propagation of the the radio wave is inhibited by the extra electrons and their collisions with neutrals
- V/U/HF radio waves are absorbed/attenuated Hours-Days
- Measured/studied with riometers



Background graphic: https://www.electronics-notes.com/articles/antennas-propagation/ionospheric/ionospheric-layers-regions-d-e-f1-f2.php

Auroral Absorption - D & E Region Enhancement



Ionization rates associated with energetic electrons
Active in the auroral zones

Multi KeV electrons

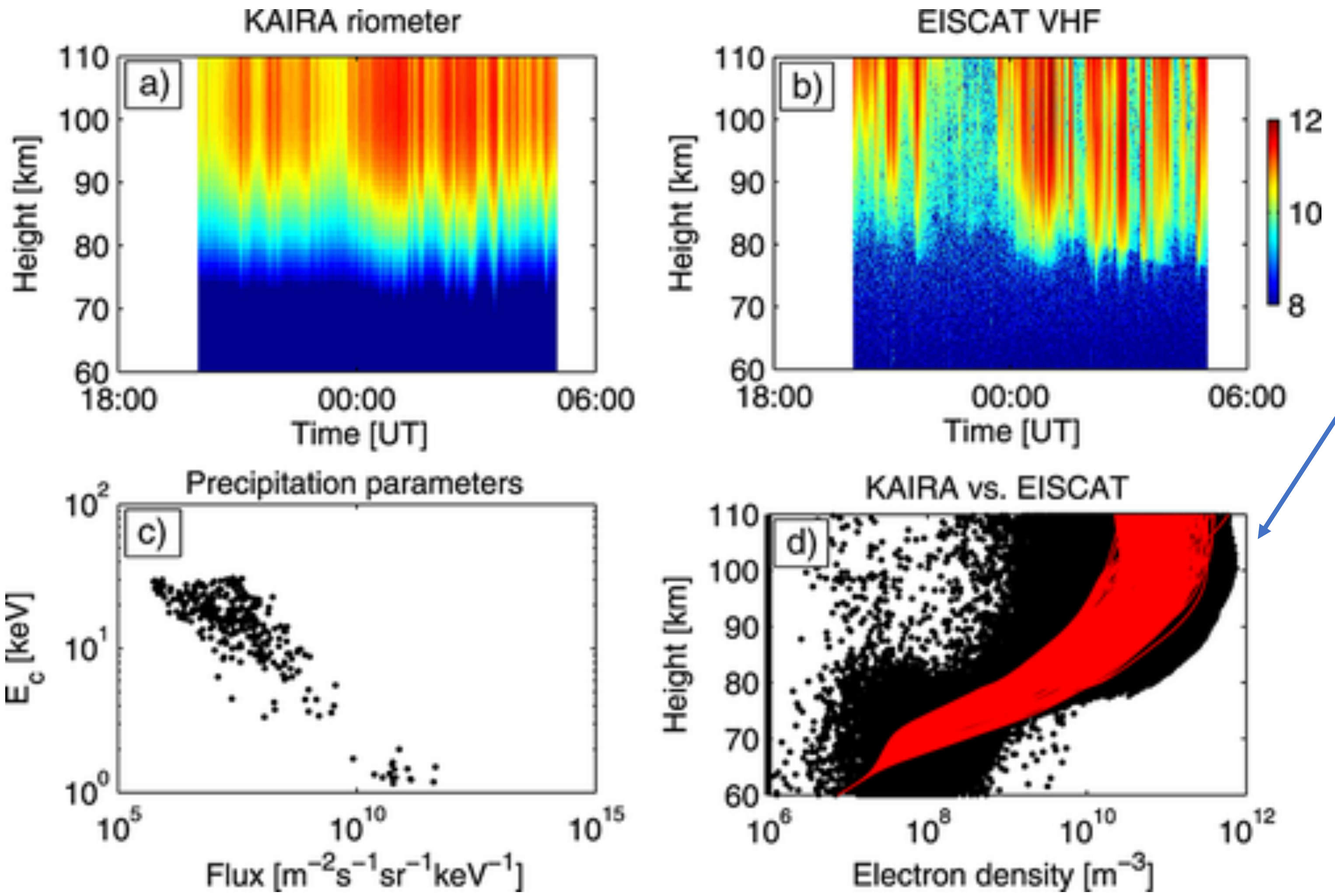
Penetrate deeply in the atmosphere

Are very efficient ionization producers

Are accelerated in the magnetosphere
during substorms (discrete)
during storms (diffuse)

Ionospheric electron density profiles inverted from a spectral riometer measurement

Auroral Absorption



High fluxes of 10-50 keV electrons

- Enhances local electron density by orders of magnitude
- AA are more irregular and impulsive variations particularly in the hours around local midnight where electron precipitation is more localized and transient in nature (discrete aurora)

Geophysical Research Letters, Volume: 41, Issue: 15, Pages: 5370-5375, First published: 29 July 2014, DOI: (10.1002/2014GL060986)

Auroral Absorption (AA) Morphology

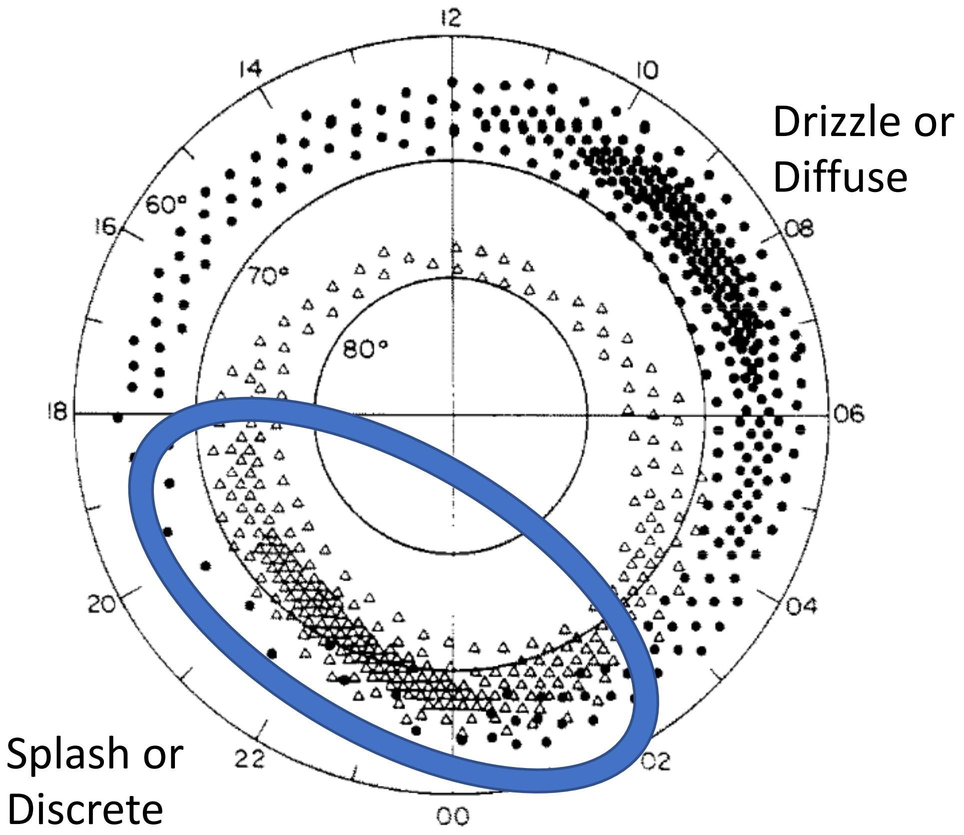
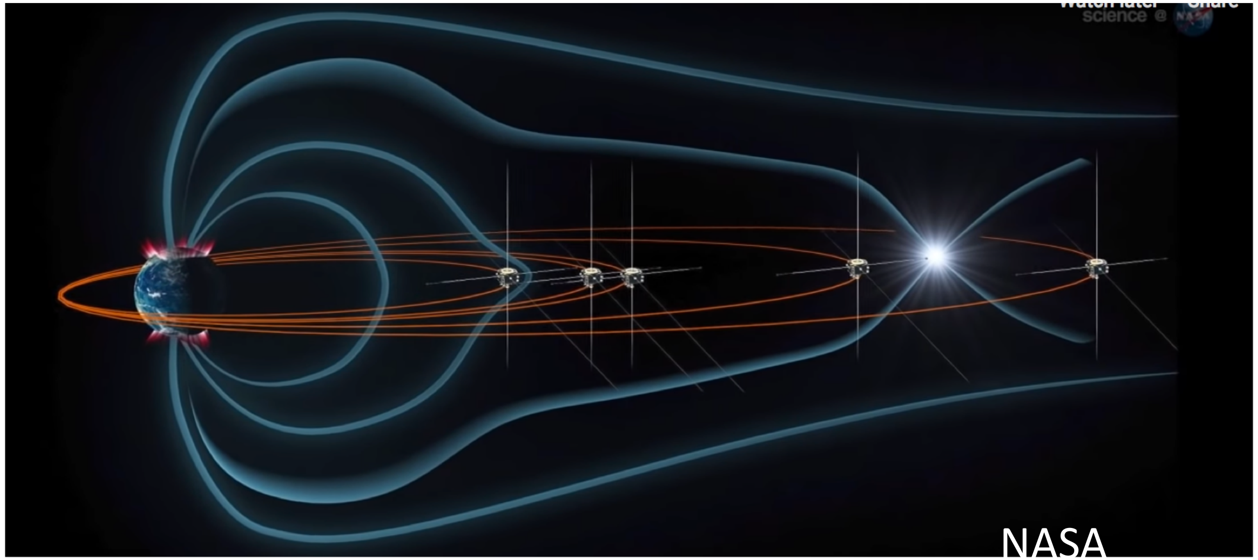


Fig. 4. Zones of precipitating particles expressed in λ and T (adapted from HARTZ and BRICE, 1967). Dots relate to the so-called 'drizzle' precipitation and triangles to the 'splash' precipitation.

Foppiano and Bradely (1985)

- AA) events occur ~60–80°mag latitude,
- Caused by precipitation of energetic electrons
  - Substorms
  - Drizzle particles of particles scattered from radiation belts
- AA is typically less than 1 dB at 30 MHz,
  - Extreme AA of up to 6dB have been observed
  - AA events are less likely to occur during the first day of an SEP



Time-out-to-think #5 & 6

PCA Events

1. Occur within hours of CME launch
2. Cover the broad polar cap
3. Affect mostly the F region
4. Must be associated with a geomagnetic storm
5. (1 and 2)

AA Events

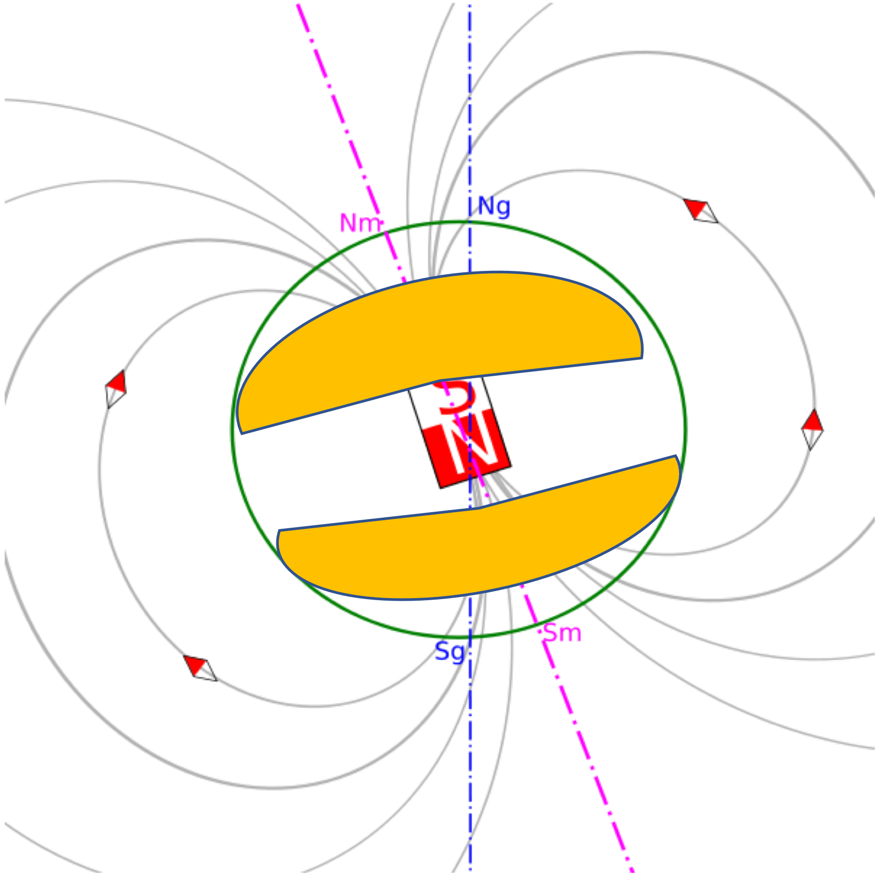
1. Occur within hours of CME launch
2. Cover the entire auroral zone
3. Affect mostly the D & E region
4. Mostly associated with geomagnetic storms
5. (3 and 4)

Learning Goals

- Describe the circumstance that reduce Maximum Useable Frequency(MUF) during stormtime
- Relate MUF reduction to neutral atmosphere structure
- Relate MUF reduction to competition between loss and production of ionization
- Explain why the [o]/[N_2] ratio is the atmospheric column in significant to space weather
- Describe behavior of MUF pre, during and post storm
- Relate TEC to GNSS Signal Delay
- Describe Equatorial Ionization Anomaly

Large Scale Structure/Morphology of Ionosphere

Maximum Useable Frequency (MUF) Depression

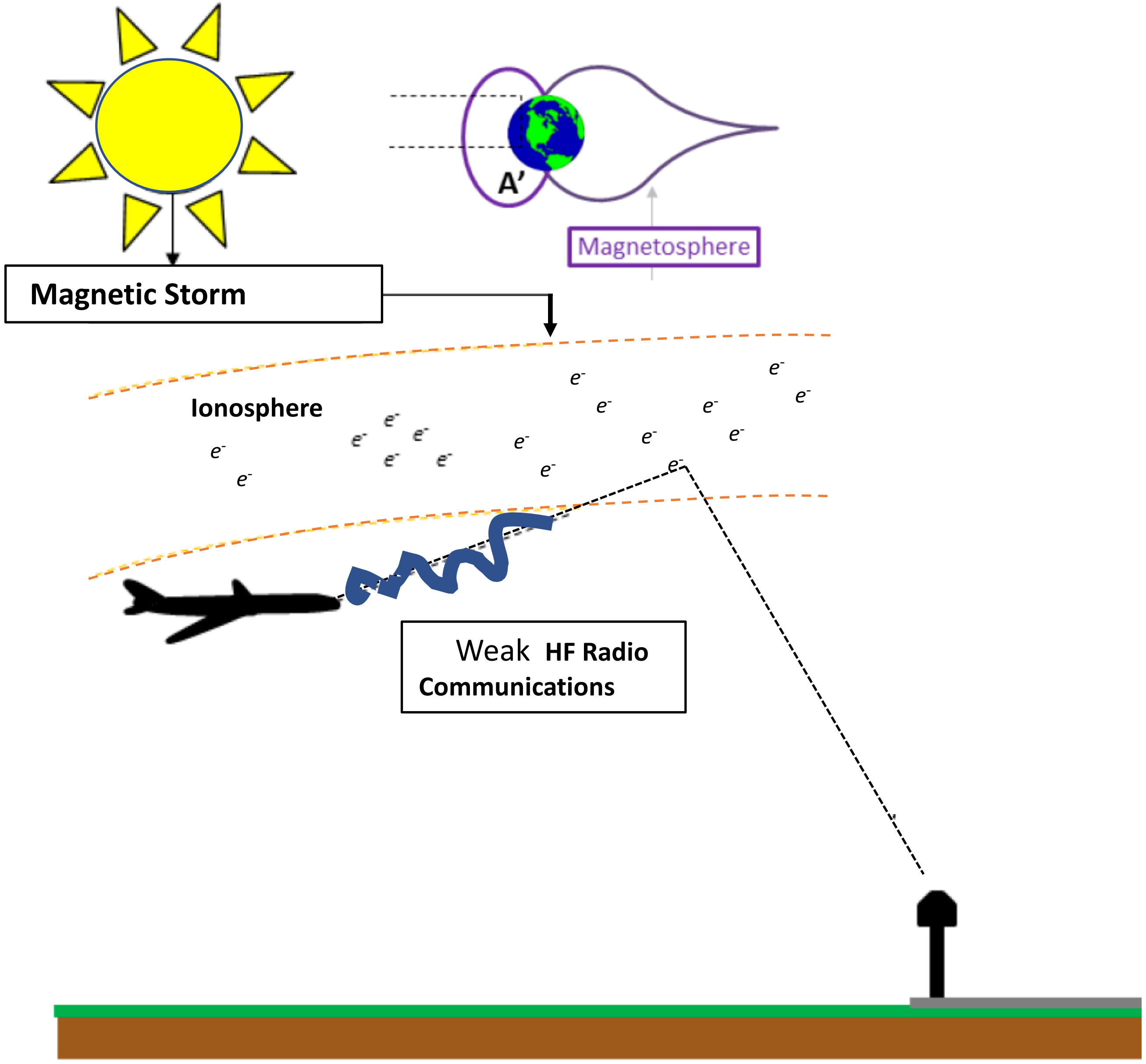


Earth + Magnetic Field

- Mid Latitudes
- Variable Longitudes

- Driven by geomagnetic storm effects at high latitudes

Ionosphere: Radio Communication Degradation



After Abt Associates, 2017 for NOAA

During a Geomagnetic Storm the magnetosphere accelerates electrons that flow into auroral ionosphere

Currents flow from the magnetosphere through the ionosphere and back out.

Flowing through the resistive ionosphere, these currents generate heat

Heating expands the atmosphere and causes composition changes.

What could go wrong?

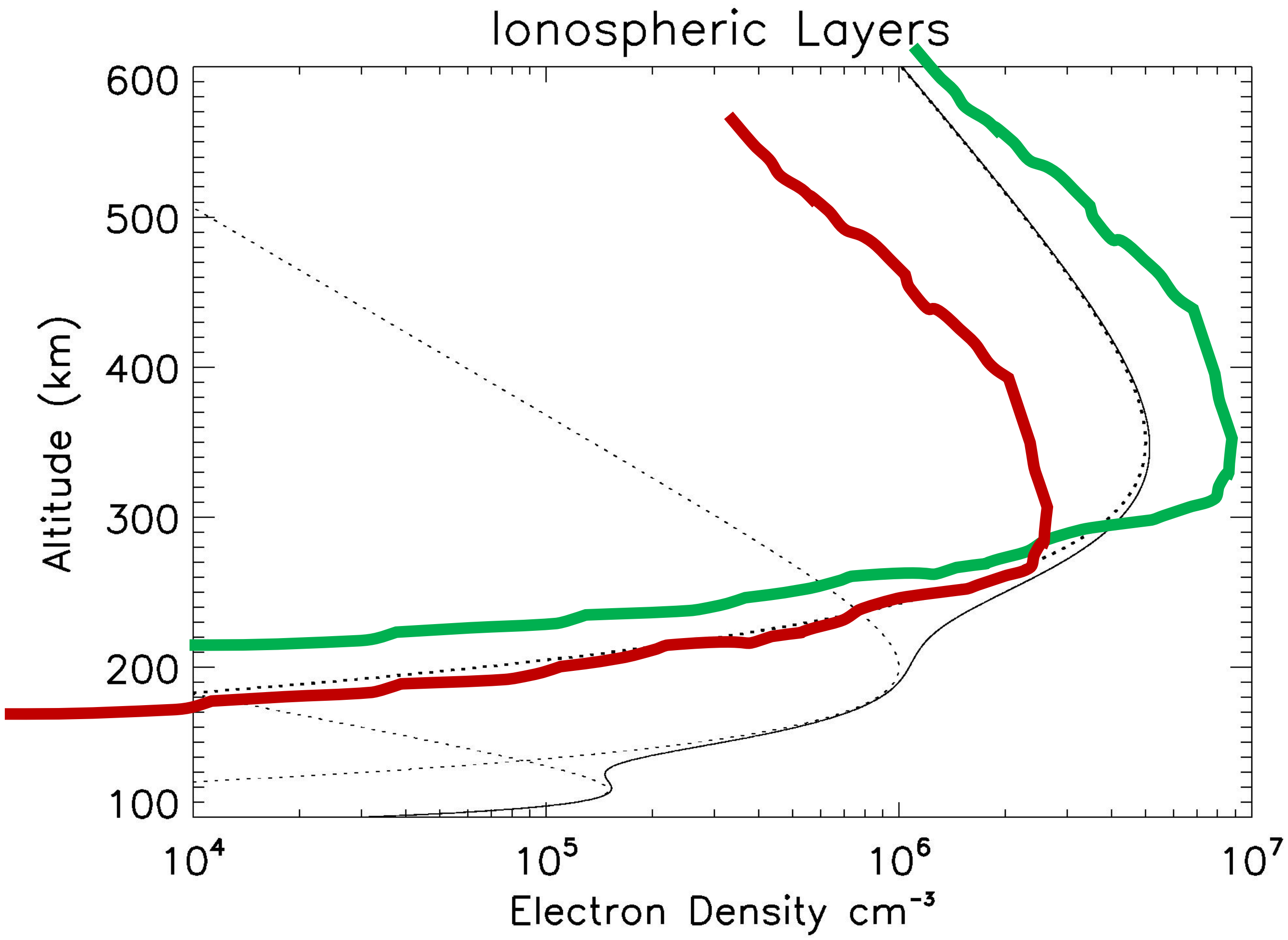
- **The F region is greatly disturbed**
- **Communication range is often shortened**

Who cares?

ICAO

Anyone using HF as comm mode

Electron Density Profiles (EDP) and Ionospheric Storms



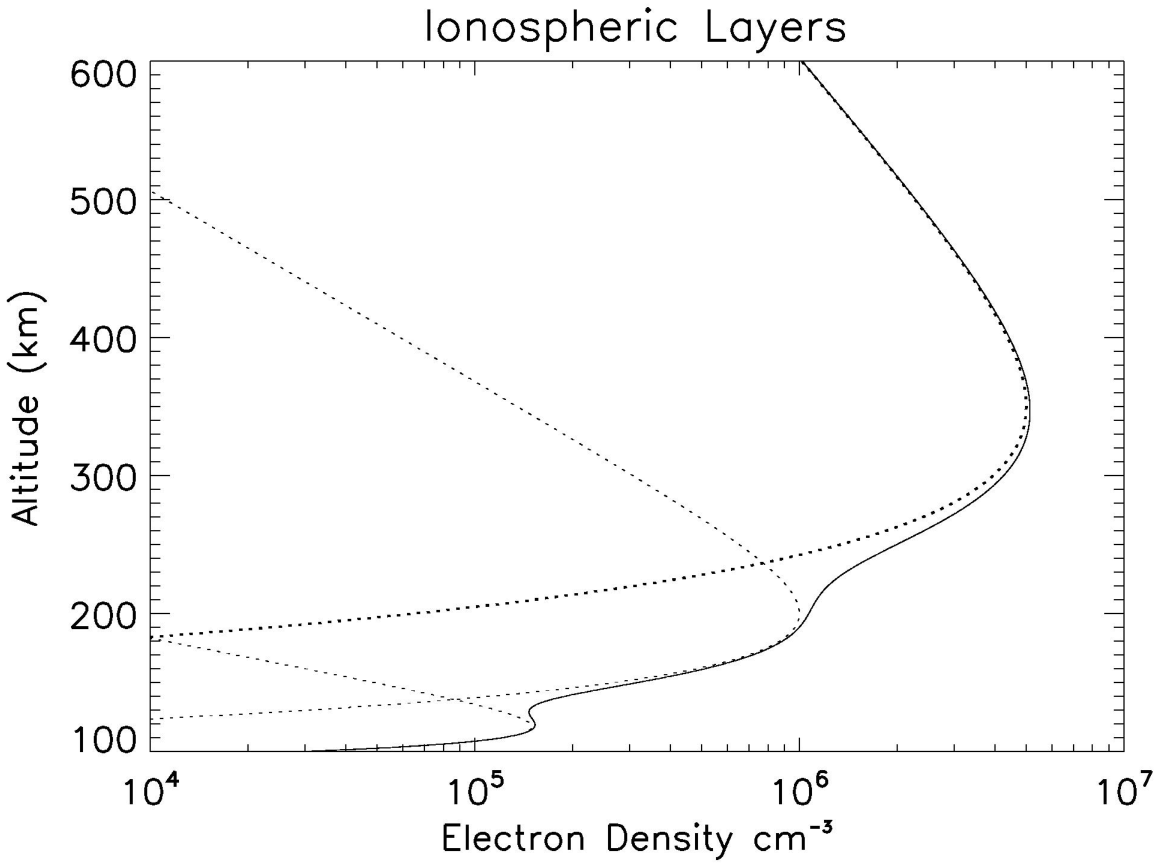
- **Maximum Density or Location of Maximum Density Deviates from Seasonal Norm**
- **Positive Storm if electron density is enhanced**
- **Negative Storm if electron density is decreased**
- **F region and Topside are primarily affected**
- **Communication range strongly affected**

Maximum Useable Frequency foF2 and Ionospheric Storms

- With the typical sequence of solar geospace storm:
- solar flare, geomagnetic storm and enhanced auroral particles
  - Should expect a positive ionosphere storm
  - More ionization at F region peak
  - High critical frequencies
  - Longer communication paths
- At mid latitudes this often occurs, but then is followed by a longer **negative storm**
  - Less ionization at F region peak
  - Lower critical frequencies
  - Shorter communication paths

Balance in Ionospheric Layer Production

- Production of ions/free electrons is balanced by recombination



- F-region

Photo-ionization

$$O + h\nu \longrightarrow O^+ + e^-$$
$$N_2 + h\nu \longrightarrow {N_2}^+ + e^-$$
$$O_2 + h\nu \longrightarrow {O_2}^+ + e^-$$

Charge exchange

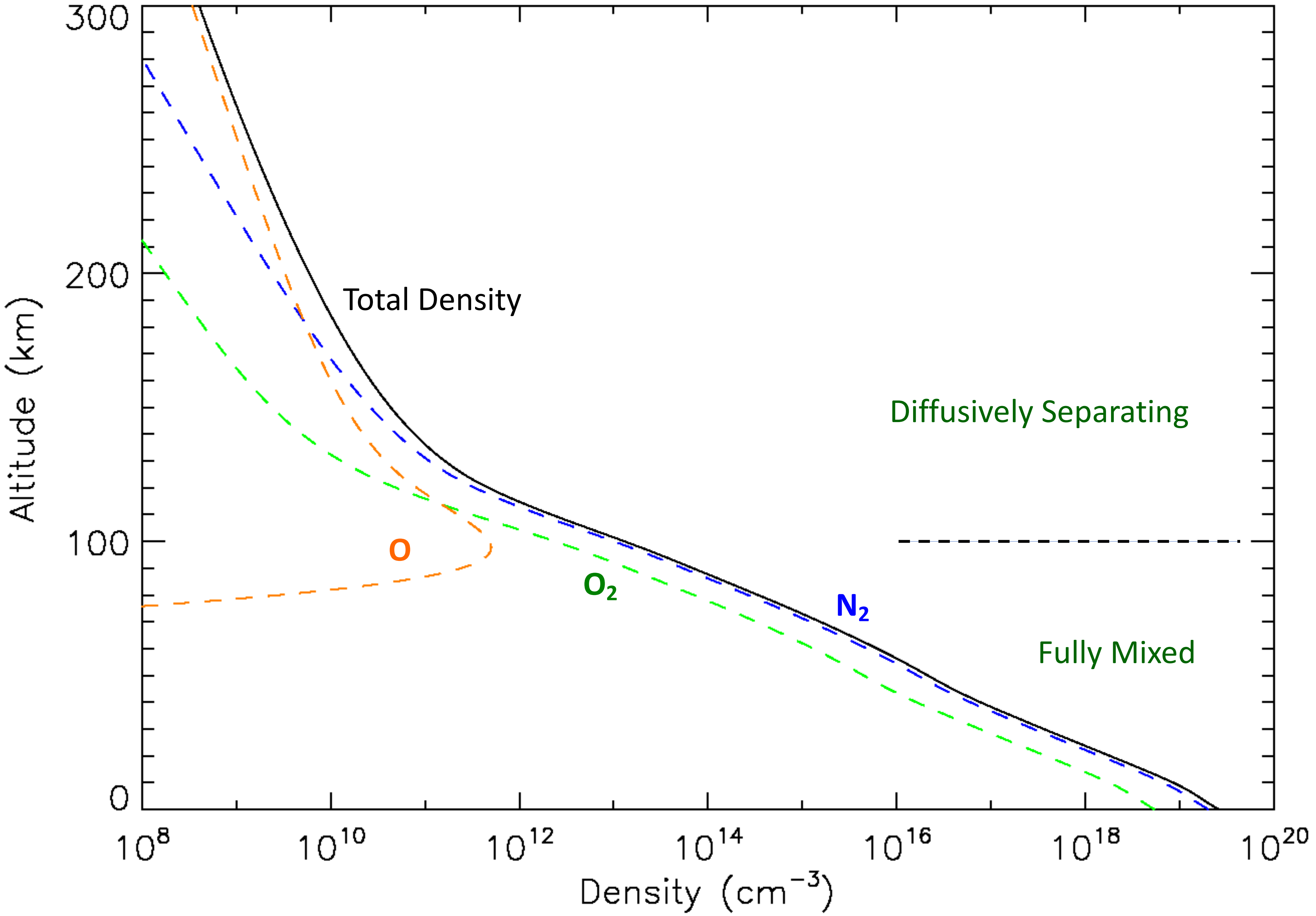
$$O^+ + N_2 \longrightarrow NO^+ + N$$
$$O^+ + O_2 \longrightarrow {O_2}^+ + O$$
$${N_2}^+ + O \longrightarrow NO^+ + N$$

Temperature dependent

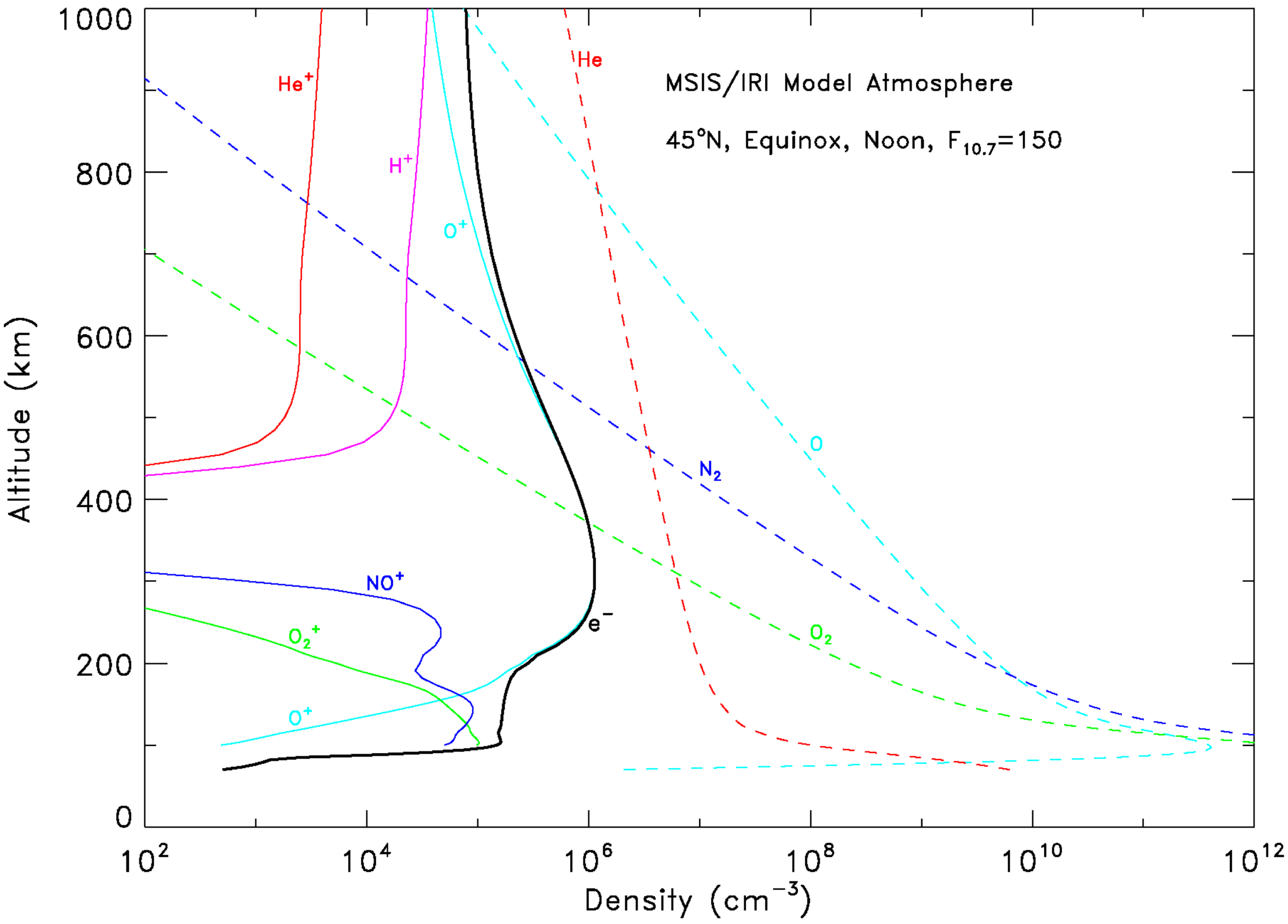
Loss by Re-comb-ination

$$NO^+ + e^- \longrightarrow N + O$$
$$ {O_2}^+ + e^- \longrightarrow O + O$$
$$ {N_2}^+ + e^- \longrightarrow N + N$$

Density Structure of the Earth's Atmosphere



Thermosphere/Ionosphere Altitude Distribution



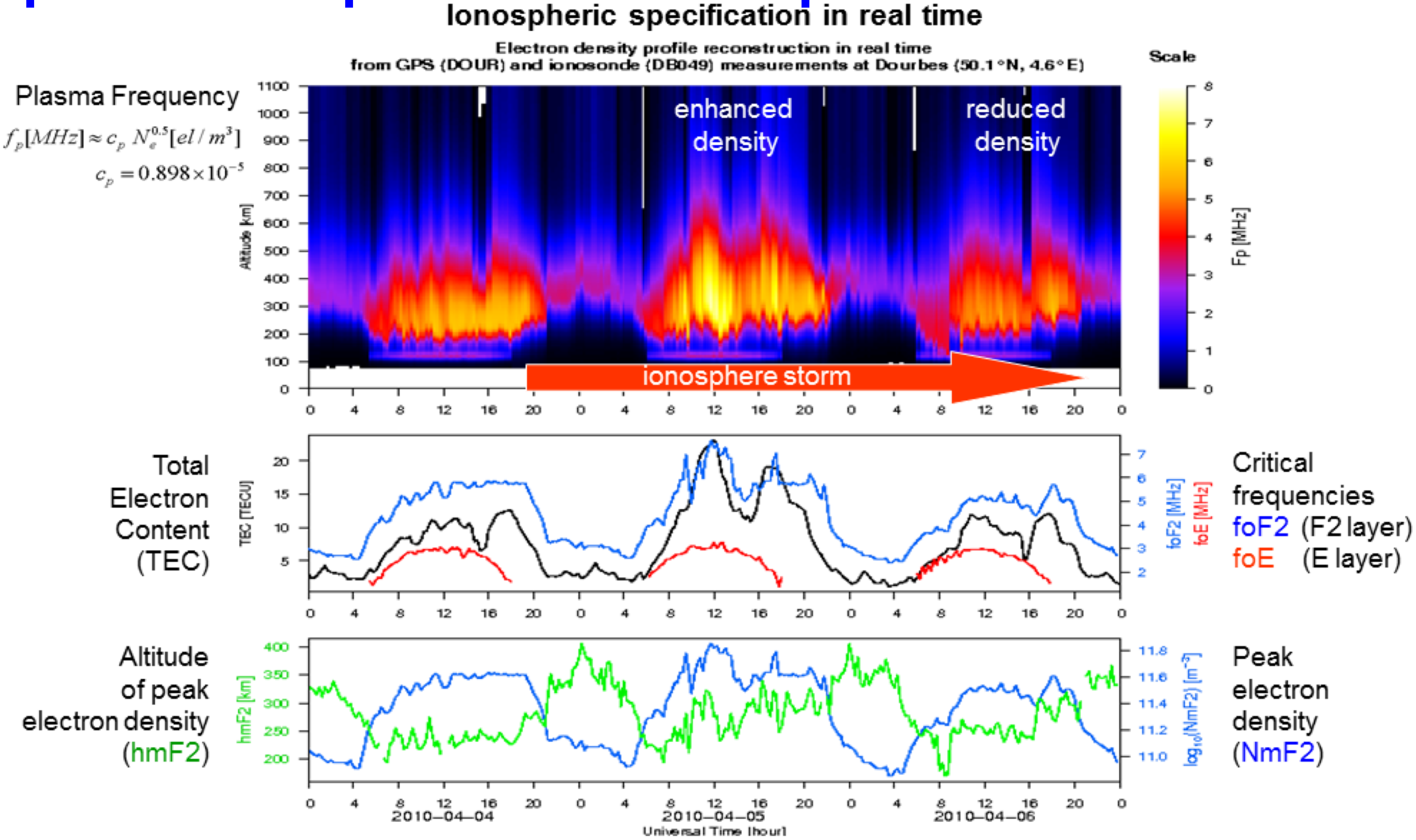
Under nominal conditions O is dominant thermospheric species and O+ is dominant ion at F layer maximum

Big Picture View of Negative Ionospheric Storm

- Ionospheric storms result from very large energy inputs to the polar atmosphere during geomagnetic storms.

- Energy flows out of auroral zones to mid latitudes
  - Heats thermospheric gas
  - Heavy N_2 gases rises (expands) relative to lighter atomic oxygen gas
  - Density of atomic oxygen decreases at F layer heights: $([O]/[N_2])$ decreases
    - Less O+ is made
    - Existing O+ readily interacts with N_2 creating a path for rapid ionization loss
    - Loss of O+ (and e-) exceeds production
  - Electron density is reduced in the F2 region
  - The maximum useable frequency goes down
  - The higher end of the HF spectrum is most affected
  - The longest ‘hop’ distances or range of communications is greatly reduced

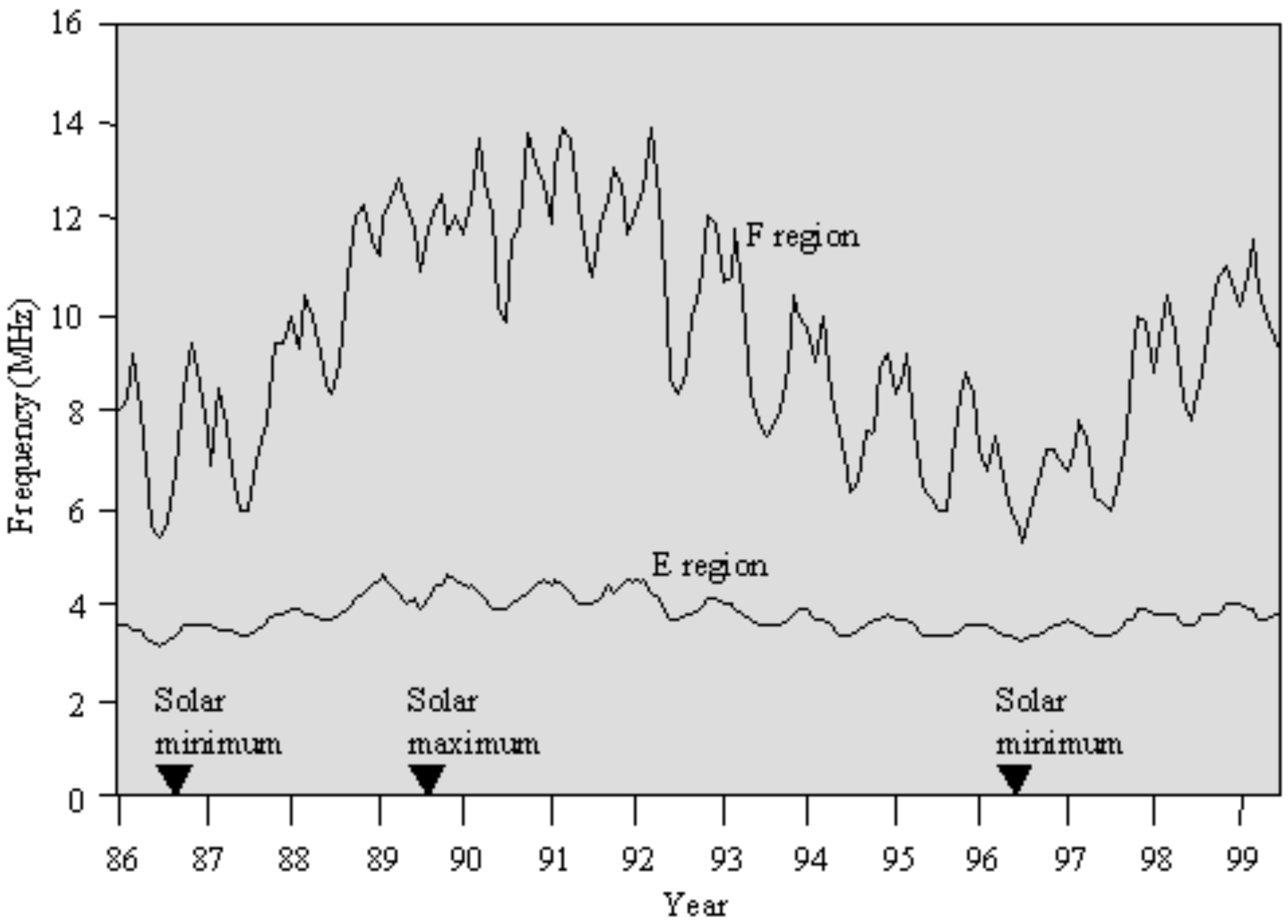
Example of Ionospheric Storm Sequence



http://ionosphere.meteo.be

Stankov et al. (2011): Local ionospheric electron density profile reconstruction in real time, Adv. Space Res. 47(7), 1172-1180

Change in ionospheric critical frequencies over a solar cycle



F region critical frequency

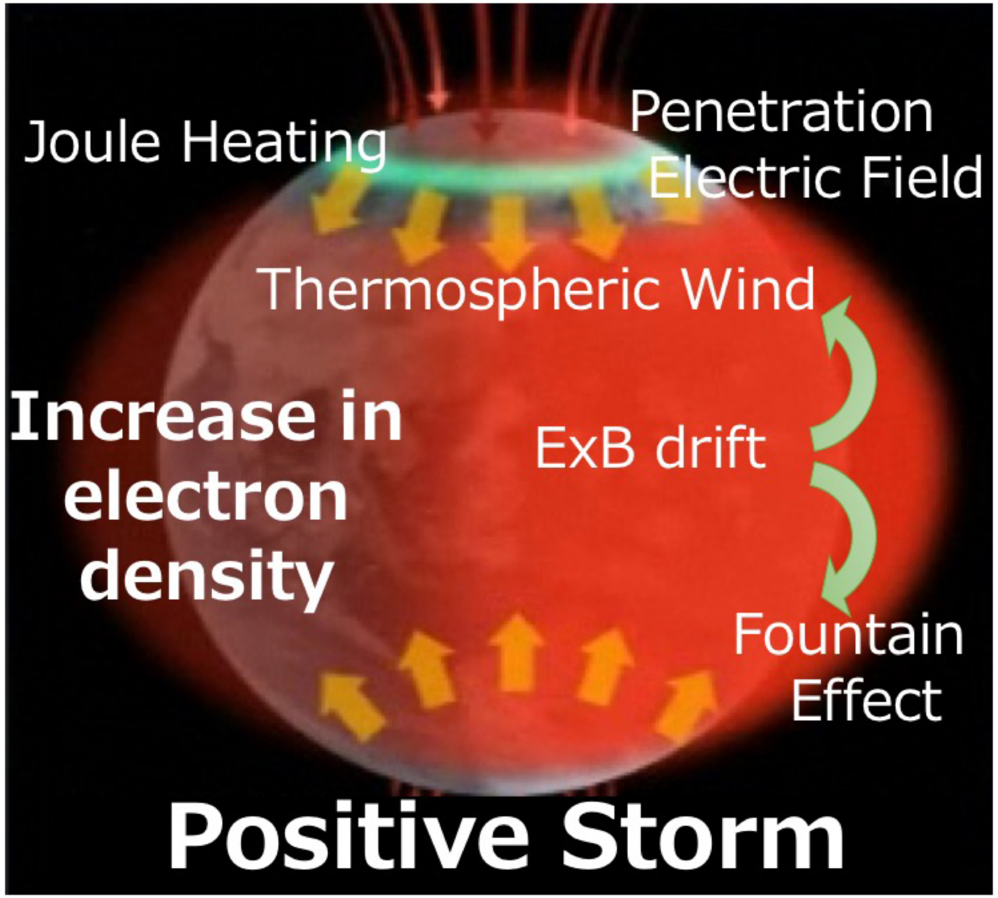
Larger variations compared to E regions

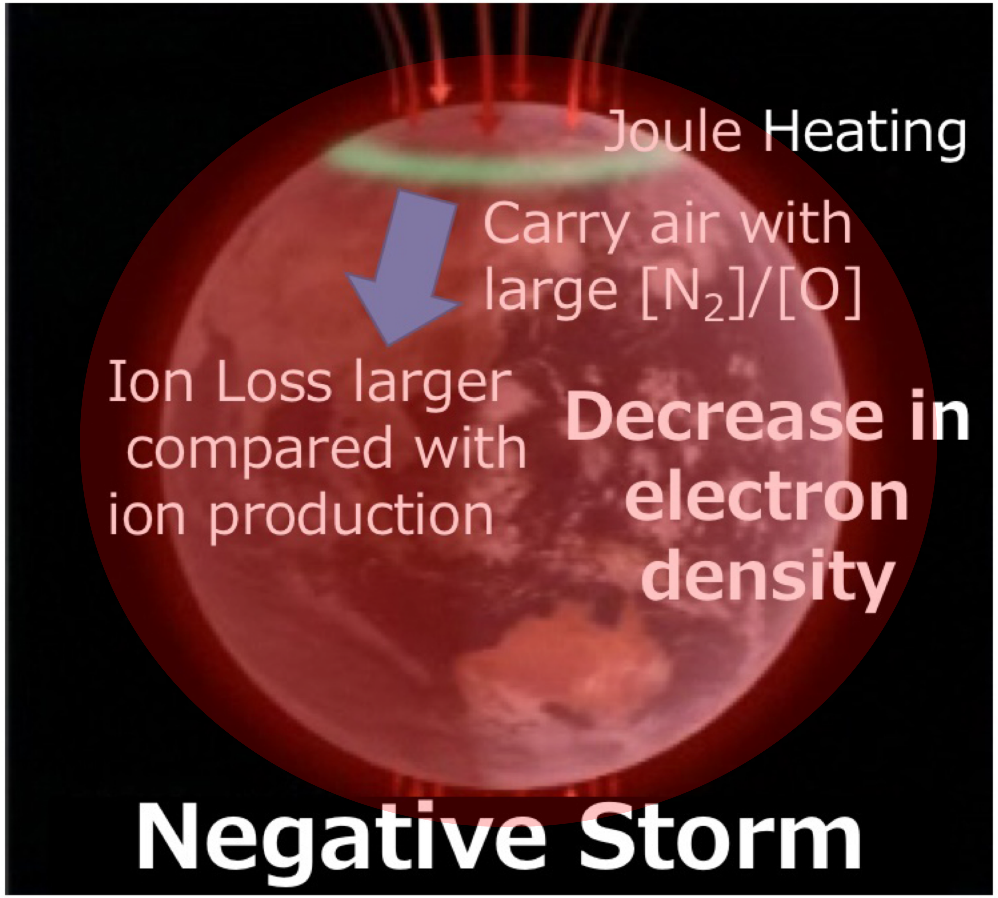
Solar Cycle Trend

Seasonal trend

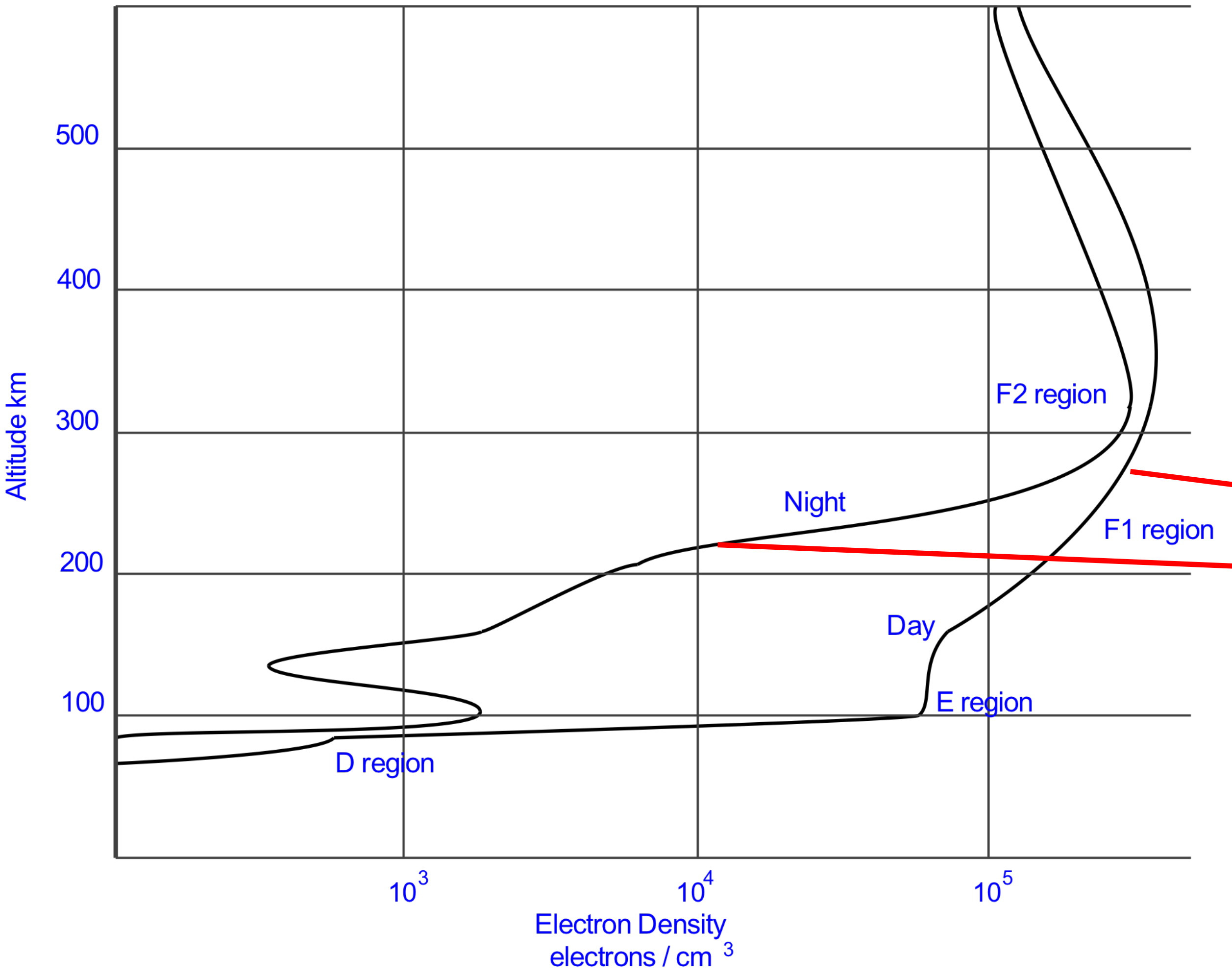
Production and Loss of Ionization is modulated by thermospheric circulaitons

Schematic Comparison of Ionospheric Storm Phases

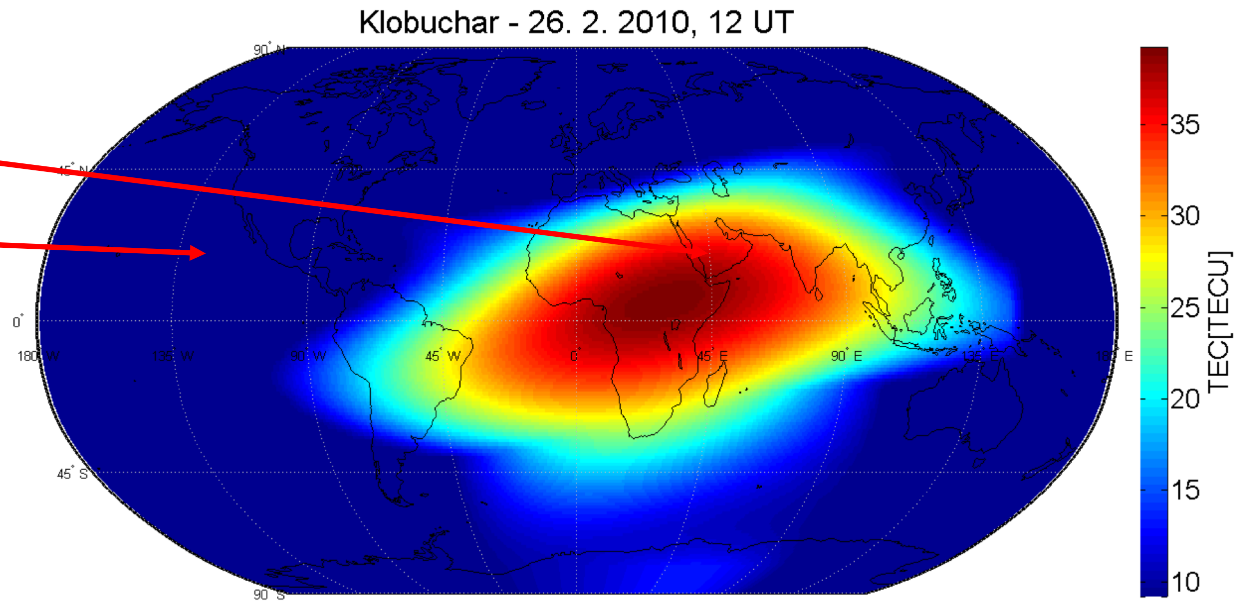




Ionosphere: Total Electron Content Patterns and Structures



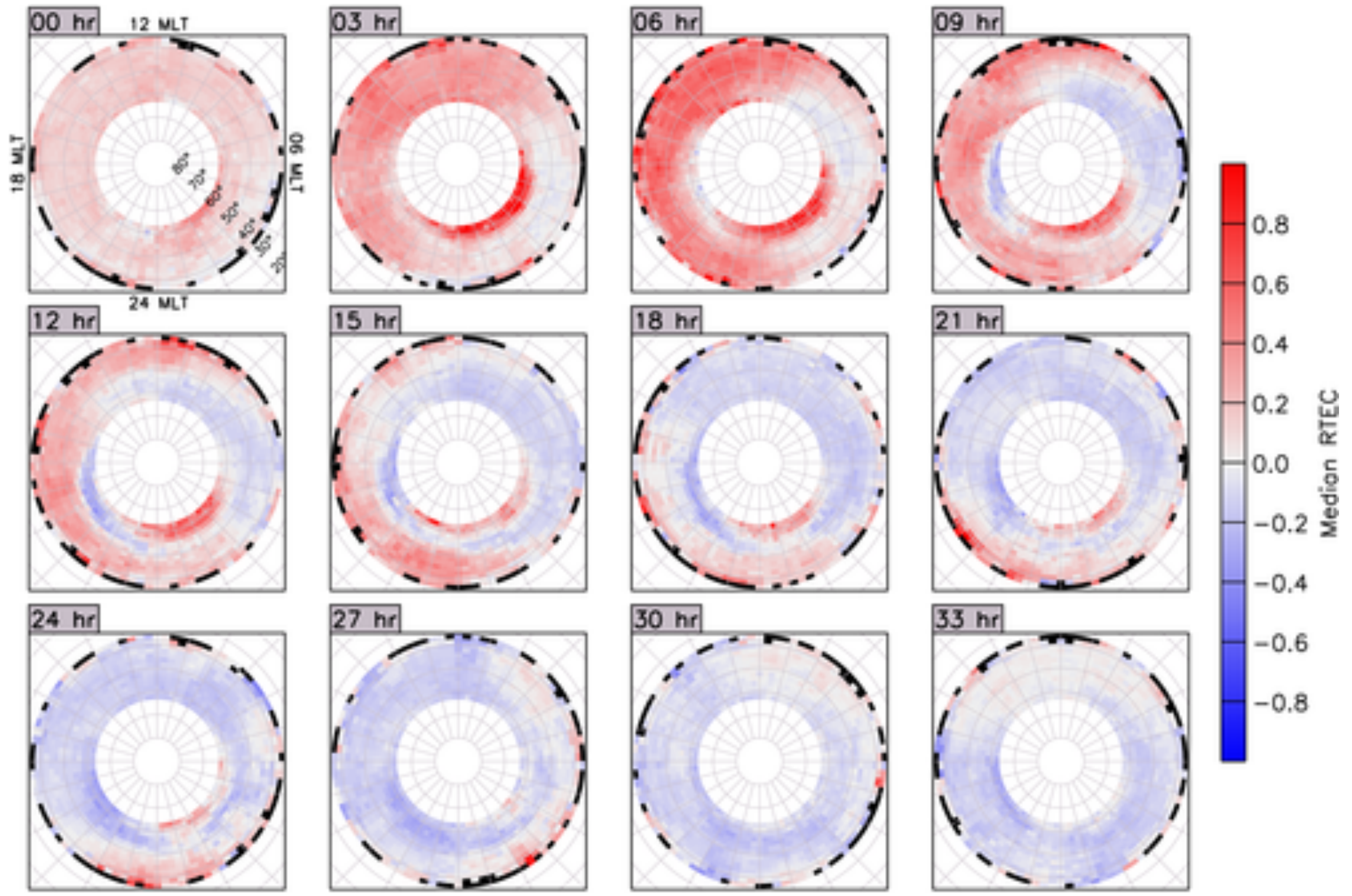
- Add up the number of free electrons in a column of unit area = 1 m^2
- Typically a few times 10^{16}
- 10^{16} /m^2 = Total Electron Content Unit (TECU)
- Produce a map every where: GIM
- Update continuously



Global Ionosphere Map (GIM)

https://www.intechopen.com/books/performance-analysis-of-empirical-ionosphere-models-by-comparison-with-code-vertical-tec-maps

The geomagnetic storm time response of GPS total electron content in the North American sector



Polar view of total electron content every three hours after storm onset for 33 hours

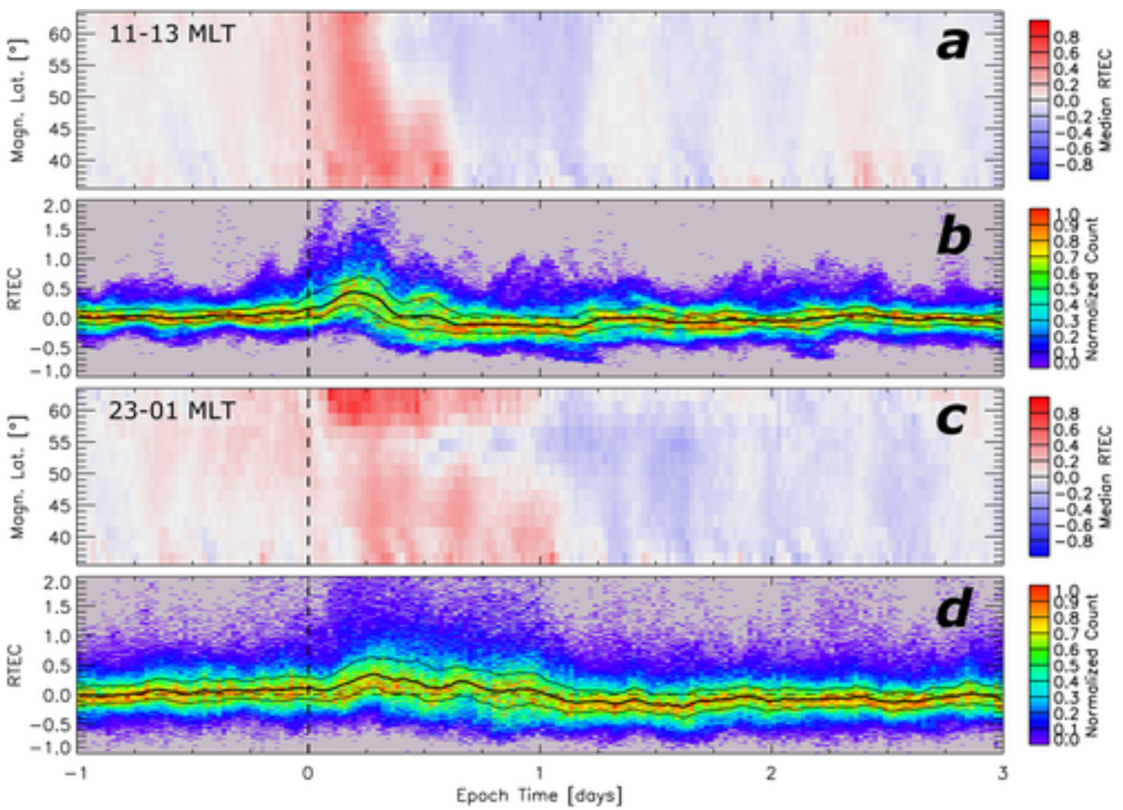
Northern Hemisphere

Data from Norther American Sector

First 9 hours: Positive Storm
Next 6 hours: Transition
Next 18 hours Negative Storm

J. Geophys. Res. Space Physics, Volume: 121, Issue: 2, Pages: 1744-1759, First published: 01 February 2016, DOI: (10.1002/2015JA022182)

The geomagnetic storm time response of GPS total electron content in the North American sector



Temporal view of total electron content for noon and midnight sectors

Northern Hemisphere

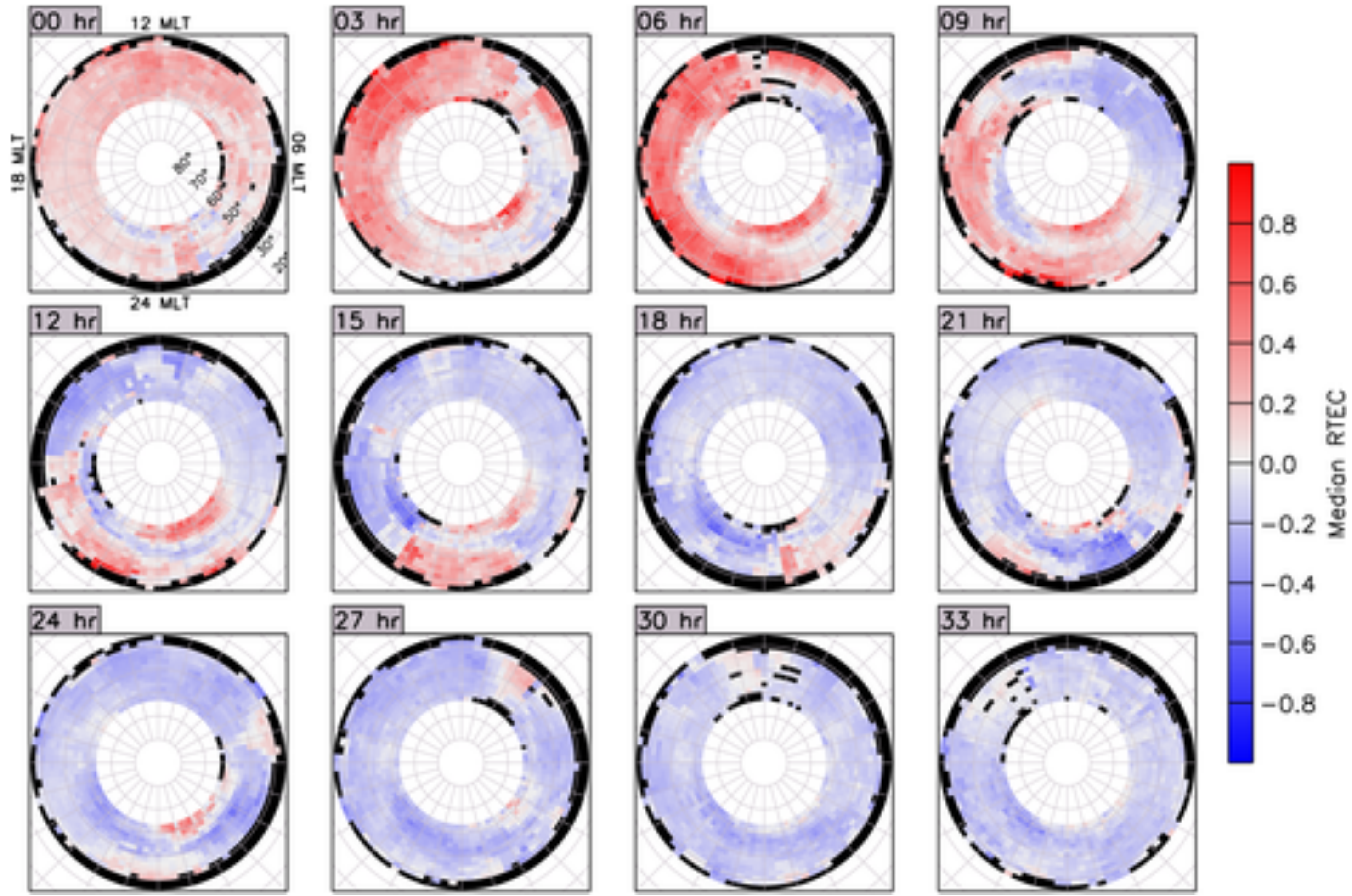
Data from Norther American Sector

Daytime: Rapid transition from Positive Storm to Negative Storm

Nighttime: Slower transition from Positive Storm to Negative Storm

J. Geophys. Res. Space Physics, Volume: 121, Issue: 2, Pages: 1744-1759, First published: 01 February 2016, DOI: (10.1002/2015JA022182)

The geomagnetic storm time response of GPS total electron content in the North American sector



Polar view of total electron content every three hours after storm onset for 33 hours

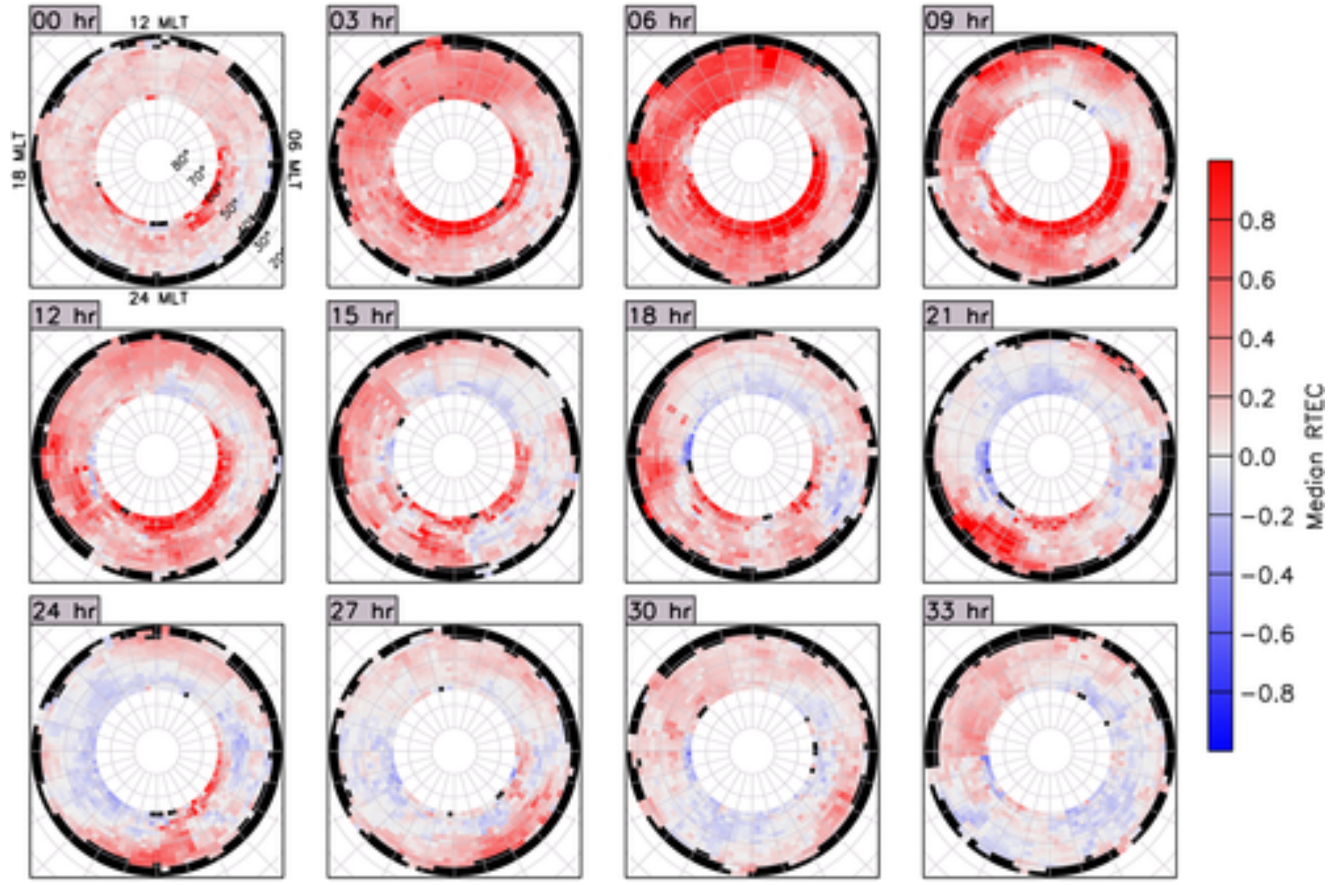
Northern Hemisphere for 55 summer storms

Data from Norther American Sector

Rapid transition to negative storm phase and deeper negative phase

J. Geophys. Res. Space Physics, Volume: 121, Issue: 2, Pages: 1744-1759, First published: 01 February 2016, DOI: (10.1002/2015JA022182)

The geomagnetic storm time response of GPS total electron content in the North American sector



Polar view of total electron content every three hours after storm onset for 33 hours

Northern Hemisphere for 39 winter storms

Data from Norther American Sector

Longer lived positive storm phase

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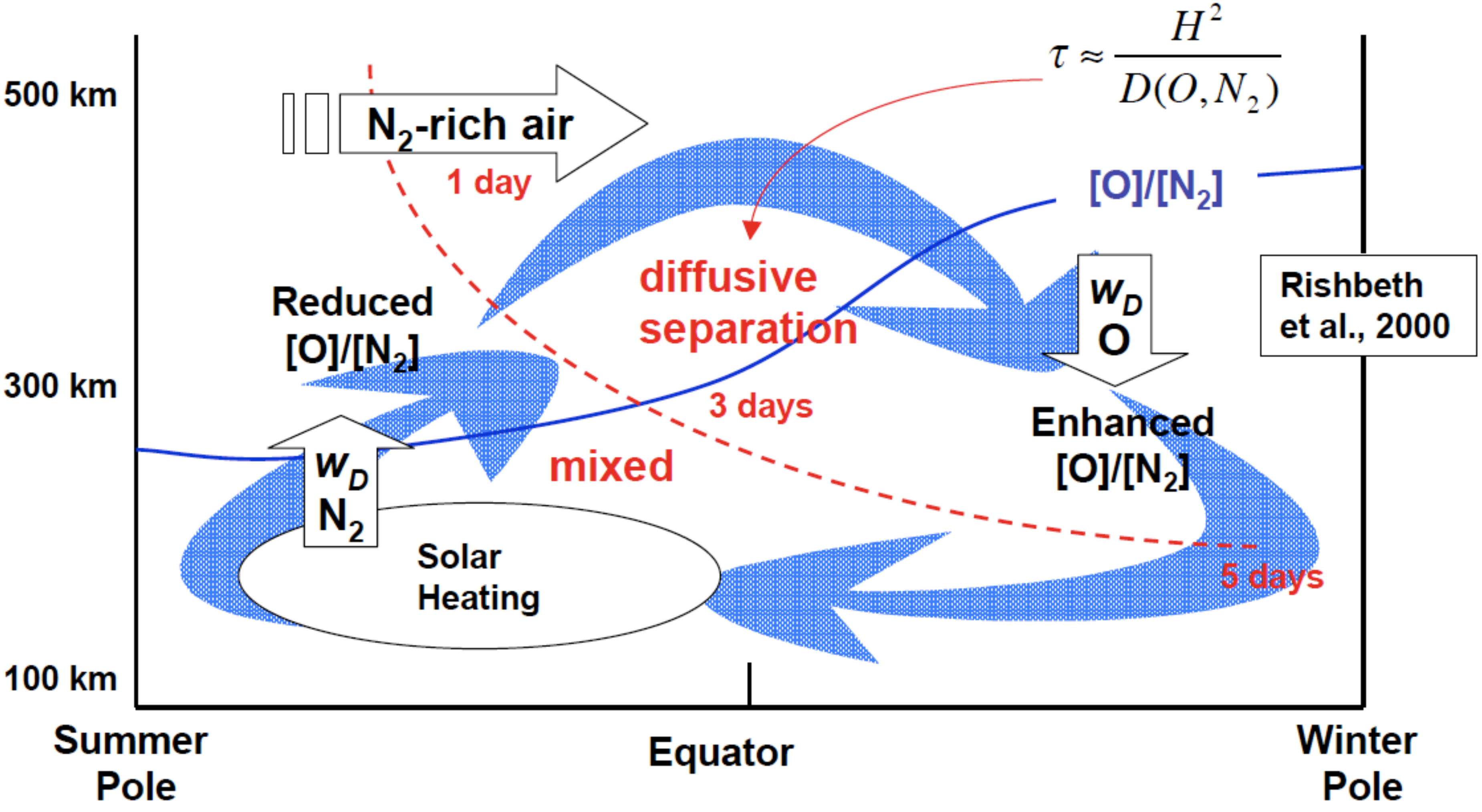
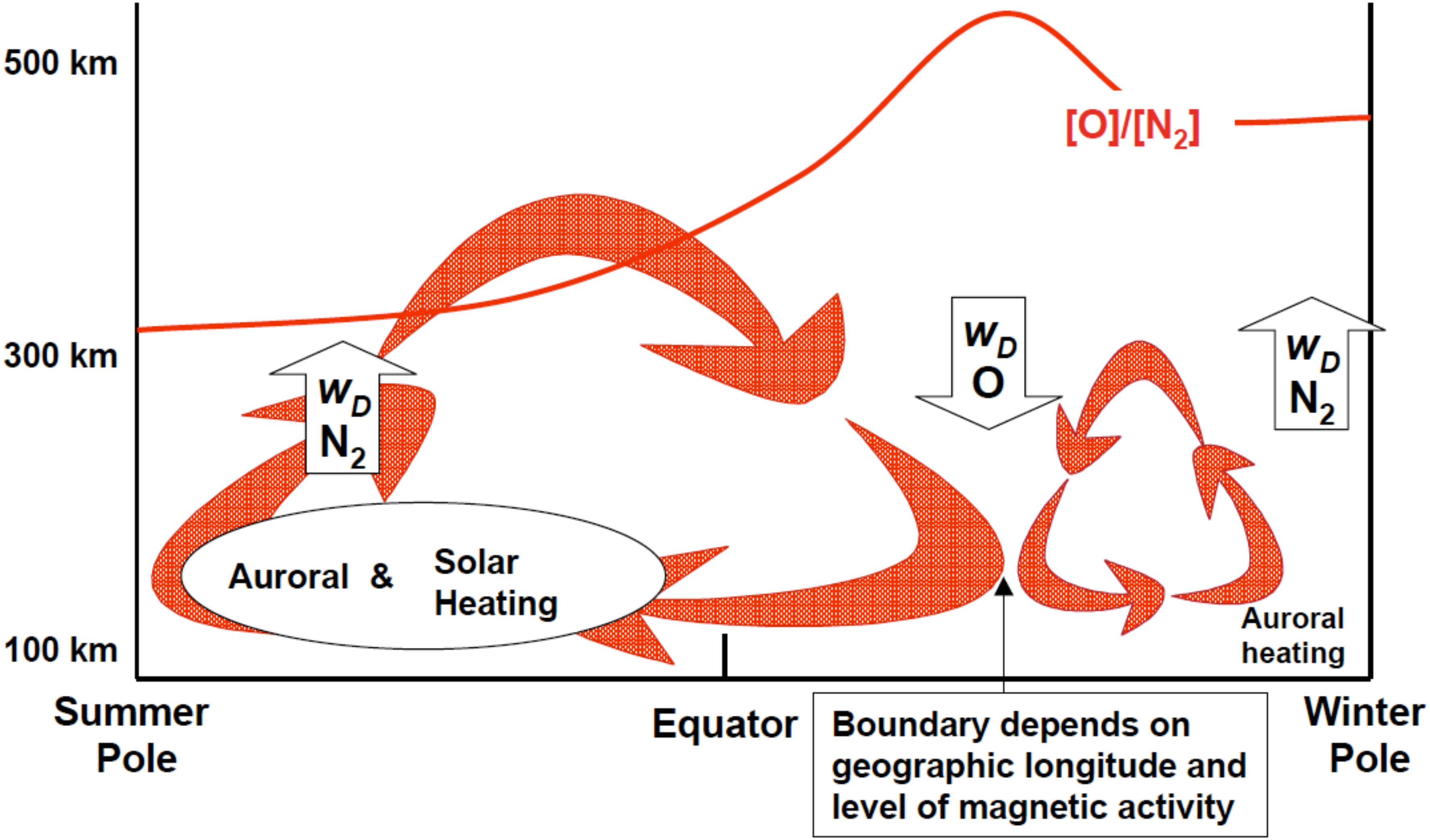
Thermospheric Circulation, Geomagnetic Quiet Conditions



Thermospheric Circulation, Geomagnetic Active Conditions



Additional Considerations for Negative Ionospheric Storms (MUF Depressions)

- The thermosphere is rather slow to relax
  - Thus the duration of an ionospheric negative storm phase can be as long as the recovery phase of the corresponding geomagnetic storm.
- Ionospheric storms with only a negative phase are more frequent in summer than in any other season
  - the background thermosphere at all heights has a lower [O]/[N2] ratio,
  - Ratio is further reduced under the chemical effects of storm-time thermospheric winds.

Summary

- Space Weather Impacts Ionosphere & Communications
- We reviewed
  - Ionospheric Structure
  - HF Comm
  - Short Wave Fade
  - Polar Cap Absorption
  - Auroral Absorption
  - Maximum Usable Frequency (MUF) Depression

Thank You!

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