An exploratory survey of the attenuation of radio signals by the ionosphere of Mars

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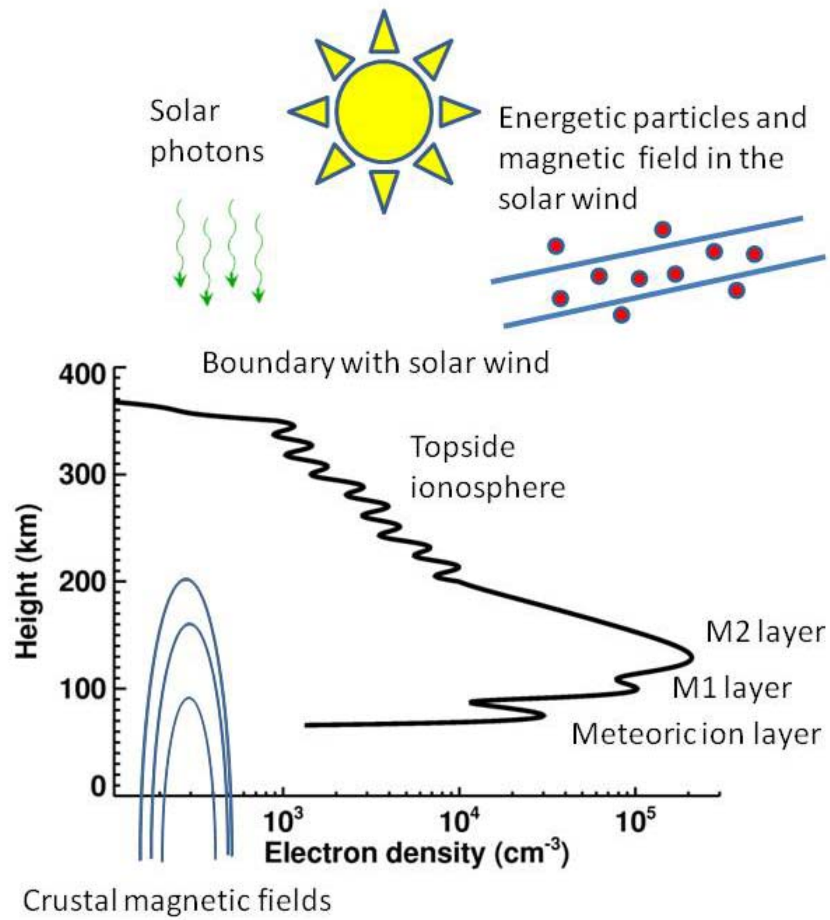
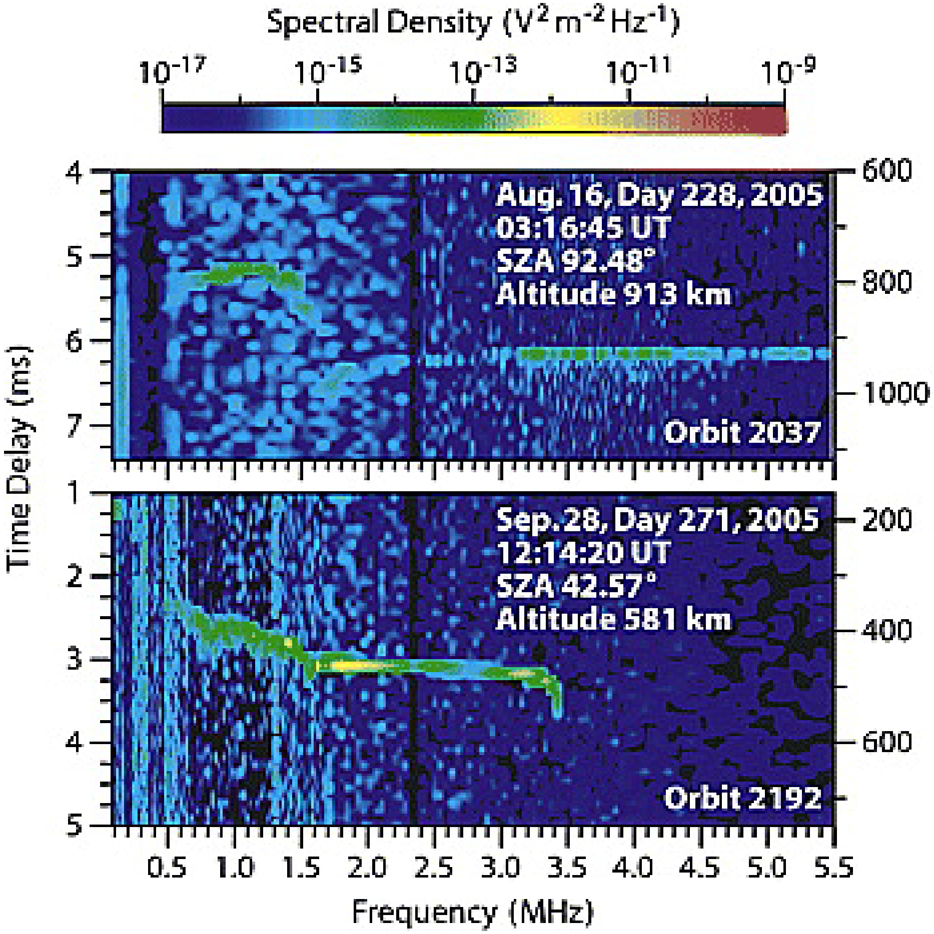
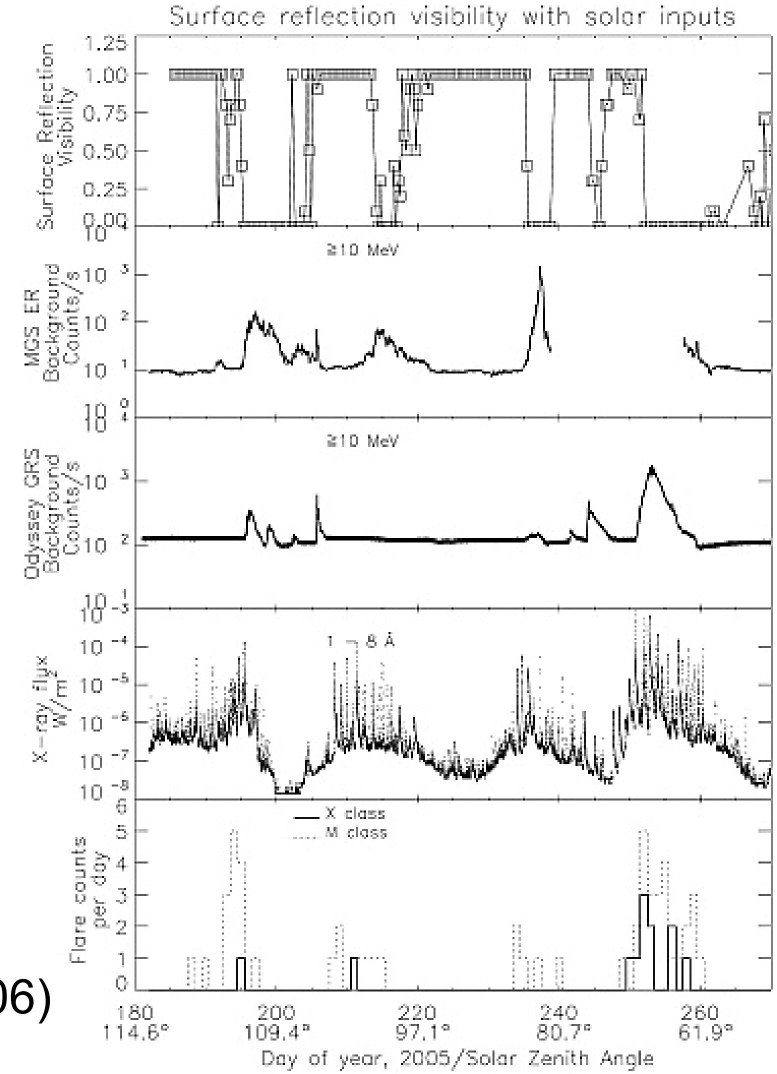


A radio signal is attenuated as it passes through a planetary ionosphere. This attenuation depends on the radio frequency, the electron-neutral collision frequency, and the vertical profile of electron density. Thus the attenuation varies with changes in ionospheric conditions. In particular, extreme solar events, such as intense solar flares or solar energetic particle events, that increase ionospheric electron densities at altitudes below 100 km may cause significantly enhanced attentuation. Such attenuation has the potential to degrade the performance of radio communications and navigation systems at Mars. It can also disrupt observations by the MARSIS topside radar sounder on Mars Express. We have developed theoretical expressions for the attenuation caused by a layer of ionospheric plasma. In this presentation, we shall use these results to explore how the attenuation depends on radio frequency and layer altitude, electron density, and width. We shall focus on three plasma layers - the M1 layer produced at 100 km by solar soft X-rays, the meteoric layer produced at 85 km by meteoroid ablation, and a potential layer at 35 km that theorists have predicted is caused by precipitating energetic particles. We shall also report on the implications for understanding surface reflection blackouts that afflict the MARSIS instrument for periods of days to weeks after solar energetic particle events.

Solar energetic particle (SEP) events disrupt radar





MARSIS radar fails to observe surface reflections during SEP events (Figures from Morgan et al., 2006)
Blackouts are global and extend to nightside

Probable explanation

- Radio signals passing through a weak plasma are attenuated due to collisions between neutrals and excited electrons
- Attenuation strongest for low-altitude plasma where neutral density is high
- SEP event causes enhanced electron densities at some low altitude, sufficient to cause 13 dB one-way power loss at 5 MHz
- Need to have global mechanism that works on both dayside and nightside

Attenuation theory (1)

$$\mu_c^2 = 1 - \frac{\omega_p^2}{\omega\left(\omega - i\nu\right)}$$

Complex refractive index, μ_c
ω = radio wave frequency
ω_p = plasma frequency
ν = electron-neutral collision frequency

$$\mu_r^4 - \left(1 - \frac{\omega_p^2}{\left(\omega^2 + \nu^2\right)}\right)\mu_r^2 - \frac{\omega_p^4 \nu^2}{4\omega^2\left(\omega^2 + \nu^2\right)^2} = 0$$

Expression for real part of refractive index, μ_r

$$\mu_r^2 \;=\; \left(1 - \omega_p^2/\omega^2\right)$$

For high radio frequencies, the above expression simplifies greatly $\omega >> \nu$
Radio waves don't propagate into regions where $\mu_r^2 < 0$
Highlights importance of max plasma frequency

Attenuation theory (2)

$$k_i = -K = \frac{-\omega_p^2}{2c\mu_r} \cdot \frac{\nu}{\nu^2 + \omega^2}$$

k_i = imaginary wavenumber of radio wave
K = amplitude absorption coefficient per unit length

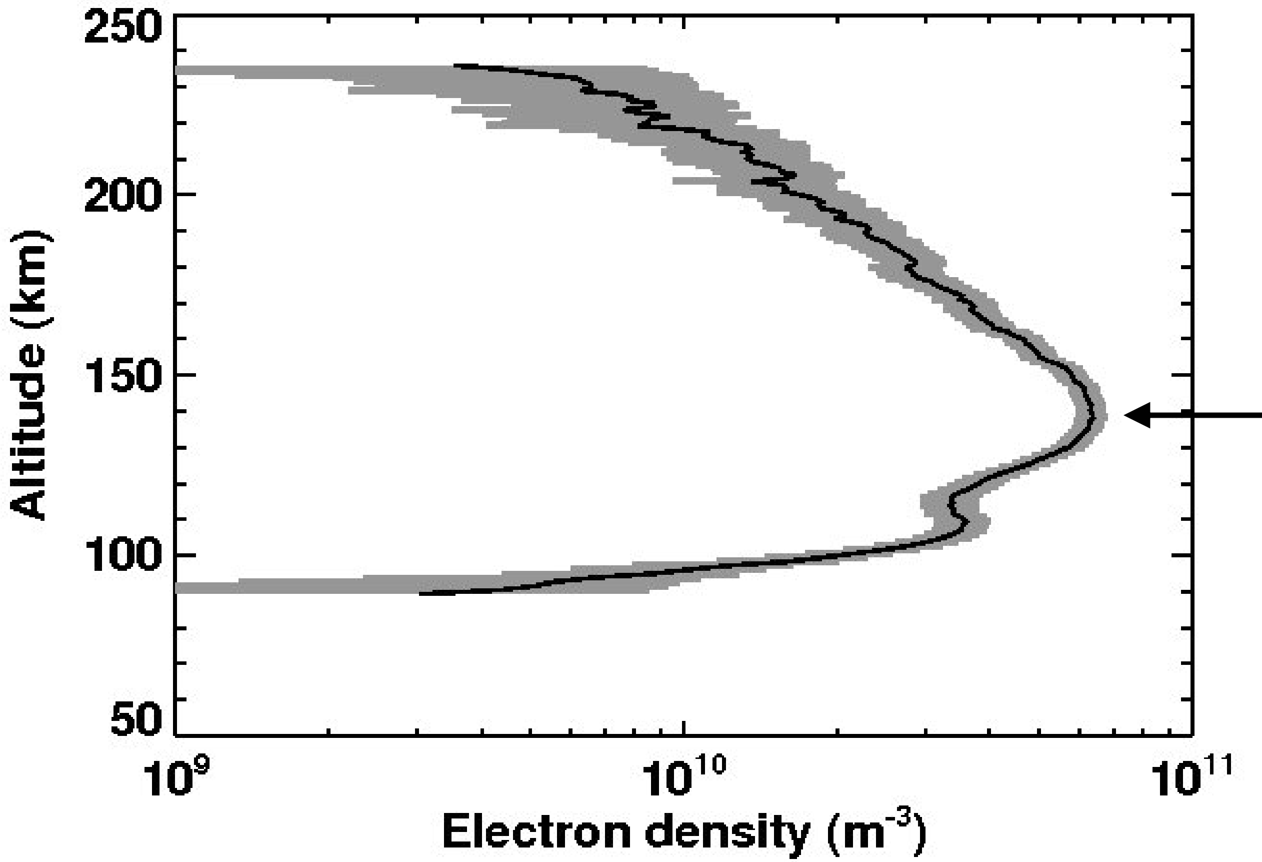
$$\frac{E_r}{E_t} = \exp\left(-\int K ds\right) = \left[\exp\left(-\int K dz\right)\right]^{\sec(\mathrm{OZA})}$$

Ratio of received energy, Er, to transmitted energy, Et, depends on K and angle OZA between ray path and vertical (ie “orbiter zenith angle”)

$$P\,(\mathrm{dB}) = -20\log_{10}\left(E_r/E_t\right) = 20\log_{10}(e)\sec(\mathrm{OZA})\left(\int K dz\right)$$

Expression for one-way power loss in decibels
Effects of multiple plasma layers are additive

Main ionospheric layer (M2)

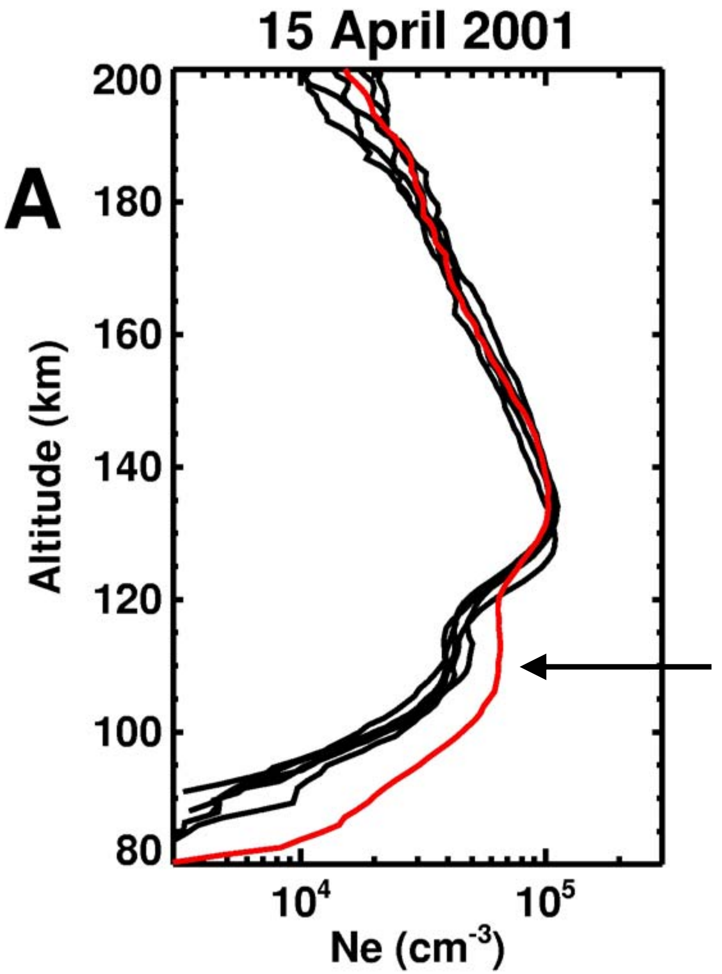


M2 layer produced by solar EUV photons

Very similar to classical Chapman layer

Subsolar peak altitude is 120 km
Subsolar peak density is 2×10^{11} m^{-3}

Lower ionospheric layer (M1)

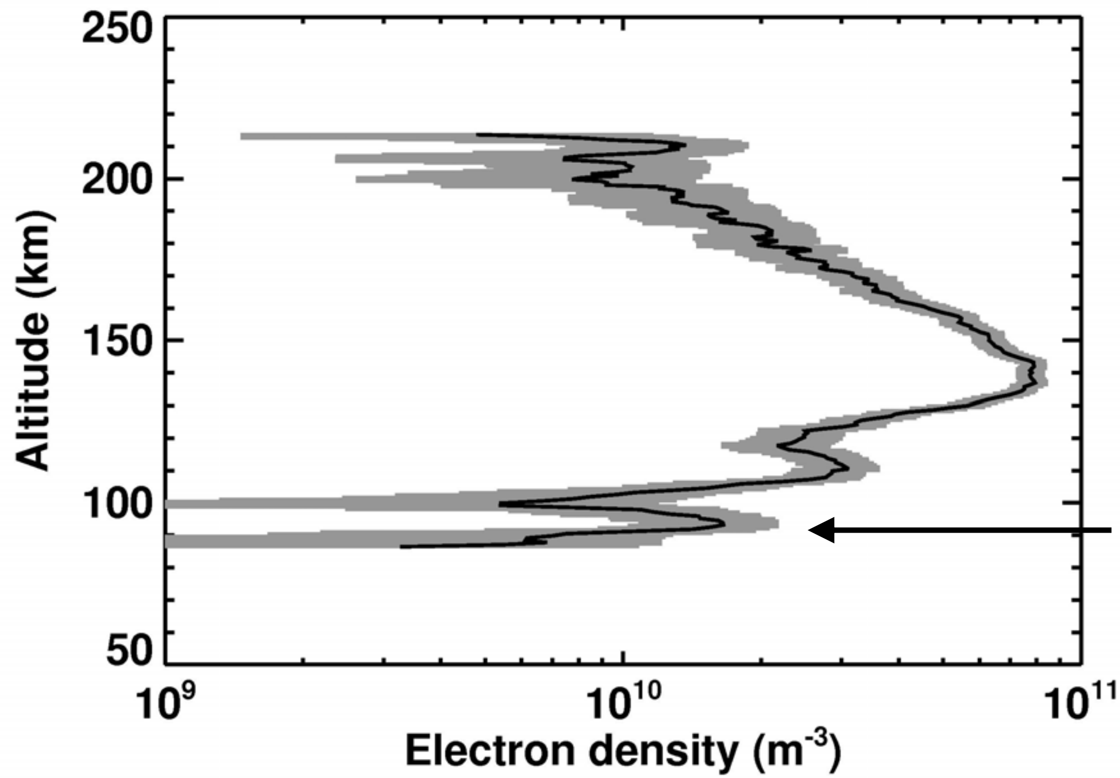


M1 layer produced
by solar X-ray photons

Highly variable since X-ray flux varies
Red line shown here corresponds
to a solar flare and strong M1 layer

Subsolar peak altitude
is 100 km
Subsolar peak density
is 1 x 10^{11} m^{-3}

Meteoric ion layer



Meteoric ion layer produced by meteoroid ablation
Sporadic and variable

Typical peak altitude is 85 km

Typical peak density is 2×10^{10} m^{-3}

Ions produced by cosmic rays

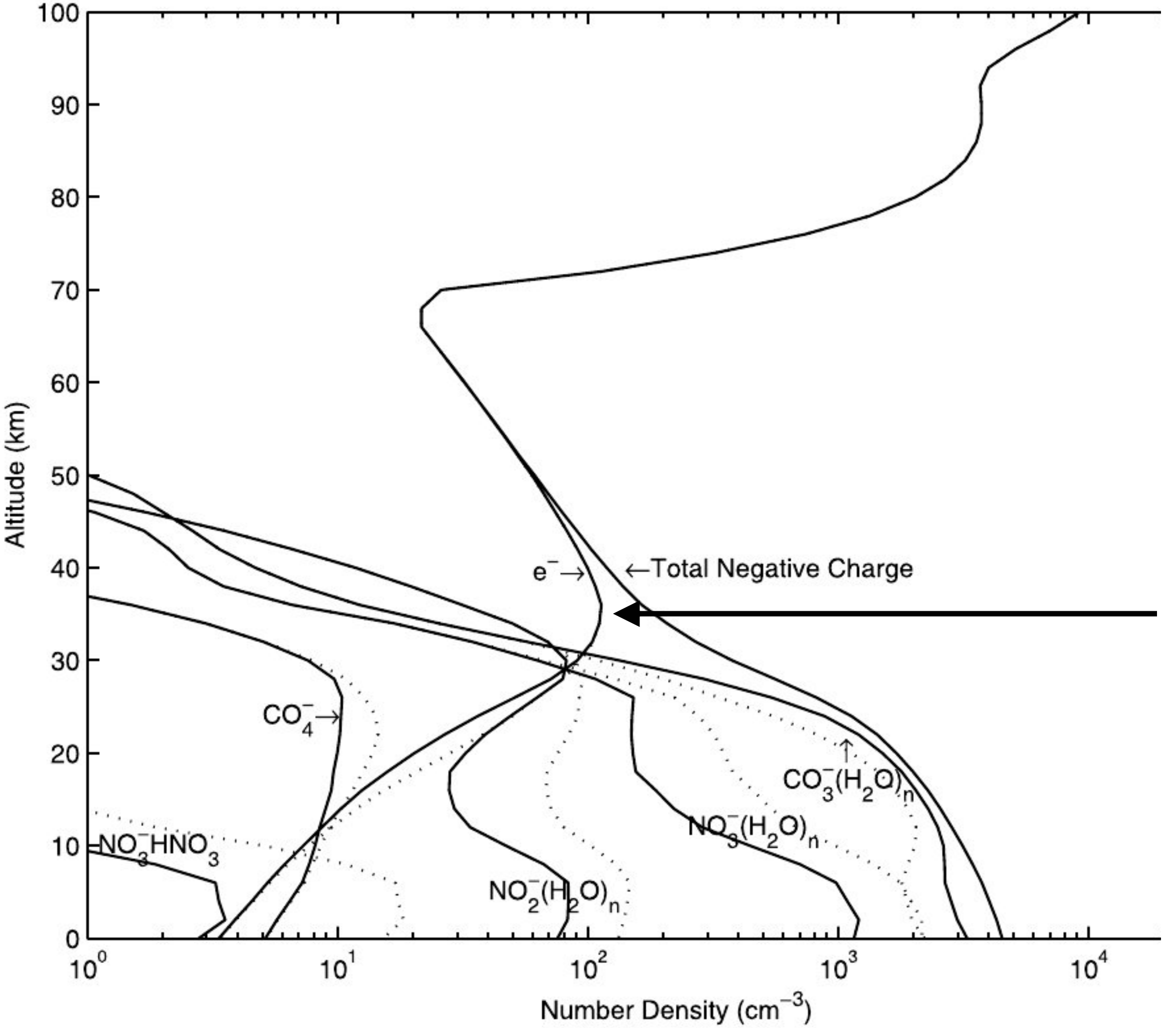


Figure from Molina-Cuberos et al. (2002)

Negative ions significant at low altitudes

Layer of electrons is predicted – but not yet observed

Typical peak altitude is 35 km

Typical peak density is 10^8 m^{-3}

Lots and lots of math…

- Assume Chapman layer shape
- Derive expressions for power loss as function of peak density and altitude
- Three cases for power loss expression
  - $\omega > \nu$ at all altitudes with significant plasma
    High radio frequencies or high peak altitude
  - $\omega < \nu$ at all altitudes with significant plasma
    Low radio frequencies or low peak altitude
  - Intermediate case
- Results consistent with full numerical integration

High frequency limit

- Power loss is proportional to
  - Layer width
  - Layer peak density
  - (Radio frequency)$^{-2}$
- Complete expression derived, but not shown here

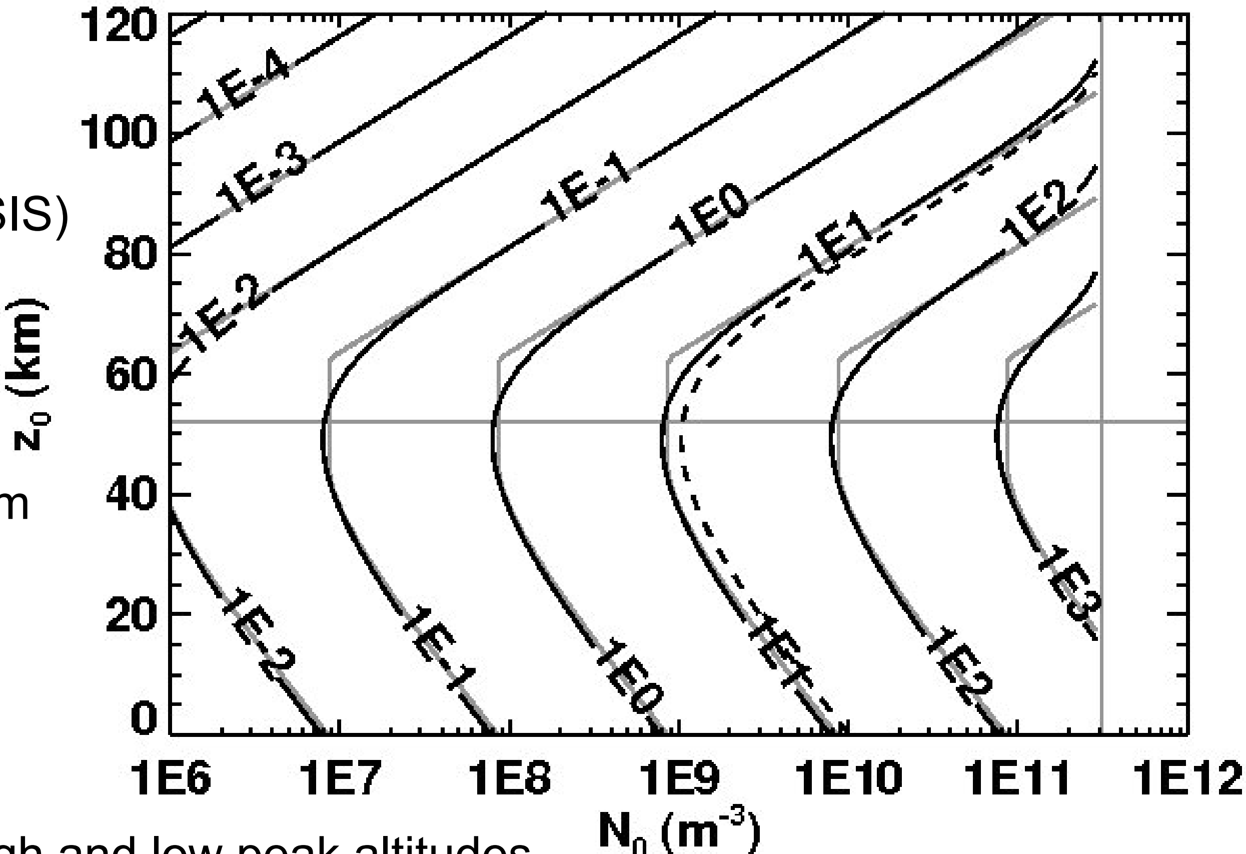
Low frequency limit

- Power loss is proportional to
  - Layer width
  - Layer peak density
  - (Electron-neutral collision frequency at layer peak)$^{-1}$
- Complete expression derived, but not shown here

Power loss (dB) as function of peak altitude and peak density in layer

f = 5 MHz (same as MARSIS)

Angular frequency of radio wave equals electron-neutral collision frequency at 50 km



Different behaviours at high and low peak altitudes
High altitudes imply high radio frequency limit
Low altitudes imply low radio frequency limit

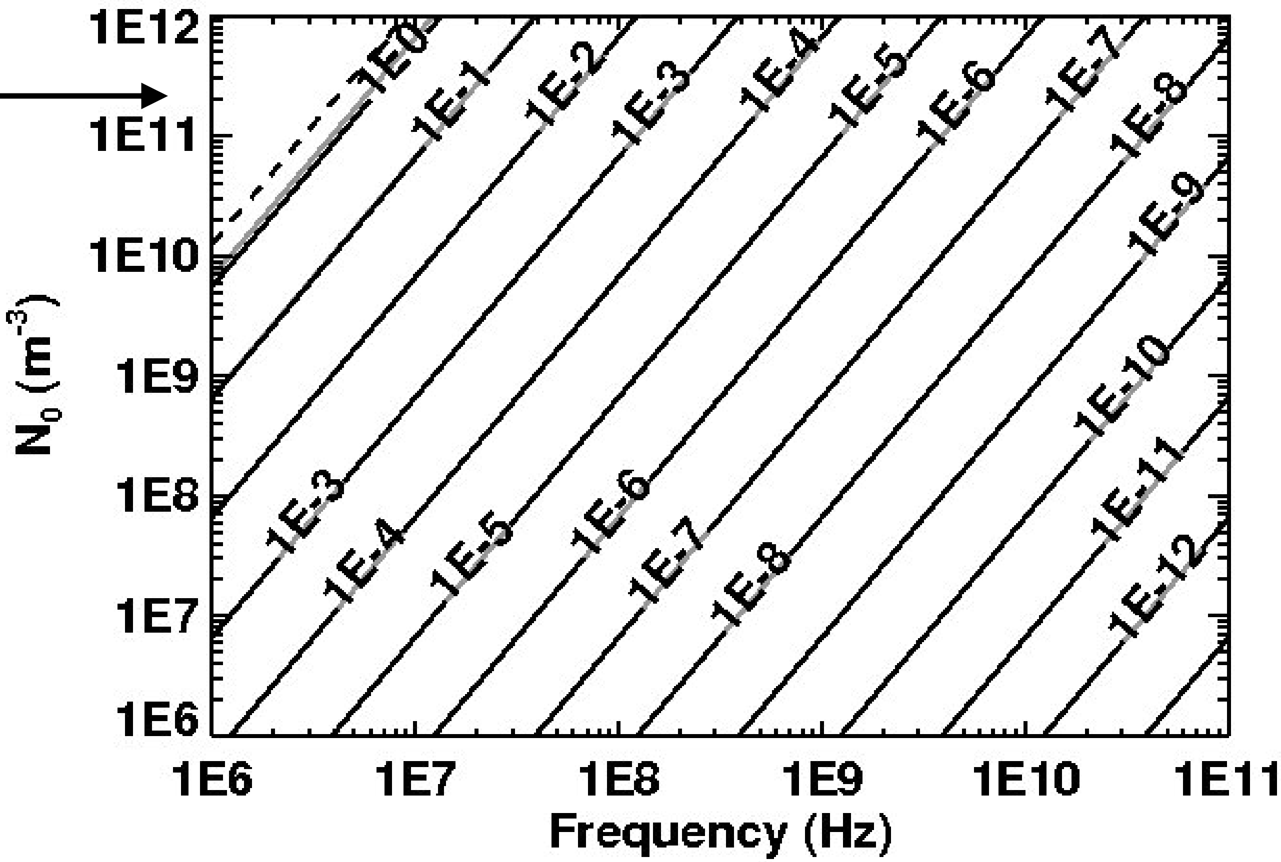
Power loss in M2 layer as function of peak density and frequency

Typical N_0 is 2×10^{11} m^{-3}

Peak altitude is 120 km

Attenuation at 5 MHz is small, about 1.5 dB

Always in high frequency limit



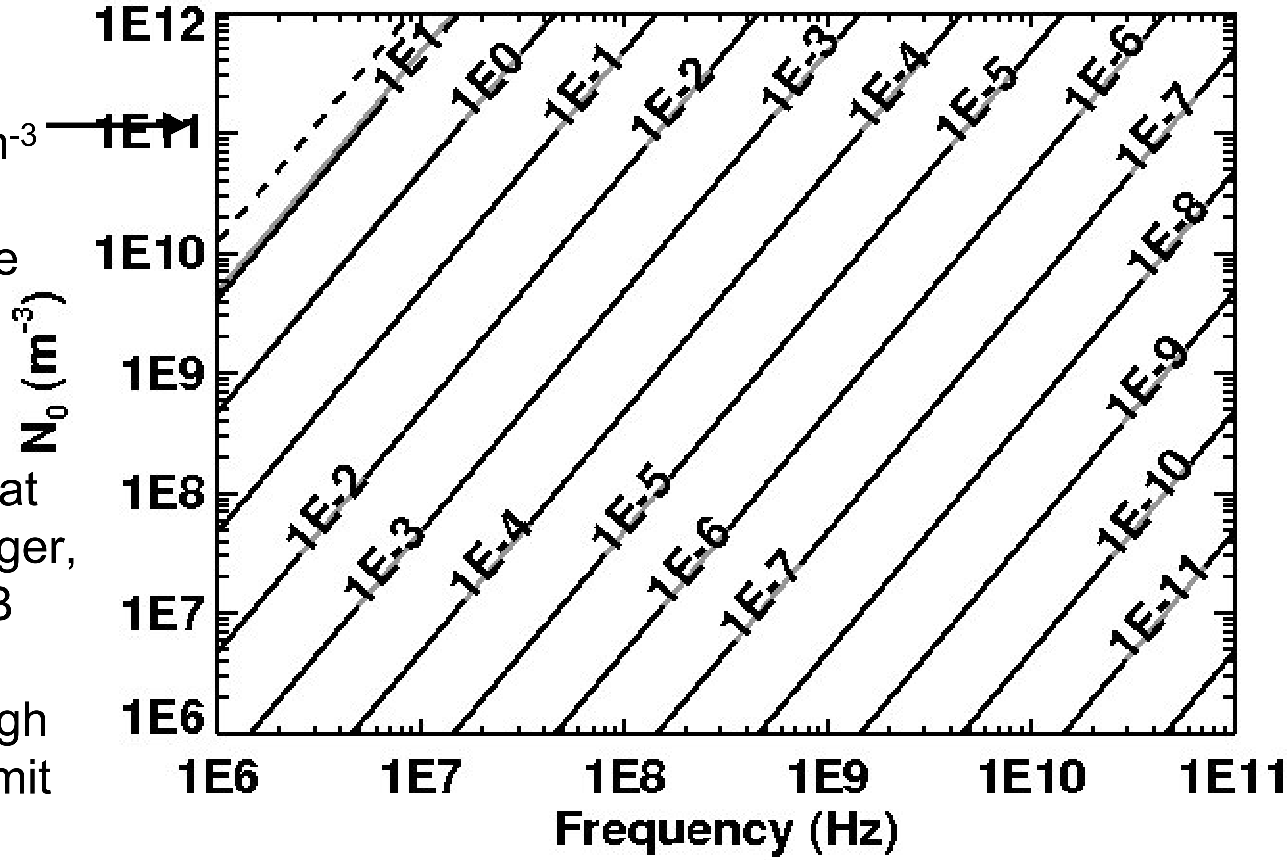
Power loss in M1 layer as function of peak density and frequency

Typical N_0 is 1×10^{11} m^{-3}

Peak altitude is 100 km

Attenuation at 5 MHz is larger, about 9.0 dB

Always in high frequency limit



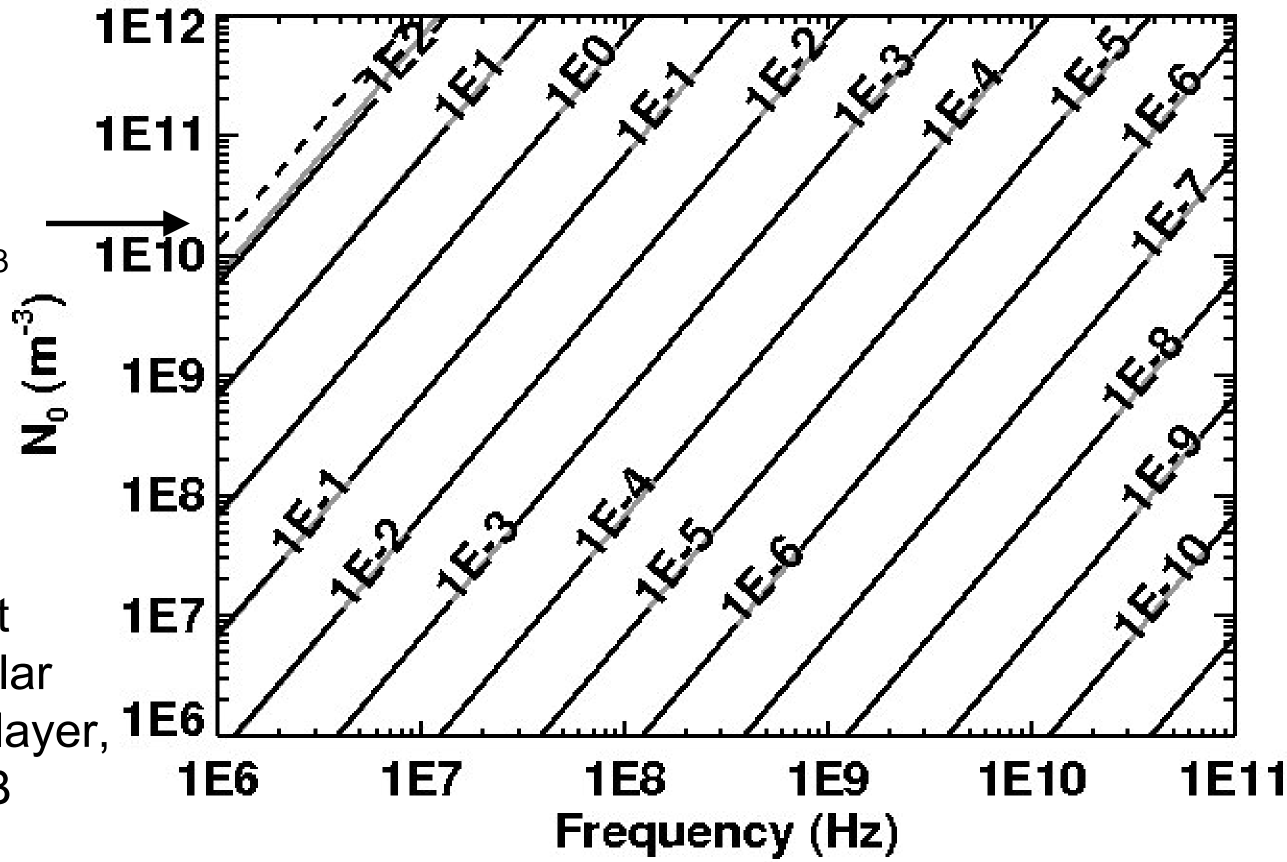
Power loss in meteoric ion layer as function of peak density and frequency

Typical N_0 is 2×10^{10} m^{-3}

Peak altitude is 85 km

Attenuation at 5 MHz is similar to that of M1 layer, about 12.8 dB

Always in high frequency limit

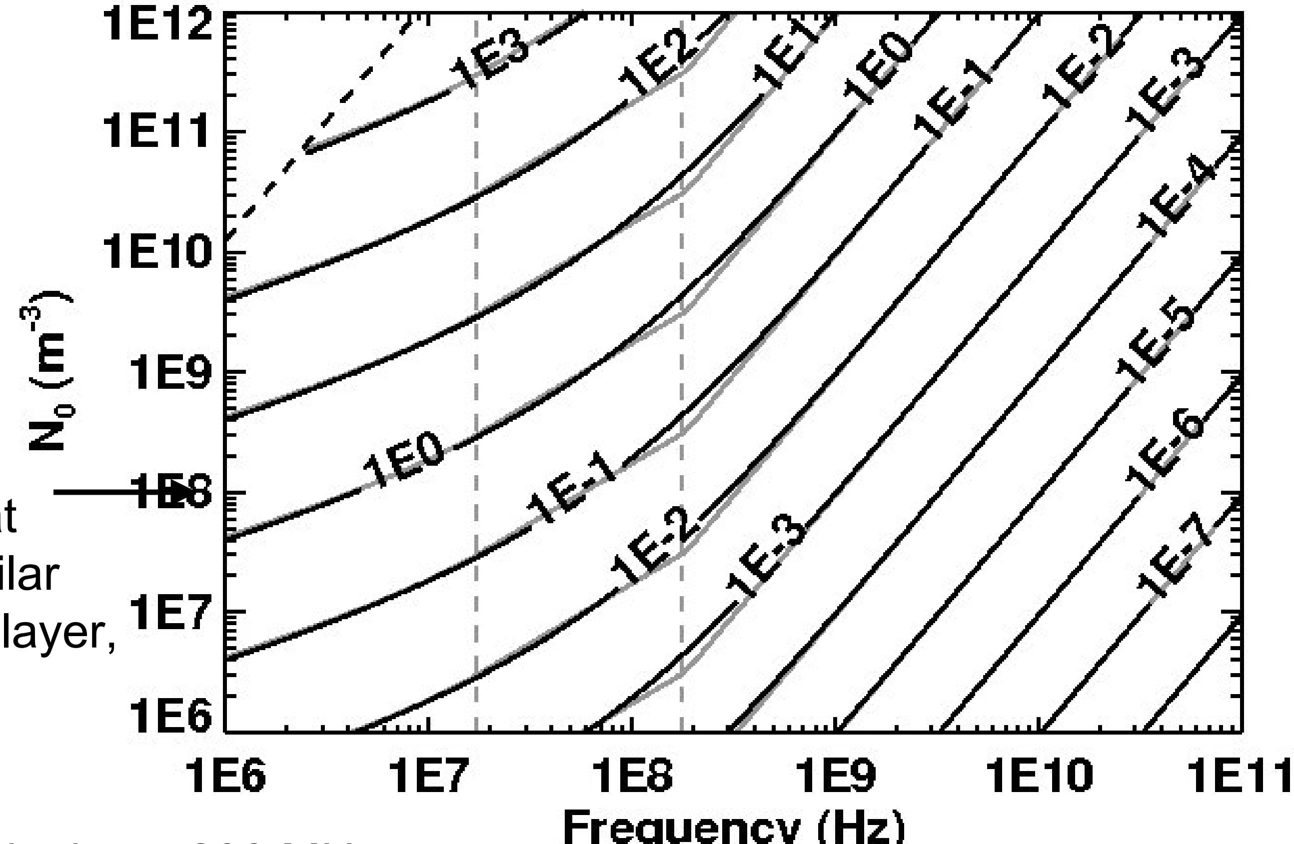


Power loss in layer of ions produced by cosmic rays as function of peak density and frequency

Typical N_0 is 10^8 m^{-3}

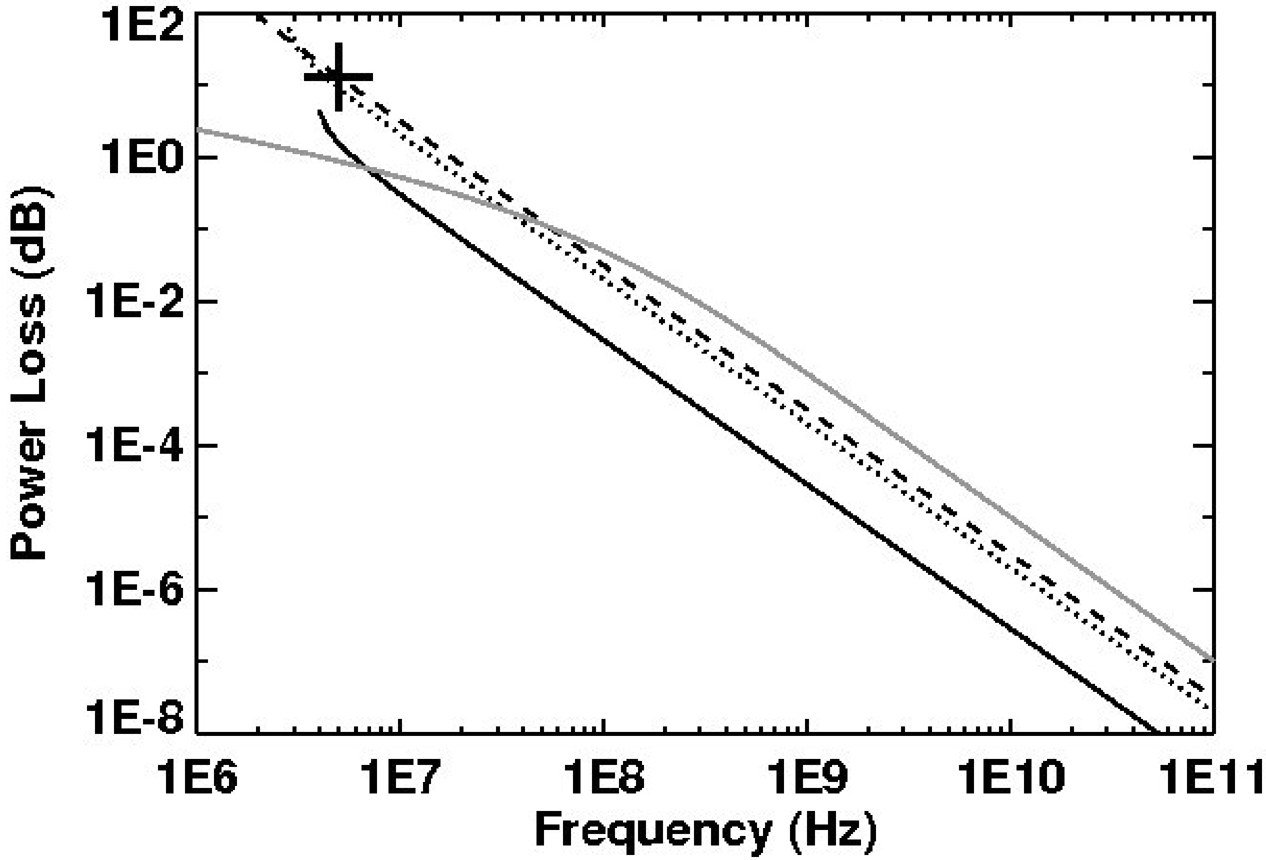
Peak altitude is 35 km

Attenuation at 5 MHz is similar to that of M2 layer, about 0.9 dB



In high frequency limit above 200 MHz
In low frequency limit below 20 MHz

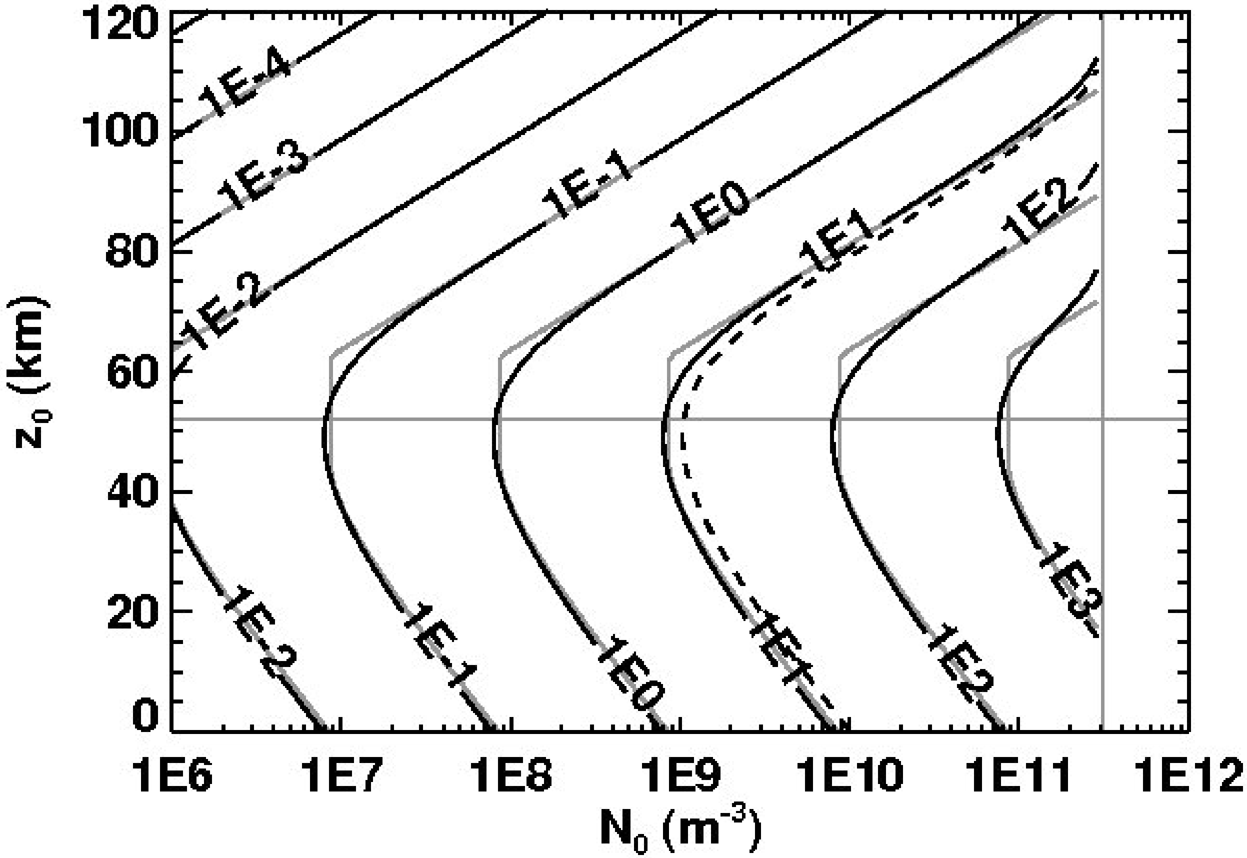
Power loss for four ionospheric layers under typical conditions



Black solid line – M2 layer
Black dotted line – M1 layer
Black dashed line – Meteoric ion layer
Grey solid line – Layer produced by cosmic rays

Cross is the 13 dB required for MARSIS blackouts at 5 MHz

Layer peak densities needed to produced MARSIS blackouts



Dashed line shows layer peak density required to produce 13 dB power loss at f = 5 MHz – and MARSIS blackout – as function of peak altitude

If peak altitude = 50 km, 10^9 m^{-3} or greater is sufficient

If peak altitude < 80 km, 10^{10} m^{-3} or greater is sufficient

If peak altitude < 100 km, 10^{11} m^{-3} or greater is sufficient

Conclusions

- Analytic expressions derived for the power loss caused by an ionospheric layer (not shown)
- Frequency-dependent power loss calculated for several ionospheric layers
- Ionospheric characteristics required to explain observations of MARSIS blackouts during SEP events predicted
- Next step – Simulate ionospheric electron density profile during SEP event
- Accepted by Radio Science, doi:10.1029/2010RS004450