International School of Space Science (ISSS) - L'Aquila 2018

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Thanks to:
Prof Craig J. Rodger
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Dunedin
New Zealand

GROUND BASED MONITORING INFRASTRUCTURES AT POLAR LATITUDES: AARDDVARK

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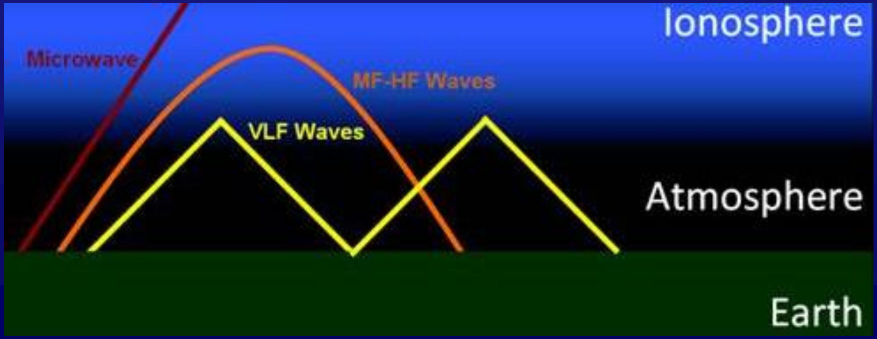
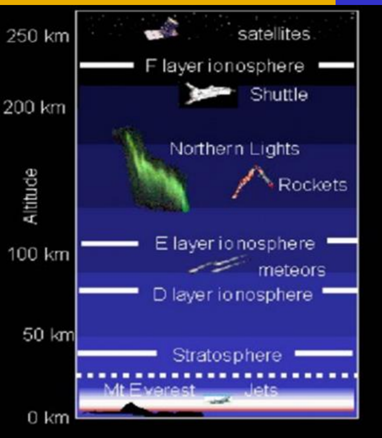


The D-region



The D-region ionosphere is the most complex part of the ionosphere in terms of chemical modelling. There are several sources that contribute to ion production:

-Lyman-alpha ionizes NO

-EUV ionizes excited oxygen (O_2*), O_2 and N_2

-X-rays (flares) ionize O_2 and N_2

-GCR ionizes major constituents at low altitude

-Energetic particles can be a main source of ionization at high latitudes.

An example of D-region ion production rates

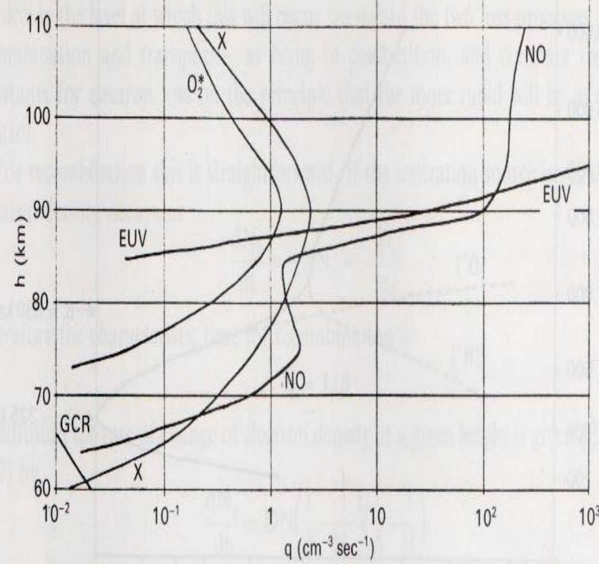


Fig. 6.13 Calculated production rates at $\chi = 42°$ due to: Extreme ultra-violet (EUV), Lyman-α and nitric oxide (NO), X-rays (X), Excited oxygen (O_2^*), Galactic cosmic rays (GCR). (J. D. Mathews, private communication)

[Taken from Hargreaves, 1992. CUP]

Background constituents

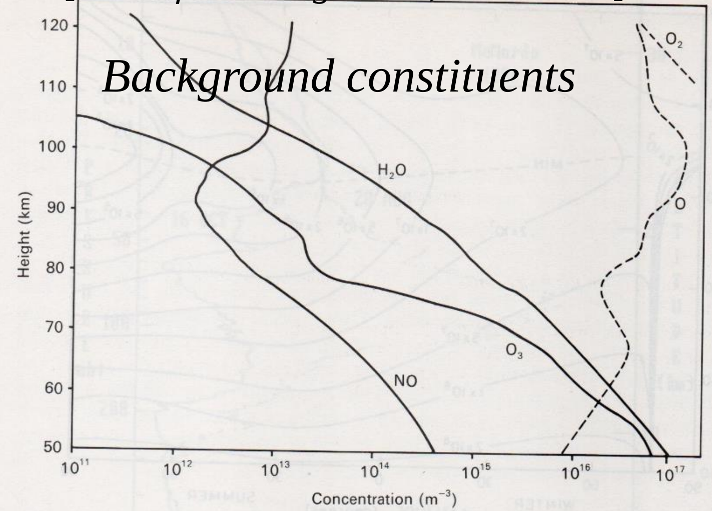


Fig. 4.8 Calculated distributions of important minor constituents for noon at 45° N latitude. and O are shown for comparison. (After *Handbook of Geophysics and the Spa Environment*, AFGL, 1985; from T. J. Keneshea *et al.*, *Planetary and Space Science* 385, 1979)

What is VLF?

Strictly speaking VLF (= Very Low Frequency) EM radiation lies in the frequency range 3-30kHz and thus free-space wavelengths of 100-10km. However, many researchers tend to "fuzz" the upper and lower frequency limits somewhat.

Ground-based VLF observations in the band are dominated by the impulsive signals radiated by lightning discharges.

⟶ radiate EM power from a few Hz to several 100 MHz

⟶ bulk of the energy in the frequency bands <30 kHz

Except at the highest latitudes, long term noise surveys undertaken in this band contain essentially no contribution from other natural radio noise sources.

i.e., the main natural VLF source is lightning

At VLF such pulses are termed "atmospherics", or simply "sferics".

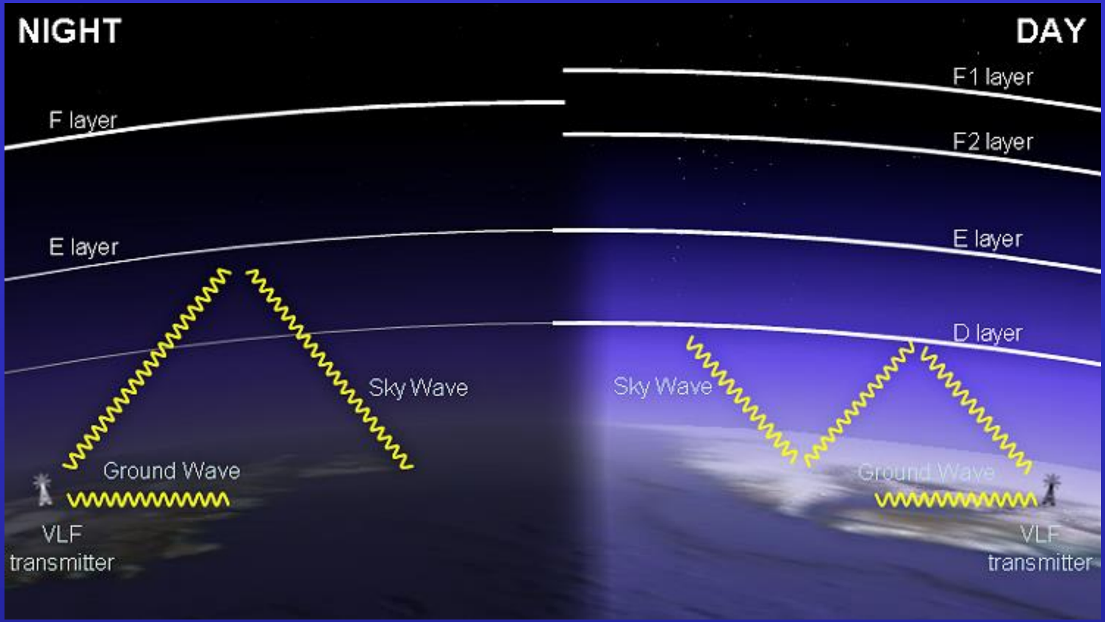
ELF	3 - 30 Hz
SLF	30 - 300 Hz
ULF	300 - 3000 Hz
VLF	3 - 30 KHz
LF	30 - 300 KHz
MF	300 - 3000 KHz
HF	3 - 30 MHz
VHF	30 - 300 MHz
UHF	300 - 3000 MHz
SHF	3 - 30 GHz
EHF	30 - 300 GHz

Frequency band [*International Telecommunication Union*].

University of Otago
Te Whare Wānanga o Otāgo
Sapere Aude
Sciences

British Antarctic Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

VLF and the Earth-ionosphere Waveguide



Most of the energy radiated by lightning discharges and manmade VLF transmitters is trapped between the conducting ground (or sea) and the lower part of the ionosphere, forming the **Earth-ionosphere waveguide**.

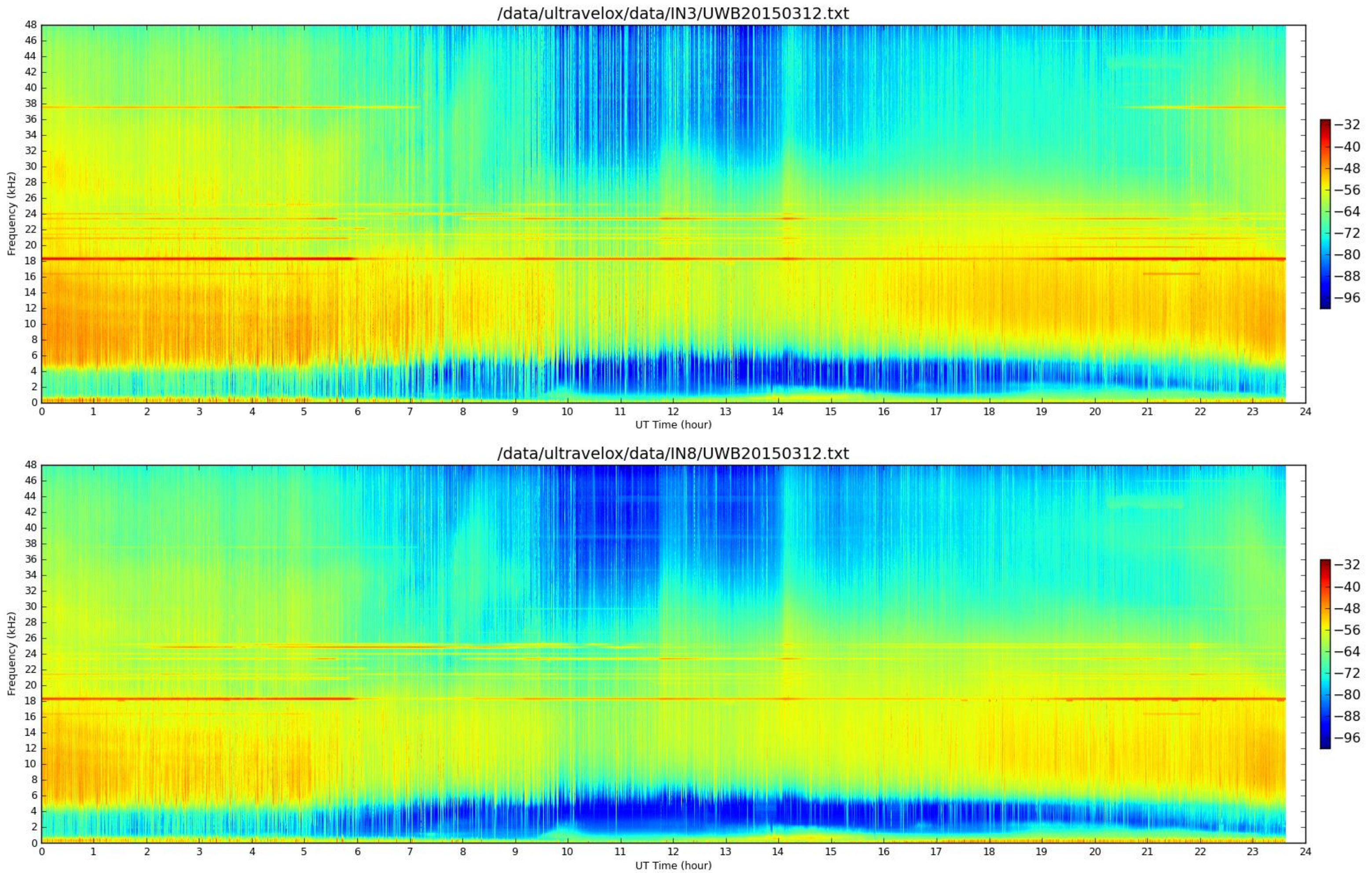
⟶ this energy is propagating "*subionospherically*", i.e., beneath the ionosphere.

Subionospheric VLF signals reflect from the ionospheric *D*-region (70-90 km), probably the least studied region of the Earth's atmosphere.

⟶ received radio waves are largely determined by propagation between the boundaries

⟶ Very-long range remote sensing is possible as these signals can be received 1000's of km from their sources!

For frequencies >10 kHz man-made transmissions from communication and navigation transmitters can be observed in almost every part of the world.



24 hours of wideband VLF amplitude measurements (NS and EW aerials) made at Halley, Antarctica, 12 March 2015. 0-48 kHz, 10 s resolution.

Electrical Conditions? As we are using a VLF electromagnetic wave we are talking about undertaking remote sensing of atmospheric electrical conductivity, σ. At low altitudes (< ~70km) the conductivity due to electrons is isotropic and given by:

$$\sigma_0 = \frac{N_e e^2}{m_e(\upsilon_{eff} - j\omega)} = \frac{N_e e^2}{m_e \upsilon_{eff}}$$

note this is under the quasi-DC approx

where N_e = electron number density
m_e = electron mass
υ_{eff} = effective collision frequency

(similar expressions can be produced for ions)

However, at higher altitudes the conductivity is anisotropic due to the influence of the geomagnetic field. Hence we introduce the Lamour frequency (or electron gyrofrequency), ω_B , and produce:

$$\sigma_1 = \frac{N_e e^2 \upsilon_{eff}}{m_e\left(\upsilon_{eff}{}^2 + \omega_B^2\right)} \qquad \sigma_2 = \frac{-N_e e^2 \omega_B}{m_e\left(\upsilon_{eff}{}^2 + \omega_B^2\right)}$$

The Pedersen and Hall conductivities, respectively. The first is perpendicular to the imposed magnetic field and parallel to any imposed electric field, while the Hall is perpendicular to both.

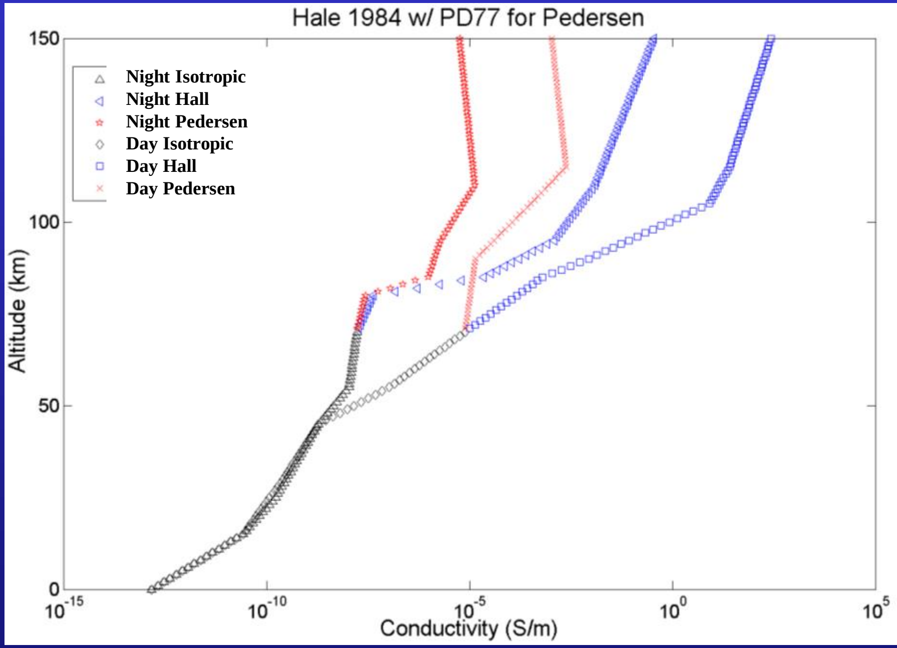
Conductivity Dependences

Thus the conductivity depends on the density and temperature of the neutral atmosphere (driving changes in υ_{eff} the effective collision frequency), the number density of ionised particles (leading to changes in N_e), and the presence of the geomagnetic field (changing the Lamour frequency).

σ_0=isotropic

σ_1= Pedersen

σ_2=Hall



The electrical conductivity of the middle atmosphere is one of the most variable quantities known in atmospheric science, ranging over many orders of magnitude from troposphere to mesosphere.

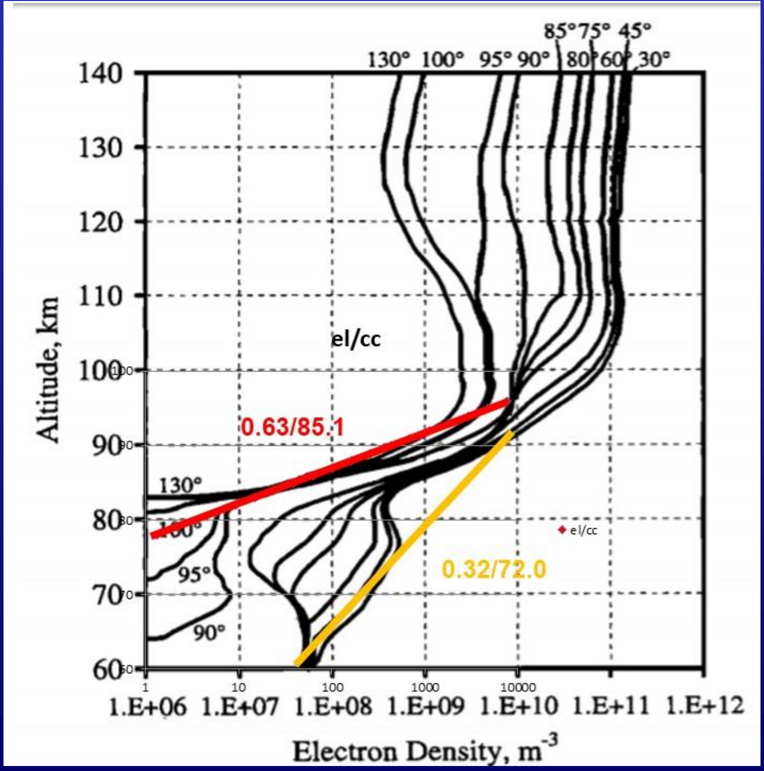
Representative midlatitude conductivity profile for night-time and day-time conditions using data scaled from [*Hale*, 1984], and [*Park and Dejnakarintra*, 1977].

Sources of Ambient Parameters - Standard Models

For the *D*-region there is a strong temptation to make use of a simple "Wait ionosphere" using a Wait ionosphere, where the electron number density (i.e., electrons per m^{-3}), N_e, increases exponentially with altitude z given by,

$$N_e(z) = 1.4265 \times 10^{13} \exp(0.15\boldsymbol{h'}) \times \exp((\boldsymbol{\beta}-0.15)(z-\boldsymbol{h'}))$$

where $\boldsymbol{\beta}$ reflects the sharpness of the profile, and $\boldsymbol{h'}$ is a reference height. Both β and h' vary depending on the time of day. Nighttime conditions are given by $h' = 85$ km and $\beta = 0.63$ km^{-1}. Daytime: by $h' = 72$ km and $\beta = 0.32$ km^{-1}



Comparisons of electron density profiles adopted for the *D*-region of the ionosphere and the FIRI model based on rocket measurements.

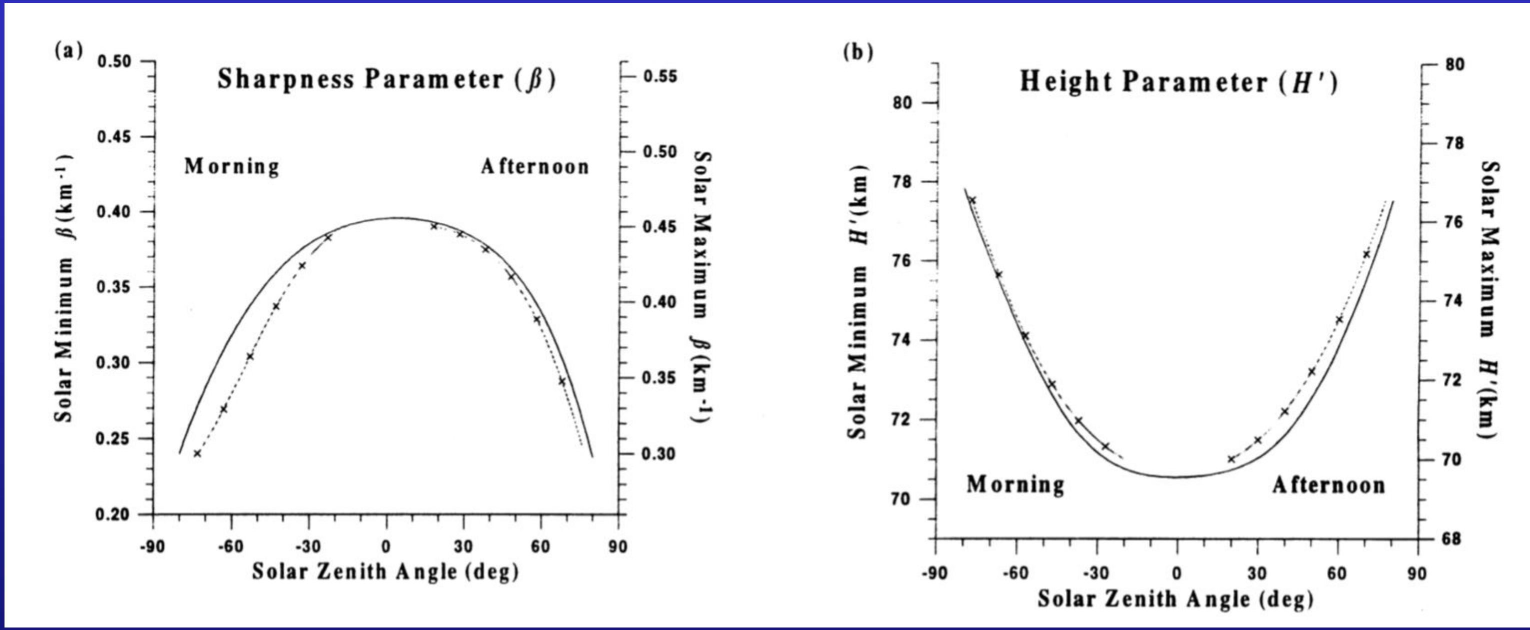
Friedrich and Torkar, 2001, JGR.

Sources of Ambient Parameters – Standard Models

$$N_e(z) = 1.4265 \times 10^{13} \exp(0.15\boldsymbol{h'}) \times \exp((\boldsymbol{\beta}\text{-}0.15)(z\text{-}\boldsymbol{h'}))$$

where $\boldsymbol{\beta}$ reflects the sharpness of the profile, and $\boldsymbol{h'}$ is a reference height.

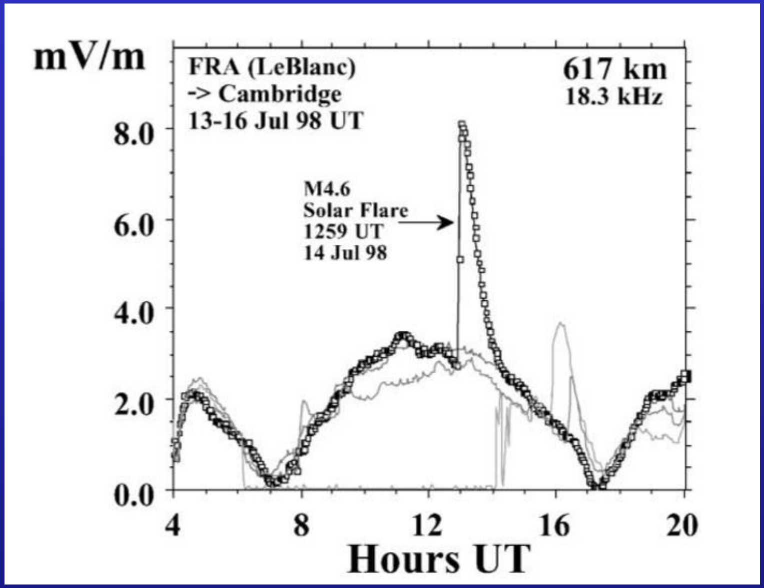
Daytime: strong control from Solar Zenith Angle

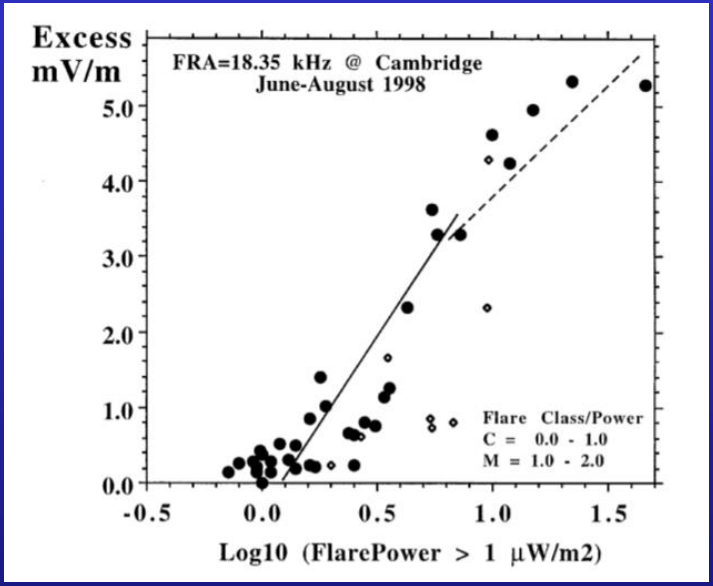


Daytime ionospheric parameters from long subionospheric VLF paths.

McCrae and Thomson, 2000, JASTP.

What happens during moderate solar flares?





On some paths there is reasonable amplitude correlation with flare magnitude

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Solar flare induced ionospheric D-region
enhancements from VLF amplitude
observations.

Thomson and Clilverd, 2000, JASTP.
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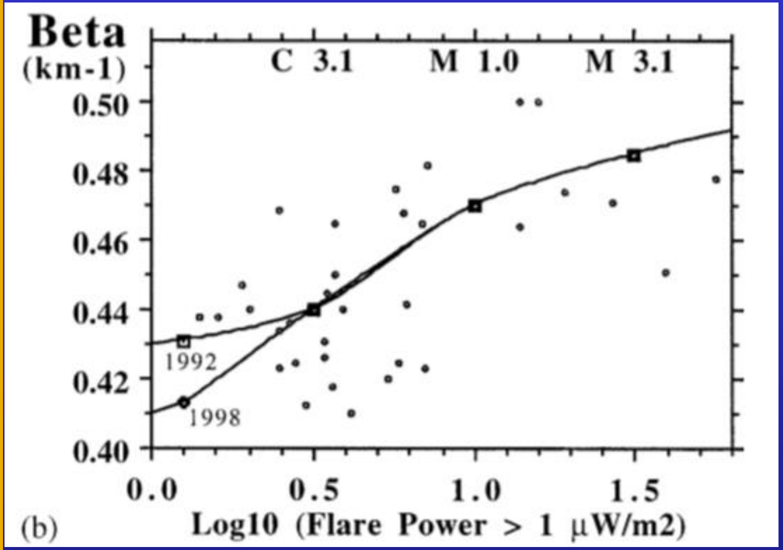
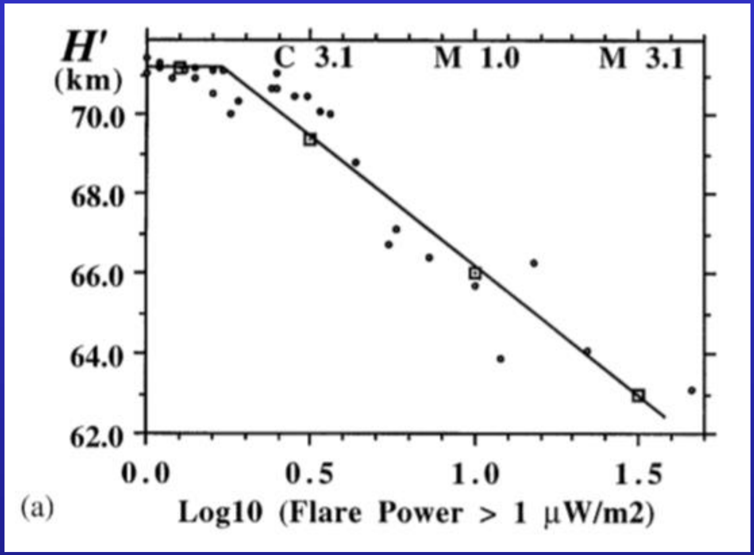
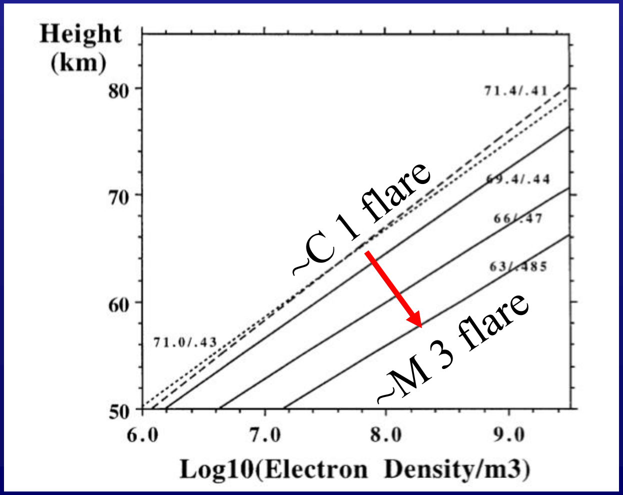
$$N_e(z) = 1.4265 \times 10^{13} \exp(0.15\boldsymbol{h'}) \times \exp((\boldsymbol{\beta}-0.15)(z-\boldsymbol{h'}))$$

where β reflects the sharpness of the profile, and h' is a reference height.





Phase is linear with Flare power,
while beta response is more complex



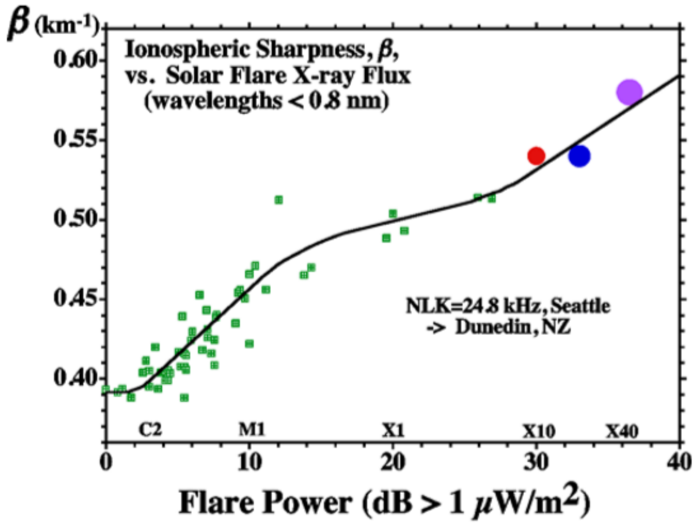
Solar flare induced ionospheric D-region enhancements from VLF amplitude observations.

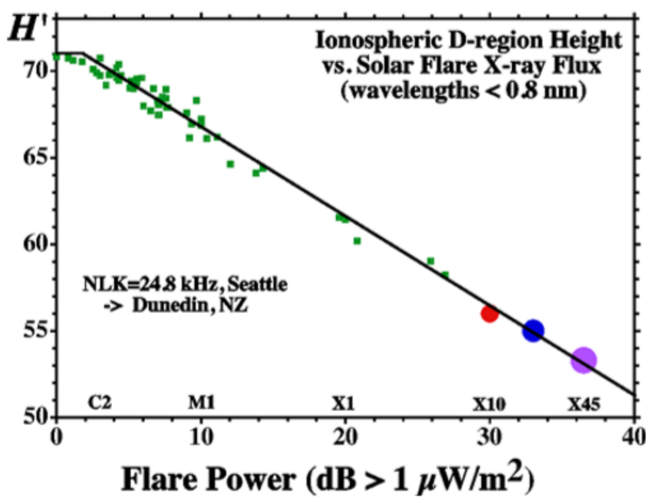
Thomson and Clilverd, 2000, JASTP.

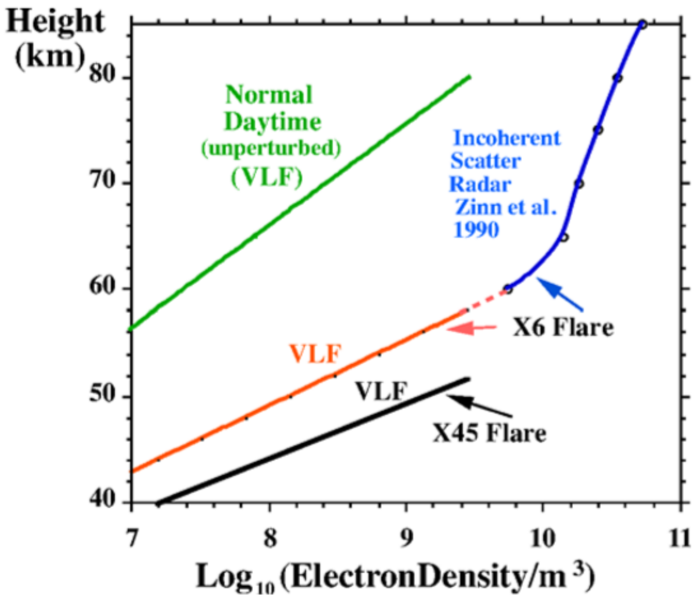
What happens during really big solar flares?

$$N_e(z) = 1.4265 \times 10^{13} \exp(0.15\boldsymbol{h'}) \times \exp((\boldsymbol{\beta}-0.15)(z-\boldsymbol{h'}))$$

where β reflects the sharpness of the profile, and $\boldsymbol{h'}$ is a reference height.





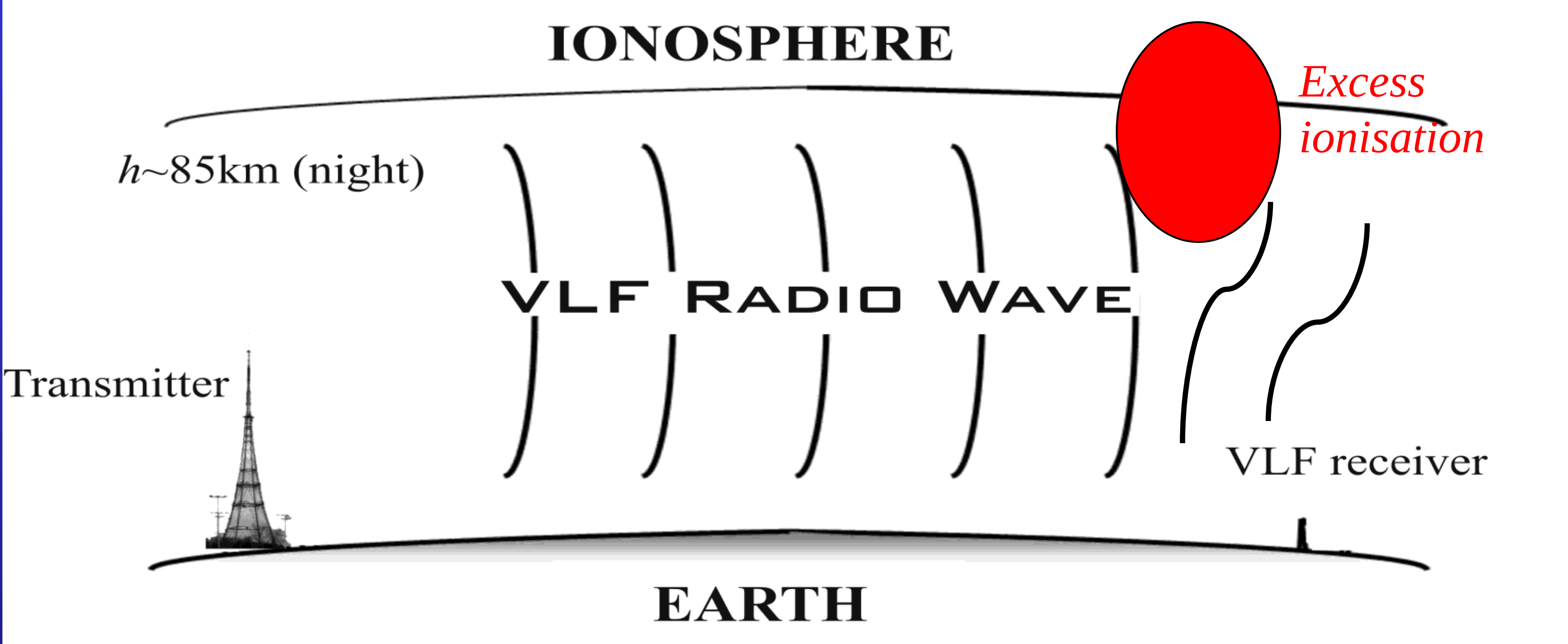


Large Solar Flares and their Ionospheric D-region Enhancements.

Thomson et al., 2005, JGR.

What is AARDDVARK?

Making measurements of Very Low Frequency (VLF) radio waves:

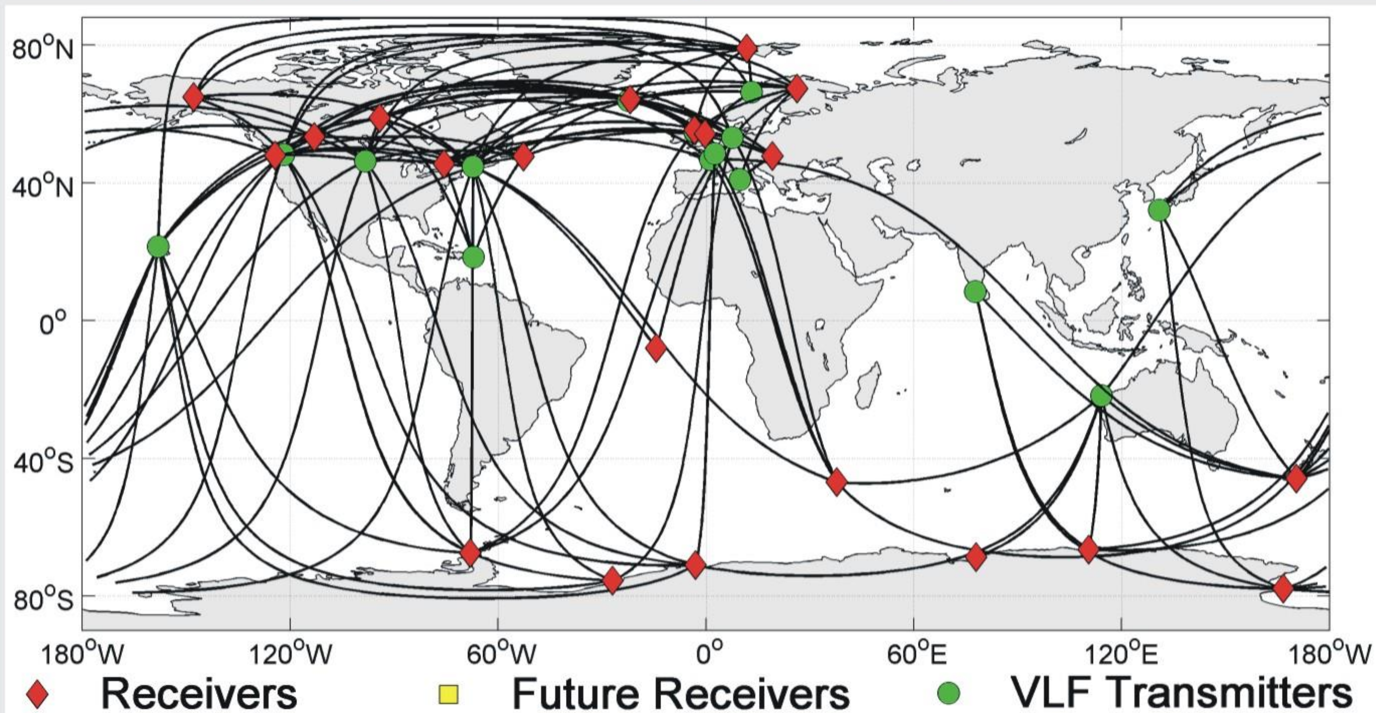


Radio transmissions at Very Low Frequencies (VLF) largely trapped between the conducting ground (or sea) and the lower part of the ionosphere (70-90 km) , forming the Earth-ionosphere waveguide.

Changes in the ionosphere cause changes in the received signal. There is very low attenuation in this frequency range, such that transmissions can propagate for many 1000km's - long range sensing of the upper atmosphere!

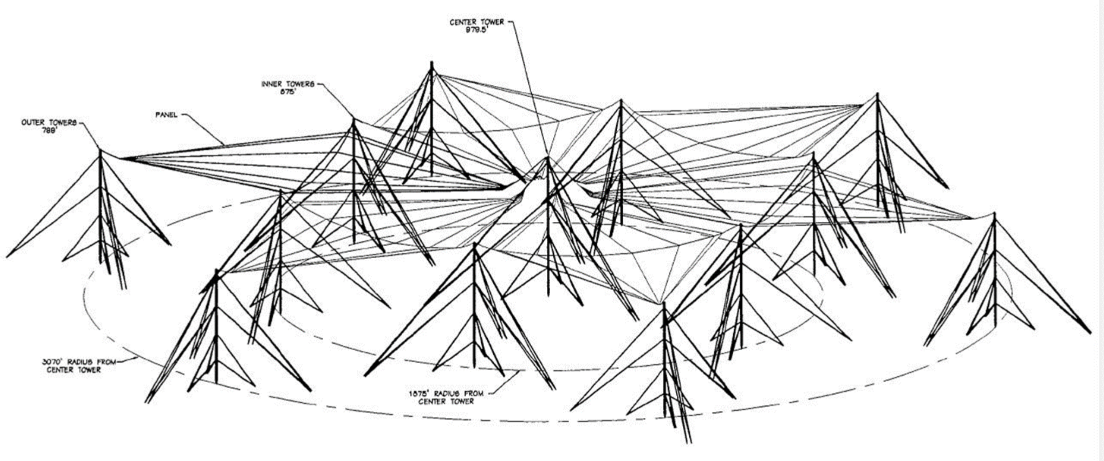
Sub-ionospheric Propagation paths: high latitude emphasis (north and south)

ANTARCTIC-ARCTIC RADIATION-BELT (DYNAMIC) DEPOSITION - VLF ATMOSPHERIC RESEARCH KONSORTIA



High Power, expensive transmitters - recorded by simple, cheap receivers

NAA transmitter, 24.0 kHz, 1 MW



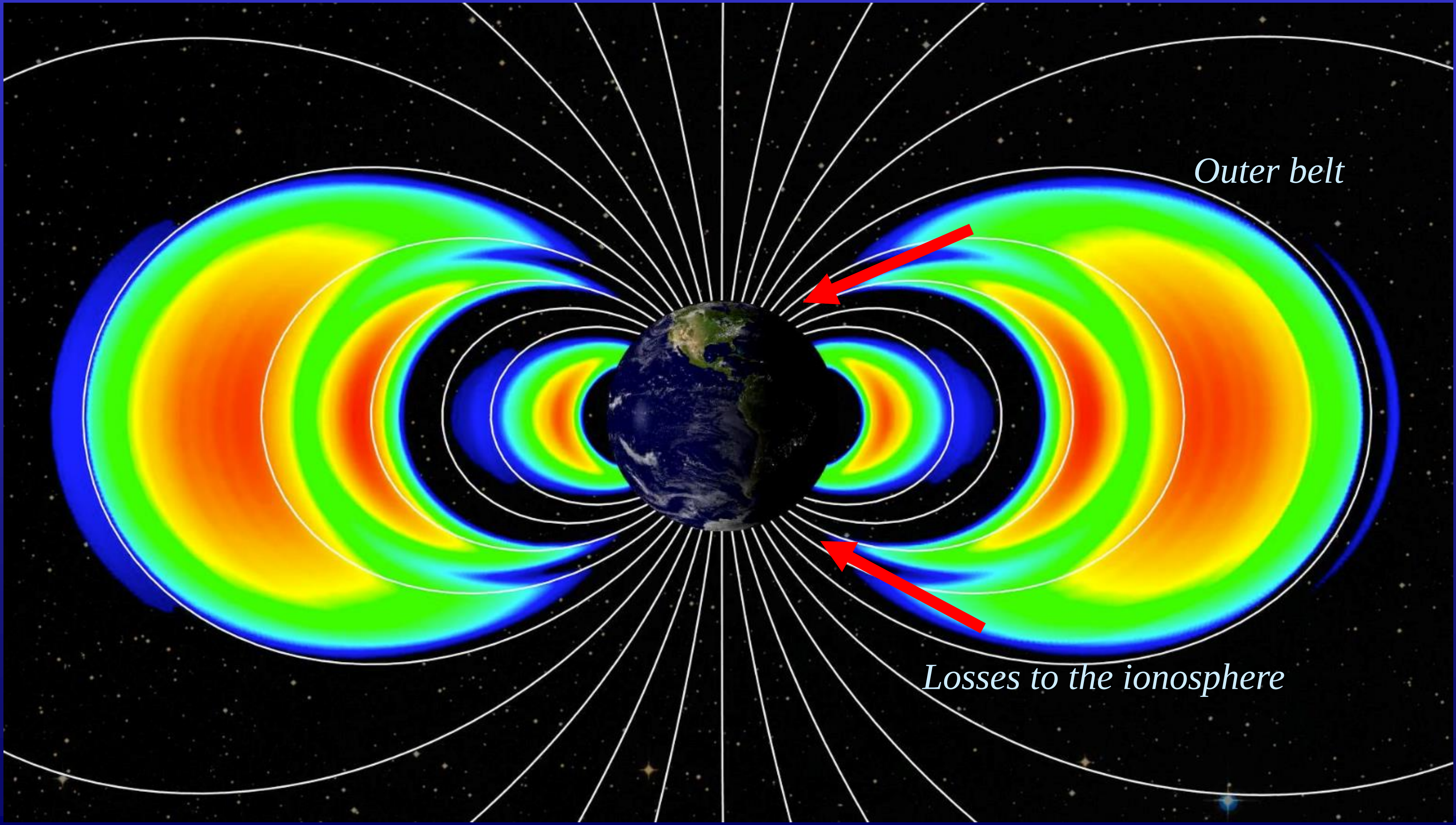
VLF receiver, Arrival heights, Antarctica.

VLF receiver, Churchill, Canada

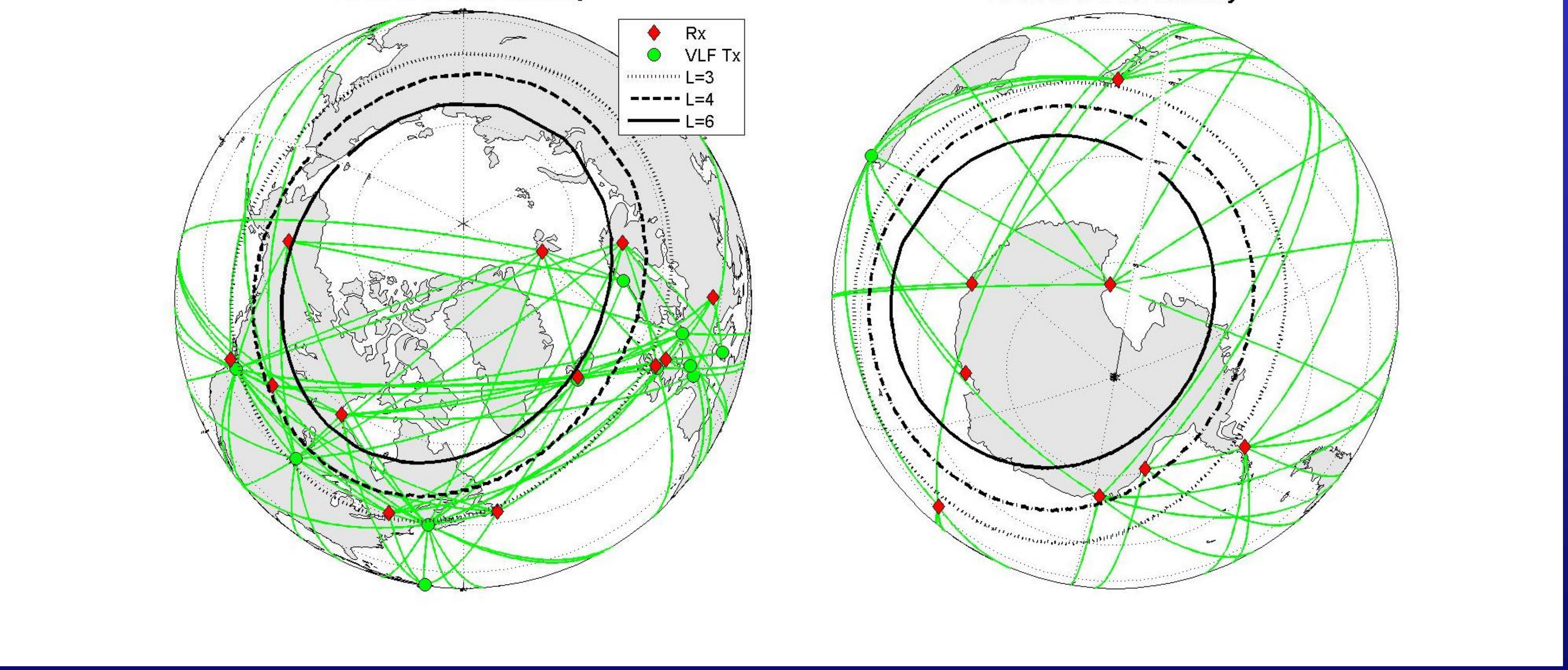
VLF receiver, Svalbard

VLF receiver, Halley, Antarctica.

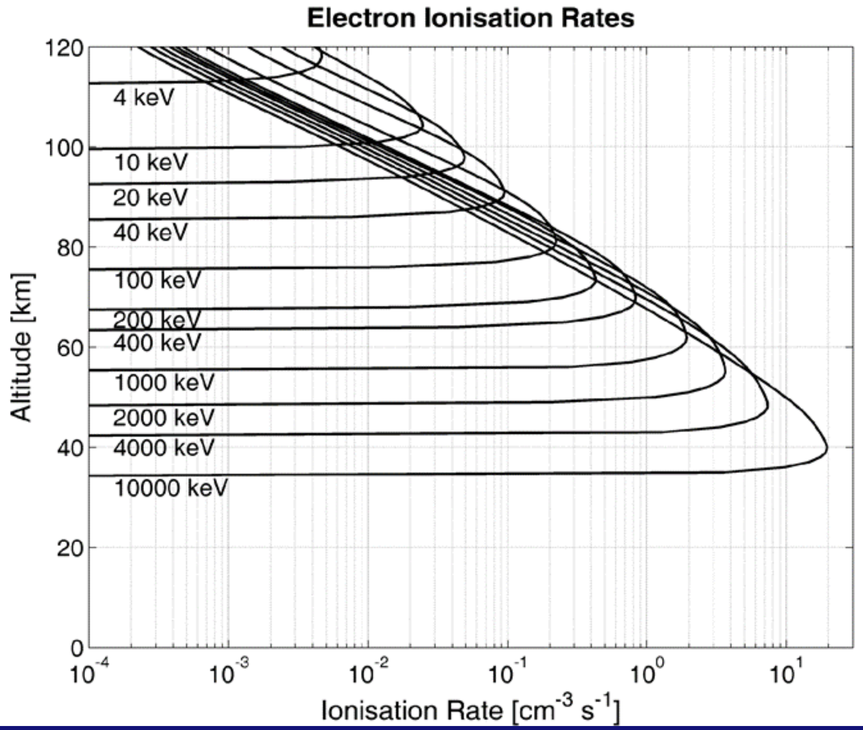
AARDDVARK: designed to detect electrons lost from the Radiation Belts

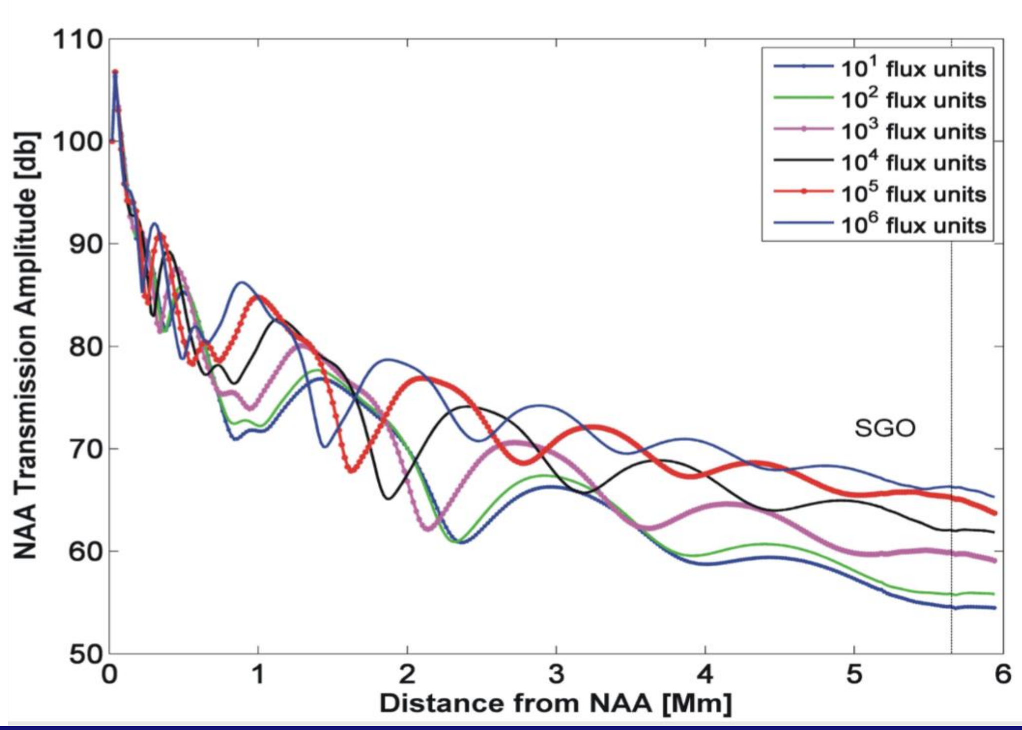


Polar projections: concentrating on radiation belt footprint latitudes (L=3-8)



Energetic electron precipitation and its affect on subionospheric propagation



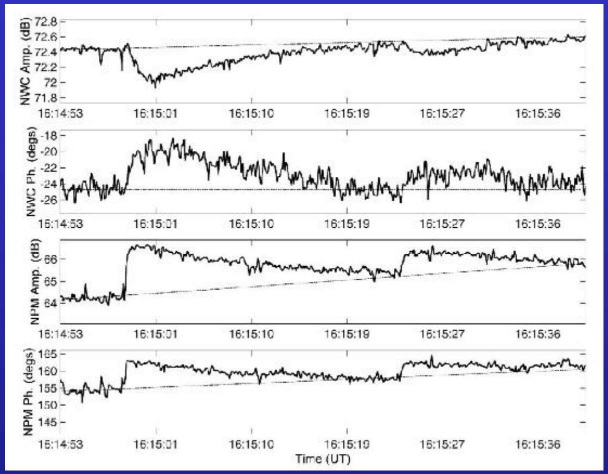


Electron precipitation from the radiation belt penetrates lower into the atmosphere as the energy increases

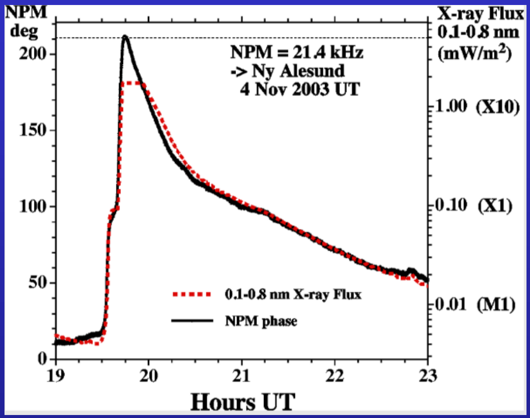
Electron precipitation causes extra ionisation, changing the Earth-ionosphere waveguide conditions

Things you can detect with AARDDVARK

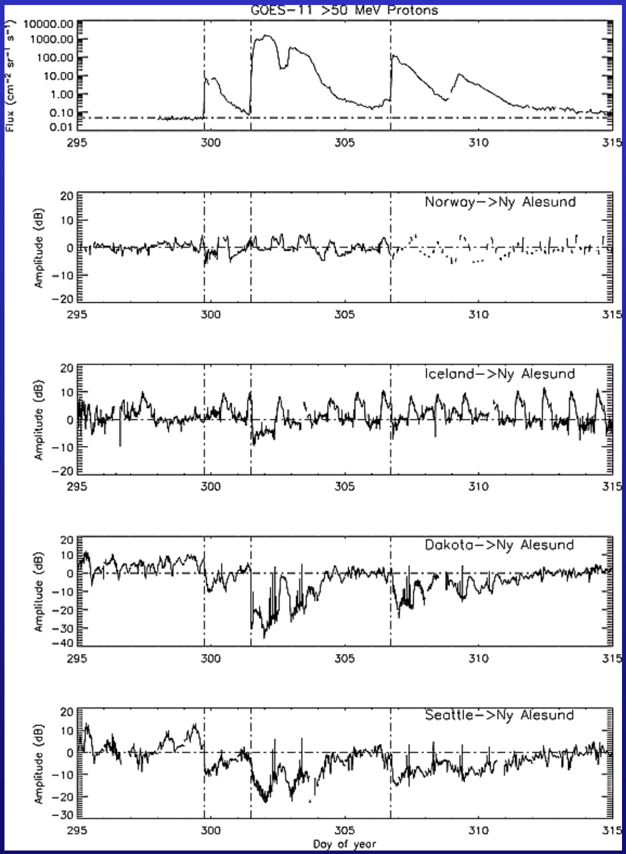
Seconds: Trimpi/Sprites



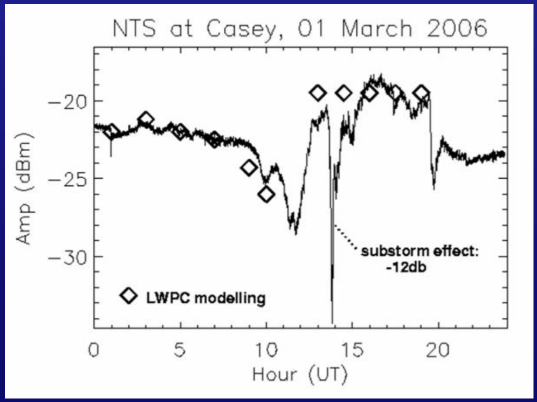
Hours: Solar Flares



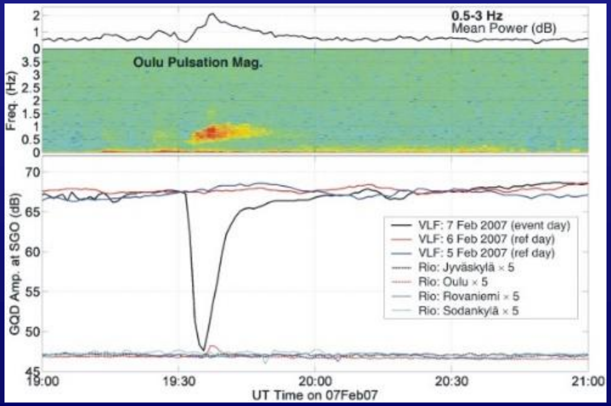
Days: Solar Proton Events



Hours: Substorms



Minutes: EMIC waves

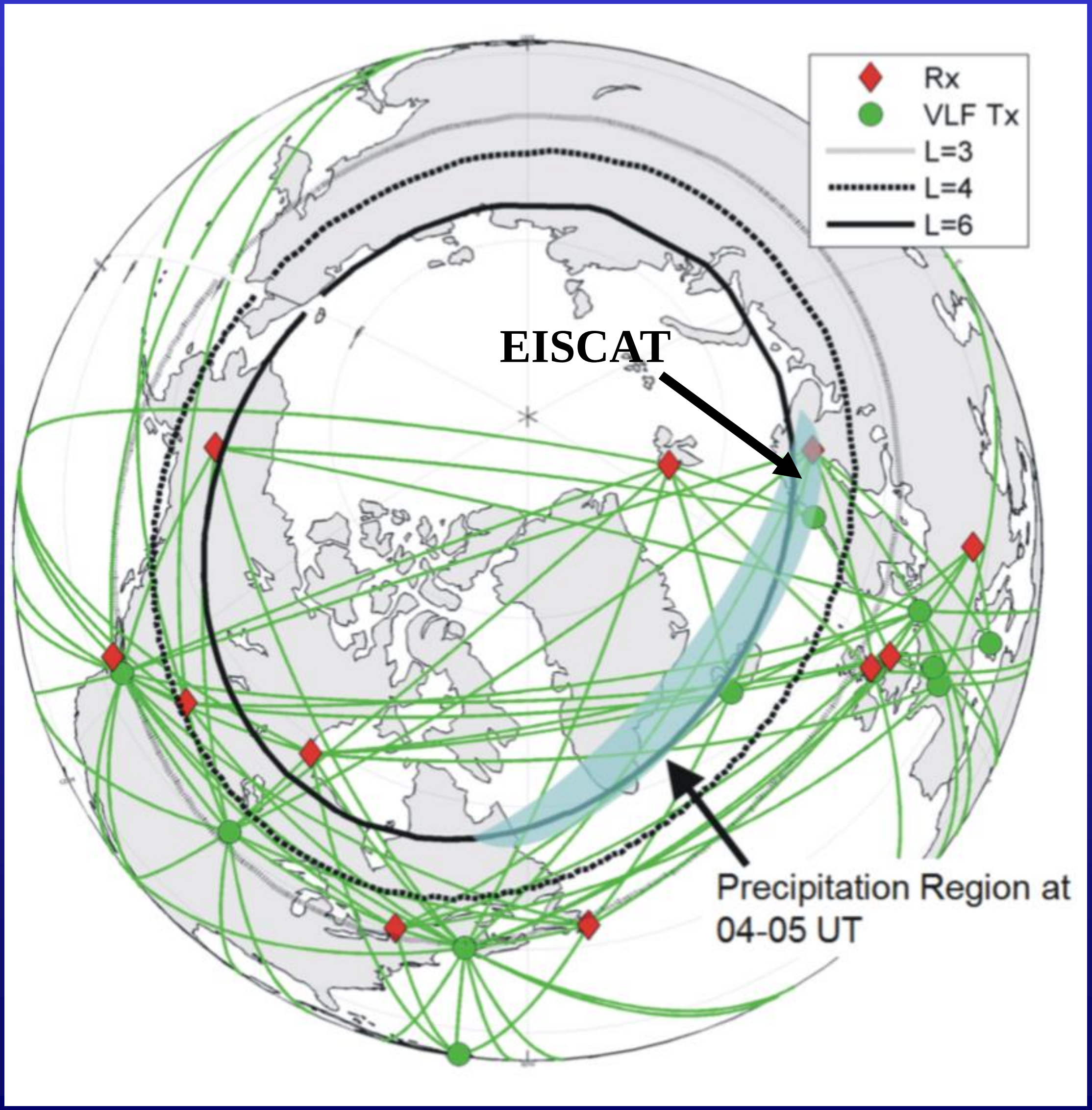


Things you can detect with AARDDVARK

Energetic electron precipitation: 10-500 keV

Linking detailed measurements from EISCAT in Tromso with the larger precipitation pattern seen co-incidently by AARDDVARK

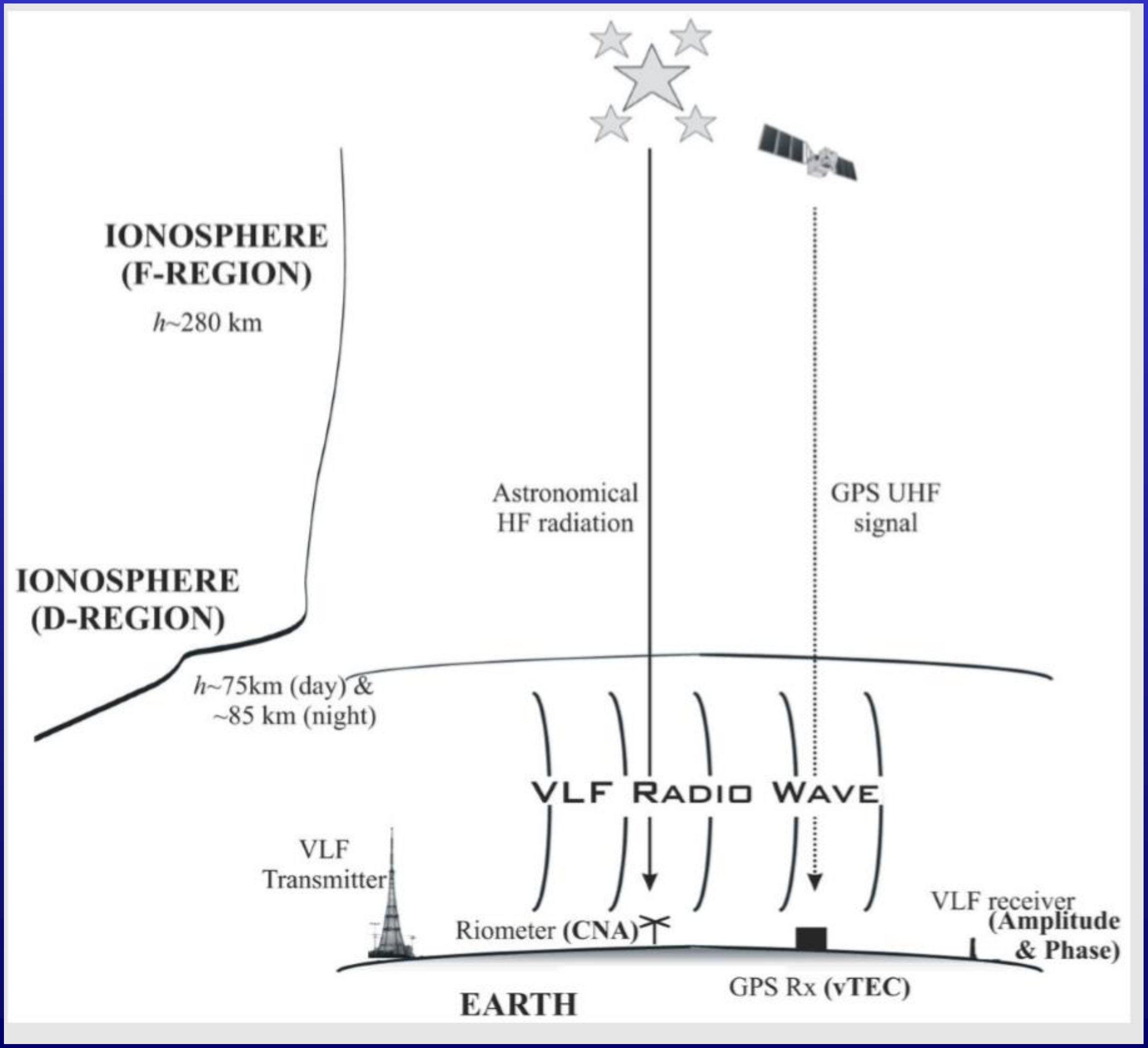
Miyoshi, Y, S et al., Energetic electron precipitation associated with pulsating aurora: EISCAT and Van Allen Probe observations, J. Geophys. Res., 120, 2754–2766, doi: 10.1002/2014JA020690, 2015.



Contrasting the responses of three different ground-based instruments to energetic electron precipitation,

GPS TEC
VLF (AARDDVARK)
Riometer Absorption

Rodger, C J, M A Clilverd, A J Kavanagh, C E J Watt, P T Verronen, and T Raita, Contrasting the responses of three different ground-based instruments to energetic electron precipitation, Radio Sci., 47(2), RS2021, doi:10.1029/2011RS004971, 2012.

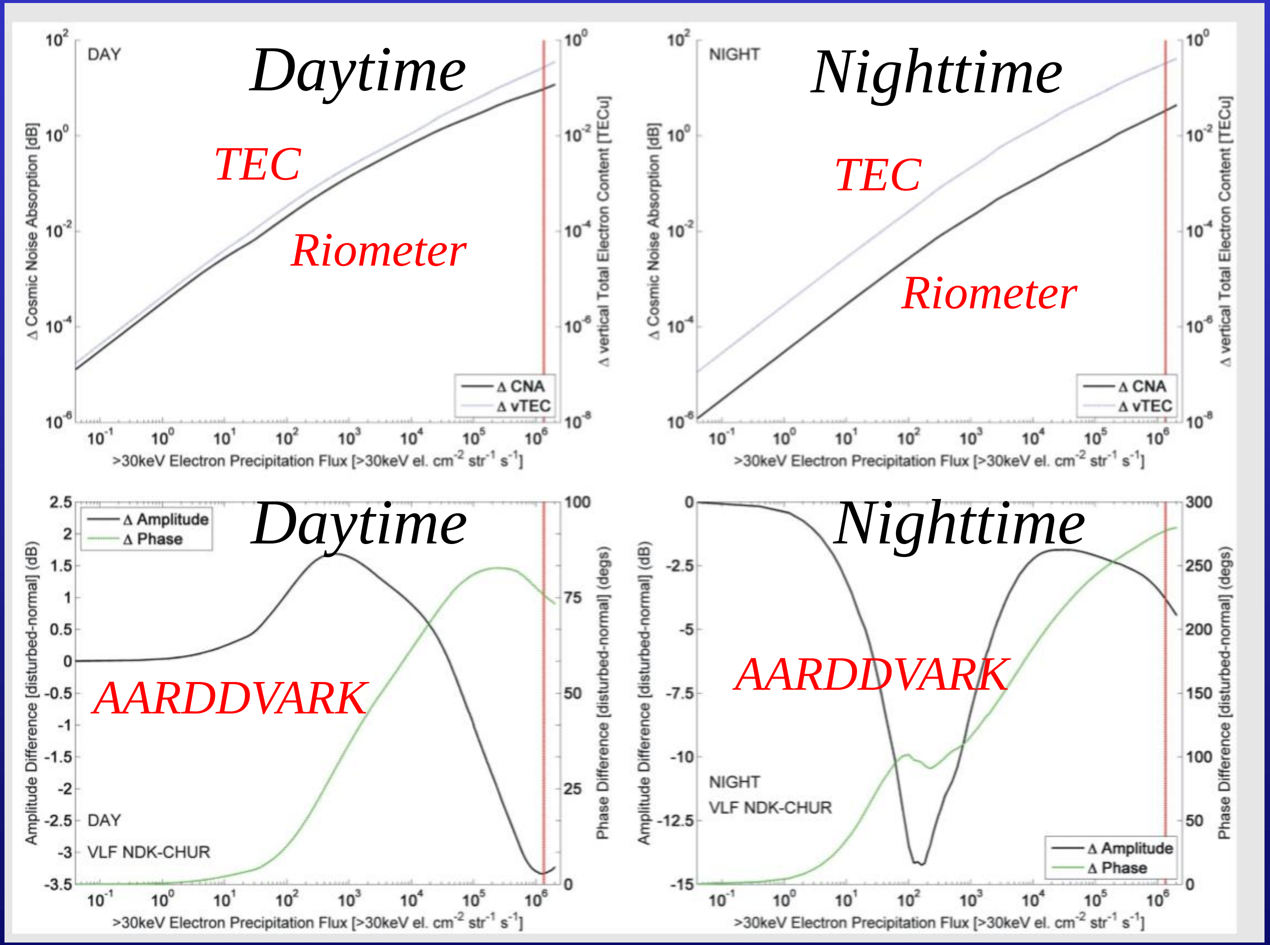


Contrasting the responses of three different ground-based instruments to energetic electron precipitation,

Small effects seen on GPS TEC, only really responds to very large fluxes, (mainly during substorms).

Riometer absorption larger during the day.

Large, complex variations in VLF amplitude. VLF phase variations less complex. More sensitivity to low level fluxes than other instruments.



Summary

►The Ionosphere at low frequency really means the D-region (50-90 km).

► The D-region is chemically complex, and several processes influence the conductivity profiles.

► Many studies can be made with subionospheric VLF waves travelling long distances (Mm) – best suited to large scale effects.

► Only energetic electron precipitation (~30 keV) causes ionisation at low enough altitudes to influence VLF subionospheric propagation conditions.

► The AARDDVARK network can be used to determine the sizes of precipitation regions.

Reading:

AARDDVARK website:
http://www.physics.otago.ac.nz/space/AARDDVARK_homepage.htm

Most of the papers cited in these notes can be found on the following website as pre-published pdf documents:

http://www.physics.otago.ac.nz/nx/space/space-physics-publications.html