Ionosphere and Radar measurements

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- Part 1: Properties of the ionosphere

Atmospheric regions by temperature

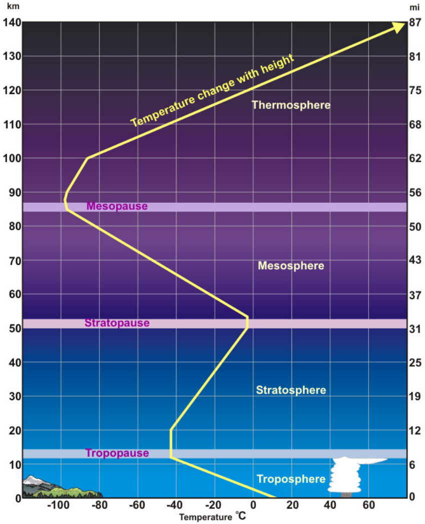


Figure: Atmospheric temperature profile.

- Troposphere is heated by the warm ground and the infrared radiation is emitted out radially => T decrease with height.
- Tropopause at 12–15 km, T_{min} $\sim$ -53° C.
- In the stratosphere, ozone (O_3) layer at 15 – 40 km absorbs solar radiation. Stratopause at 50 km with T_{max} $\sim$ 7° C.
- In the mesosphere heat is removed by radiation in infrared and visible airglow as well as by eddy transport. Mesopause close to 85 km with T_{min} $\sim$ -100° C.
- In thermosphere UV radiation is absorbed due to dissociation of molecules and ionization of atoms and molecules.

Thermospheric temperature

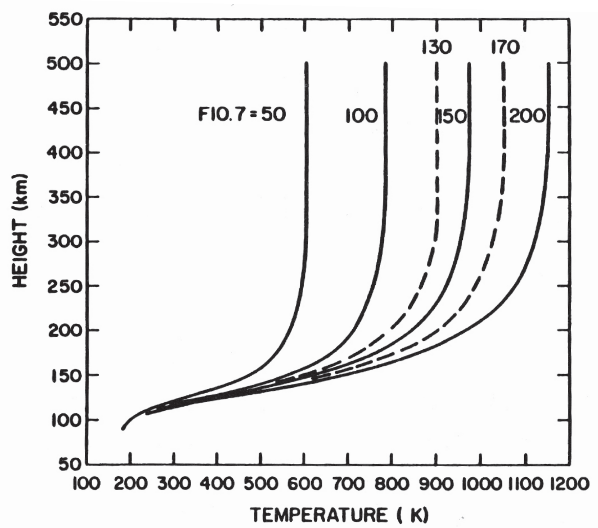


Figure: The variability in the thermospheric temperature for different values of the solar radio flux index $F_{10.7}$ in units of 10^{-22} $\mathrm{Wm^{-2}Hz^{-1}}$ at 1 AU.

Atmospheric regions by composition

1. The homosphere is the region below about 100 km altitude, where all gas constituents are fully mixed; i.e. the relative concentrations of different molecular species are independent of height. This is caused by turbulent mixing of the air.
2. The turbopause is the upper boundary of the homosphere at an altitude of about 100 km.
3. The heterosphere is the region above the homosphere. In the absence of atmospheric turbulence, each molecular species distribute with height independently of the other species (according to its own scale height)=> At great altitudes light molecular species dominate.

Composition in the heterosphere

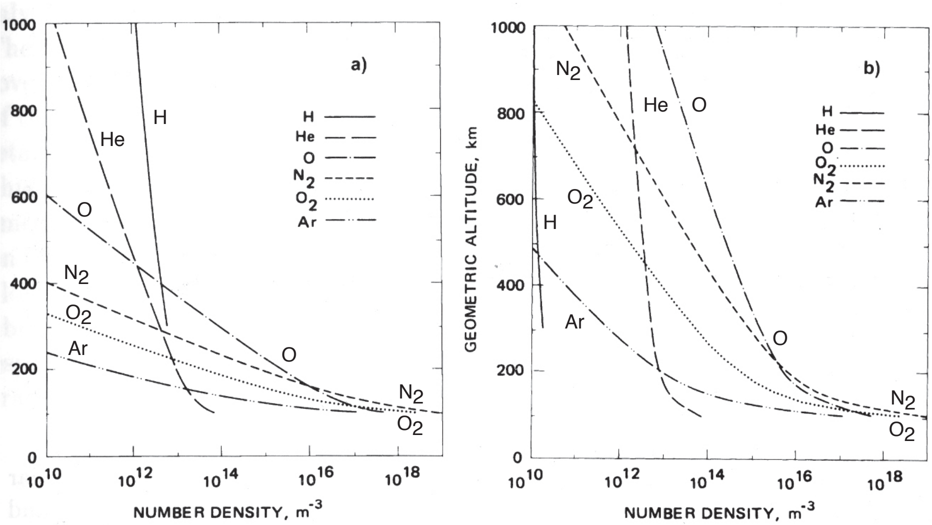


Figure: Atmospheric composition during (a) solar minimum and (b) solar maximum (U.S. Standard atmosphere, 1976).

Ionospheric regions

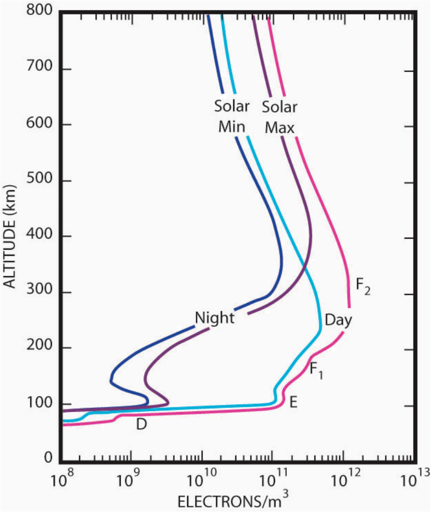


Figure: Typical ionospheric electron density profiles.

Ionospheric regions and typical daytime electron densities:

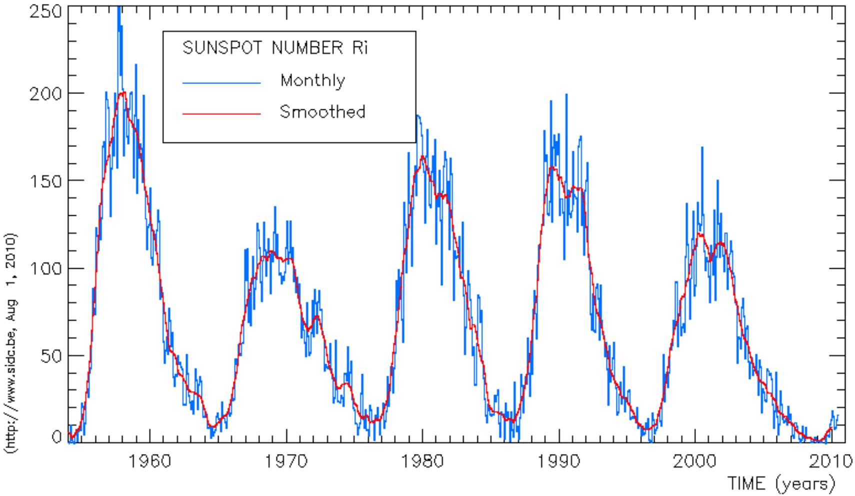
- D region: 60–90 km, $n_e = 10^8$–10^{10} m^{-3}
- E region: 90–150 km, $n_e = 10^{10}$–10^{11} m^{-3}
- F region: 150–1000 km, $n_e = 10^{11}$–10^{12} m^{-3} .

Ionosphere has great variability:

- Solar cycle variations (in specific upper F region)
- Day-night variation in lower F, E and D regions
- Space weather effects based on short-term solar variability (lower F, E and D regions)

Current solar activity

- Activity is slowly rising after the deep solar minimum.



Ion composition

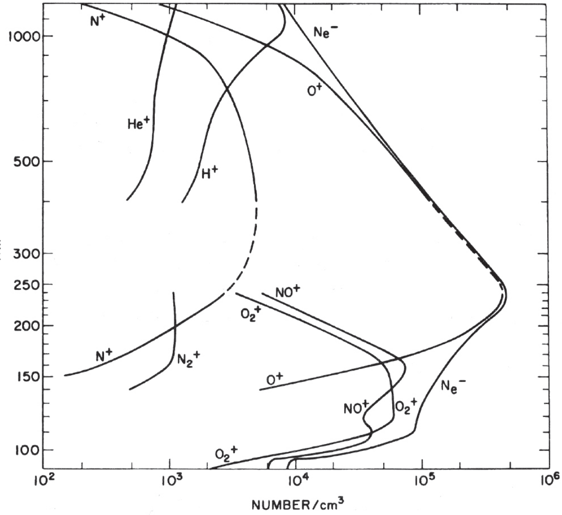


Figure: Daytime solar minimum ion profiles.

- NO^+ and O_2^+ are the dominant ions in E and upper D regions (Ion chemistry: e.g. $N_2^+ + O \longrightarrow NO^+ + N$).
- O^+ dominates around F region peak and H^+ starts to increase rapidly above 300 km.
- D-region (not shown) contains positive and negative ions (e.g. O_2^-) and ion clusters (e.g. $H^+(H_2O)_n$, $(NO)^+(H_2O)_n$).

Ionospheric temperatures

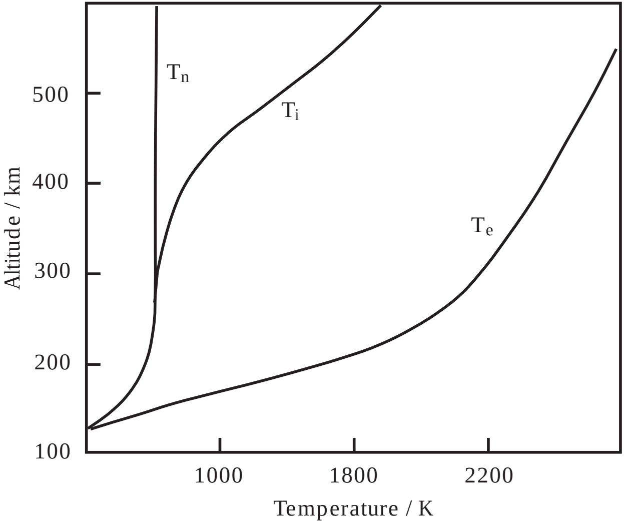


Figure: An example of neutral, ion and electron temperature profiles.

Ionization source: solar radiation

The classical theory of ionospheric ionization by means of photoionization was presented by S. Chapman. The theory assumes that

- the atmosphere is isothermal (T=constant) and obeys the hydrostatic equation so that the scale height H is independent of altitude
- the atmosphere is composed of a single neutral species and the absorption cross section is constant (monochromatic radiation)

Hydrostatic equation for the neutral density n:

$$n = n_{m,0} \exp\left(-\frac{z - z_{m,0}}{H}\right) = n_{m,0} e^{-h},$$

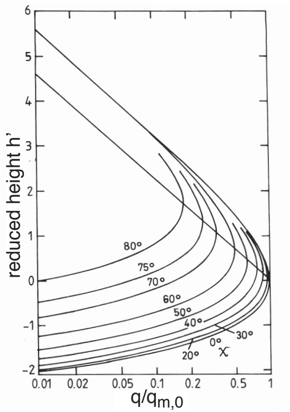
where scale height $H = kT/(mg)$.

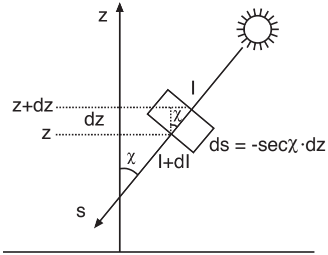
Ionization source: solar radiation cont'd

Chapman production function by using a height variable $h' = h - \ln\sec\chi$:

$$q(\chi, h') = q_{m,0}\cos\chi \cdot \exp\left[1 - h' - e^{-h'}\right] ,$$

where χ is the solar zenith angle and $h = (z - z_{m,0})/H$, where H is atmospheric scale height.





- With larger zenith angle χ, the peak of ionization rate rises in altitude and decreases by a factor $\cos\chi$.

Ionization source: particle precipitation (electrons)

- High-energy electrons deposit the energy at lower altitudes.

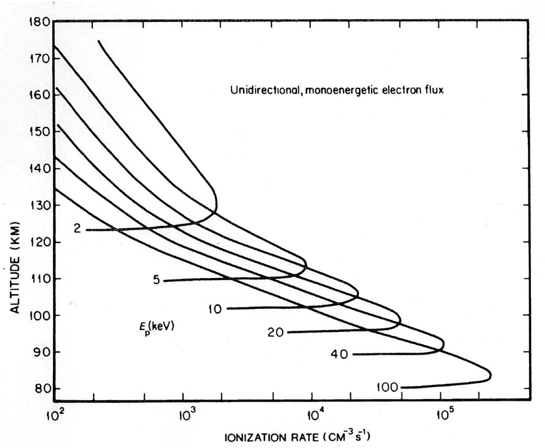


Figure: Ionization rate for monoenergetic electrons with energies 2–100 keV.

Ionization source: particle precipitation (protons)

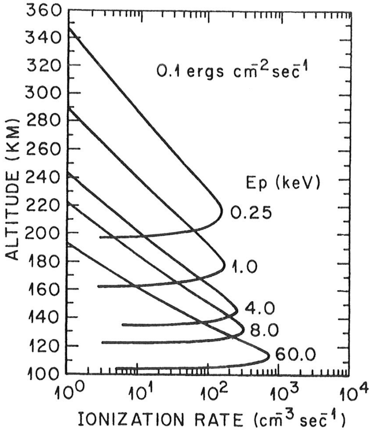


Figure: Ionization rate for monoenergetic protons with energies 0.25–60 keV (Rees, 1982).

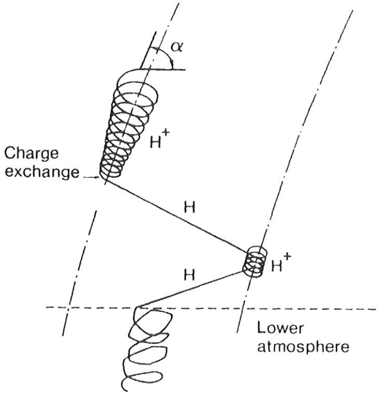


Figure: Protons may make charge exchange with neutral hydrogen.

Ionosphere at high, middle and low latitudes

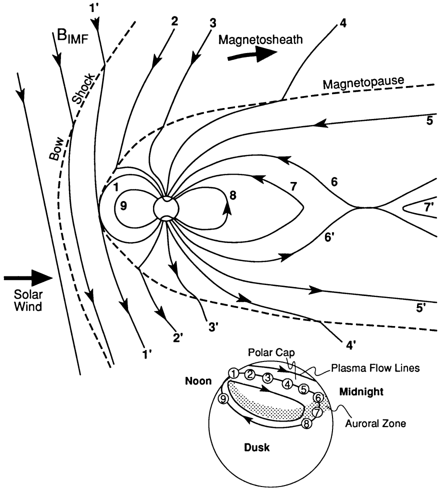


Figure: Magnetospheric plasma flow.

- High-latitude ionosphere (polar cap, cusp, auroral oval): intense electric fields mapping from the magnetosphere, particle precipitation, space weather effects
- Mid-latitude ionosphere: occasionaly high-latitude electric fields may penetrate to mid-latitudes
- Low-latitude ionosphere: small electric fields, high day-time conductivities due to solar radiation (equatorial electrojet)

Some ionospheric phenomena

Time to wake up! A not-too-serious exercise follows...

The following pictures contain some EISCAT measurements from the high-latitude and polar ionosphere.

- Plots are mostly time vs. height, in some cases latitude vs. height.
- Some plots contain only N_e, some all parameters: N_e, T_e, T_i, v_i (line-of-sight ion velocity).
- Use your /group's previous knowledge or just guess to name the phenomena!

- Part 2: Radio waves in the ionosphere

Invention of the ionosphere

- In 1901 first trans-Atlantic transmission of a radio signal (500 kHz, MF) from Cornwall to Newfoundland by G. Marconi (Nobel Prize in Physics in 1909).
- O. Heaviside (UK) and A. Kennelly (USA) suggested independently, that the radio waves have been reflected by a layer of ionised gas (so-called Heaviside layer).
- Term ionosphere was originally proposed by R. Watson-Watt (in 1926) and it was taken into use about 1932.

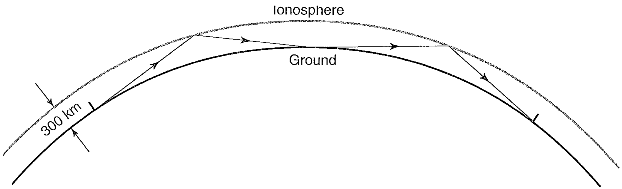


Figure: Long distance propagation of MF signal by multiple hops between the ionosphere and the ground.

Radio spectrum

Band name	Abbr	Frequency	Wavelength in air
Extremely low frequency	ELF	3–30 Hz	10^5 km – 10^4 km
Super low frequency	SLF	30–300 Hz	10^4 km – 1000 km
Ultra low frequency	ULF	300–3000 Hz	1000 km – 100 km
Very low frequency	VLF	3–30 kHz	100 km – 10 km
Low frequency	LF	30–300 kHz	10 km – 1 km
Medium frequency	MF	300–3000 kHz	1 km – 100 m
High frequency	HF	3–30 MHz	100 m – 10 m
Very high frequency	VHF	30–300 MHz	10 m – 1 m
Ultra high frequency	UHF	300–3000 MHz	1 m – 100 mm
Super high frequency	SHF	3–30 GHz	100 mm – 10 mm
Extremely high frequency	EHF	30–300 GHz	10 mm – 1 mm

Table: ITU (International Telecommunication Union) radio bands.

Radio spectrum

Band	Frequency	Example uses
ELF	3–30 Hz	Submarine communications
SLF	30–300 Hz	Submarine communication
ULF	300–3000 Hz	Mine communication
VLF	3–30 kHz	Submarine communication, avalanche beacons
LF	30–300 kHz	Navigation, AM longwave broadcasting, RFID
MF	300–3000 kHz	AM (medium-wave) broadcasts
HF	3–30 MHz	Shortwave broadcasts, amateur radio, RFID
VHF	30–300 MHz	FM radio, TV, ground-to-aircraft communications
UHF	300–3000 MHz	TV, GPS, mobile phones, wireless LAN, Bluetooth
SHF	3–30 GHz	wireless LAN, radars, communications satellites
EHF	30–300 GHz	Radio astronomy, microwave remote sensing

Propagation mechanisms

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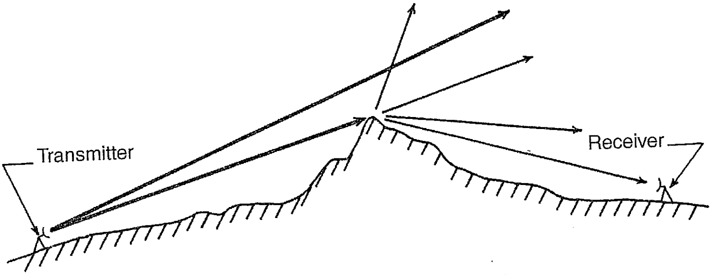

Figure: Terrain diffraction (Levis, 2010).

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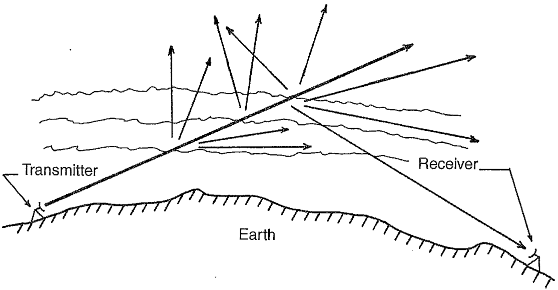

Figure: tropospheric scatter fom tropospheric irregularities: e.g. White Alice (UHF) communication system in Alaska late 1950's.

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- Whistler propagation

Magnetoionic theory for MF and HF radiowave propagation

The dispersion equation of radio waves in collisional magnetised cold plasma can be quite easily derived (e.g. Levis et al., 2010) and then the refractive index n is given by

$$n^2 = 1 - \frac{2X(1-X-iZ)}{2(1-iZ)(1-X-iZ) - Y_T^2 \pm [Y_T^4 + 4Y_L^2(1-X-iZ)^2]^{1/2}} \ ,$$

where

$$X = \frac{\omega_p^2}{\omega^2}, \ \ Y_T = \frac{\omega_e}{\omega}\sin\theta, \ \ Y_L = \frac{\omega_e}{\omega}\cos\theta, \ \ Z = \frac{\nu_e}{\omega}$$

and ω is the wave angular frequency, $\omega_e = eB/m_e$ is the electron gyrofrequency, ν_e is the electron-neutral collision frequency, $\omega_p = \sqrt{n_e e^2/\epsilon_0 m_e}$ is the angular plasma frequency and θ is the angle between the wave vector and the direction antiparallel to the external magnetic field. This is the Appleton-Hartree equation (Appleton-Lassen) equation.

MF and HF radiowave propagation cont'd

Appleton-Hartree equation gives two values of the complex refractive index for each frequency (plus and minus sign in the denominator), so that two modes: ordinary (o-) wave and extraordinary (x-) wave exist. Those wave modes have

- a particular polarization that depends on the properties of ionosphere (electron density) and magnetic field (magnitude and angle with respect to a wave vector)
- a particular attenuation (complex refractive index)
- a particular phase velocity => modes travel different paths
- when the waves propagate along **B** (longitudinal propagation), the characteristic polarisations are circular
- when the waves propagate transverse to **B** they are linear

Ionosonde (ionospheric sounder)

A ionosonde is a high-frequency (HF) radar, which sweeps over a wide range of frequencies (in Sod 0.5–16 MHz). The signal is reflected back from the ionosphere and the measurement is displayed in the form of an ionogram, a graph of virtual reflection height versus carrier frequency. For vertical transmission, the reflection occurs at a height where $n = 0$ (when $\nu_e \sim 0$). It can be shown that this corresponds to the group refractive index $n_g = \infty$ and therefore to the group velocity $v_g = 0$. Close to the reflection height, the wave slows down. In the ordinary mode, $n = 0$ when the wave frequency matches the plasma frequency $f_p \propto \sqrt{n_e}$. When frequency is further increased, the wave penetrates the layer. Ionogram gives:

- the critical frequencies $f_{oE}, f_{oF_2}, f_{xE}, f_{xF_2}$. Usually the o-mode critical frequencies are used to derive the electron densities at E and F_2 region maxima (possibly also F_1 and E_s) .
- virtual heights corresponding to the critical frequencies, $h' = ct/2$, where t is the travel time of the pulse to the receiver
- real heights corresponding to virtual heights require further analysis

Schematic ionogram

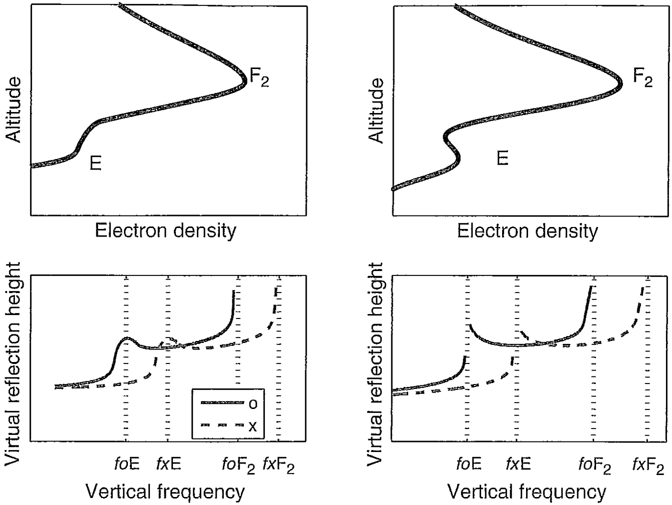
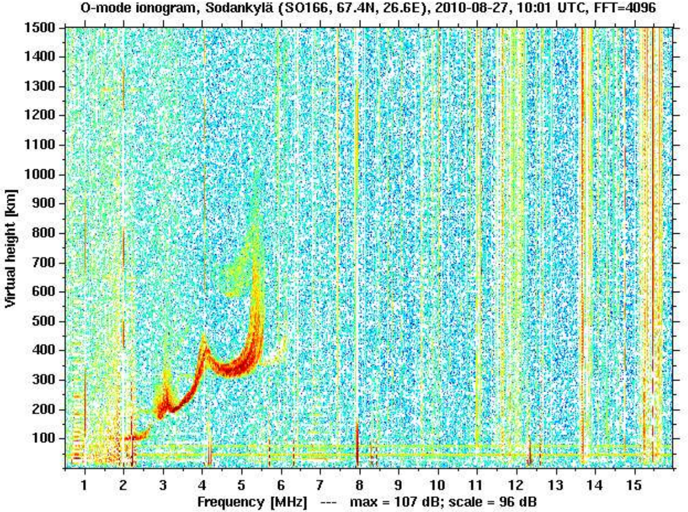


Figure: Electron density profiles and corresponding ionograms.

Real ionogram ("Alpha Wolf" in Sodankylä)



Absorption

The complex refractive index can be written as $n = n_R - jn_I$, where n_R and n_I are the real and imaginary parts of the refractive index. The specific attenuation α in nepers per unit length, is given by $\alpha = -Im(k_1) = -Im(k_0 n) = k_0 n_I$, where k_1 and k_0 are the wave vectors in the medium and in free space, respectively. When the magnetic field is neglected, a simple result from the Appleton-Hartree equation is obtained:

$$\alpha = \left(\frac{e^2}{2\varepsilon_0 m_e c} \right) \frac{\nu_e n_e}{n_R(\omega^2 + \nu_e^2)}$$

- Attenuation decreases with (angular) radio wave frequency ω.
- Attenuation increases:
  - Deviative absorption: n_R is small, occurs near the reflection height.
  - Non-deviative absorption: product of electron-neutral collision frequency ν_e and electron density n_e is large. Maximum is most easily obtained in the D/lower E regions during strong ionization, e.g. due to particle precipitation.

Oblique transmission of MF/HF signal

Snell's law is $n_1 \sin\theta_1 = n_2 \sin\theta_2$. Since n generally increases when going up, then the angle with vertical increases, too, and the wave is refracted.

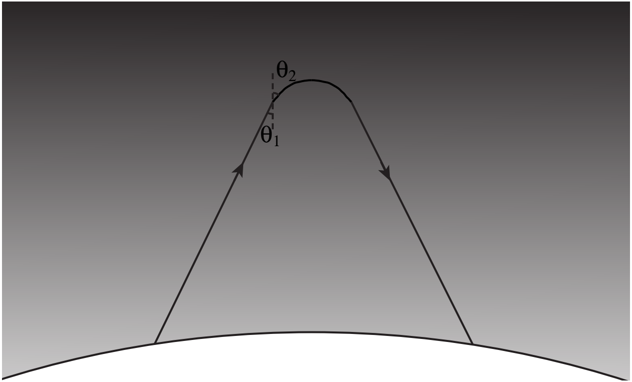


Figure: Oblique transmission (for a frequency that is not penetrating the ionosphere).

HF SuperDARN radar

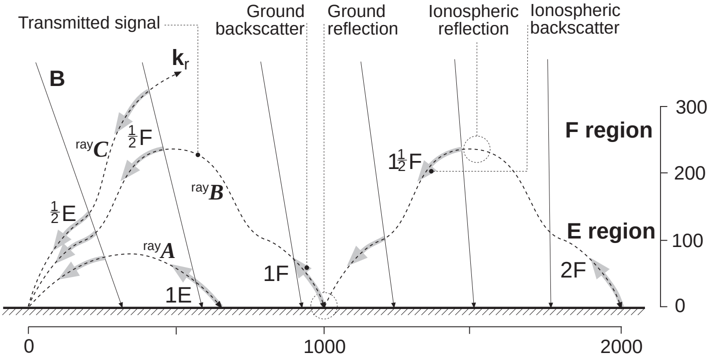


Figure: Different ray paths for the HF signal (Milan et al., 1997).

- CUTLASS is a coherent scatter radar, sensitive to field-aligned irregularities.
- It operates in the frequency range 8 - 20 MHz. Frequency is selected to make the radar wave vector to orthogonal to field-aligned irregularities, and to get the signal to the area of interest.

HF SuperDARN radar (CUTLASS)

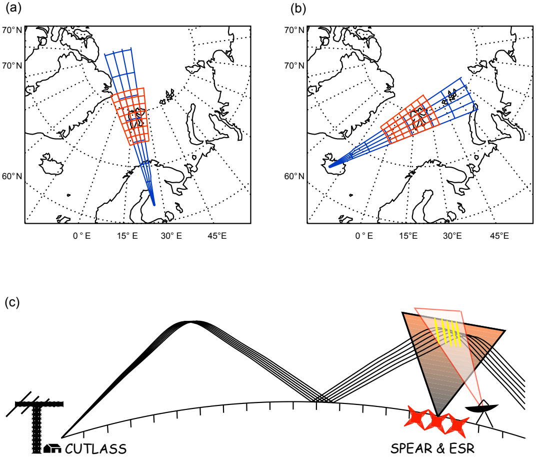
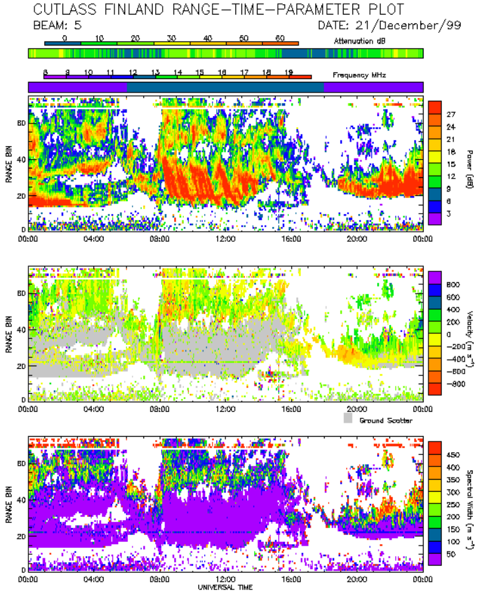


Fig. 5. Summary of CUTLASS experimental operations. **(a)** Scanning pattern for CUTLASS Finland, **(b)** scanning pattern for CUTLASS Iceland, **(c)** schematic of 1.5-hop propagation path between CUTLASS radar and SPEAR/ESR sites.

Figure: HF signal makes 1.5 hops in the F region (Robinson et al., 2006).

HF SuperDARN radar (CUTLASS) data



EISCAT radar - incoherent scatter

- Tiny amount of the VHF/UHF signal is scattered by quasi-random thermal fluctuations of the ionosphere (ion-acoustic and electron-acoustic waves)
- The scattered signal depends on the properties of the ionosphere: $N_e, T_e, T_i, m_i, \nu_{in}, v_i$

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- The scattered signal depends on the properties of the ionosphere: $N_e, T_e, T_i, m_i, \nu_{in}, v_i$
- Coming talks are devoted to the details of incoherent scatter (IS) mechanism as well as measurement and analysis techniques of IS signals.
- ENJOY!

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