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MAKING THE IONOSPHERE
— All in a Morning's Work

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“MAKING THE IONOSPHERE — All in a Morning’s Work”

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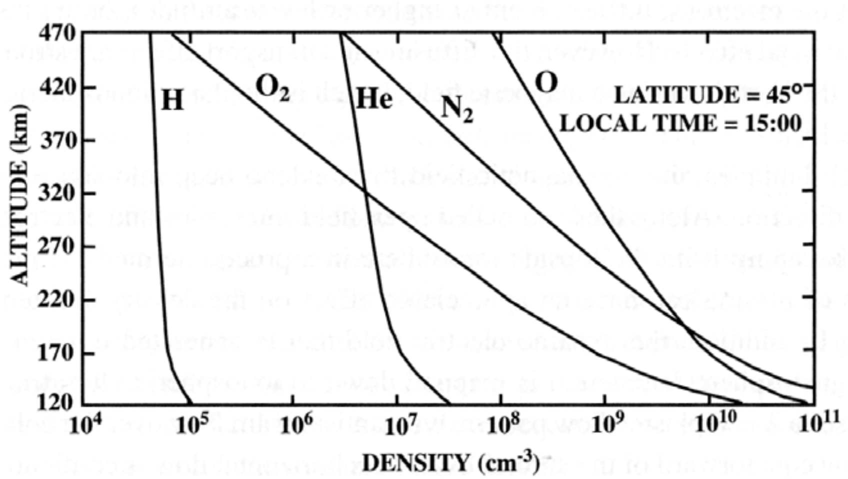
1. The Photo-Ionization Process

- Start with Neutral Atmosphere [Re: Prof. Forbes' Lecture]



(from S&N, '00)

- Ionization Potentials of Atoms and Molecules

Species	Energy (ev)
O	13.62
O_2	12.06
N_2	15.58

$\lambda_{ionization}$
910 Å
1028 Å
796 Å

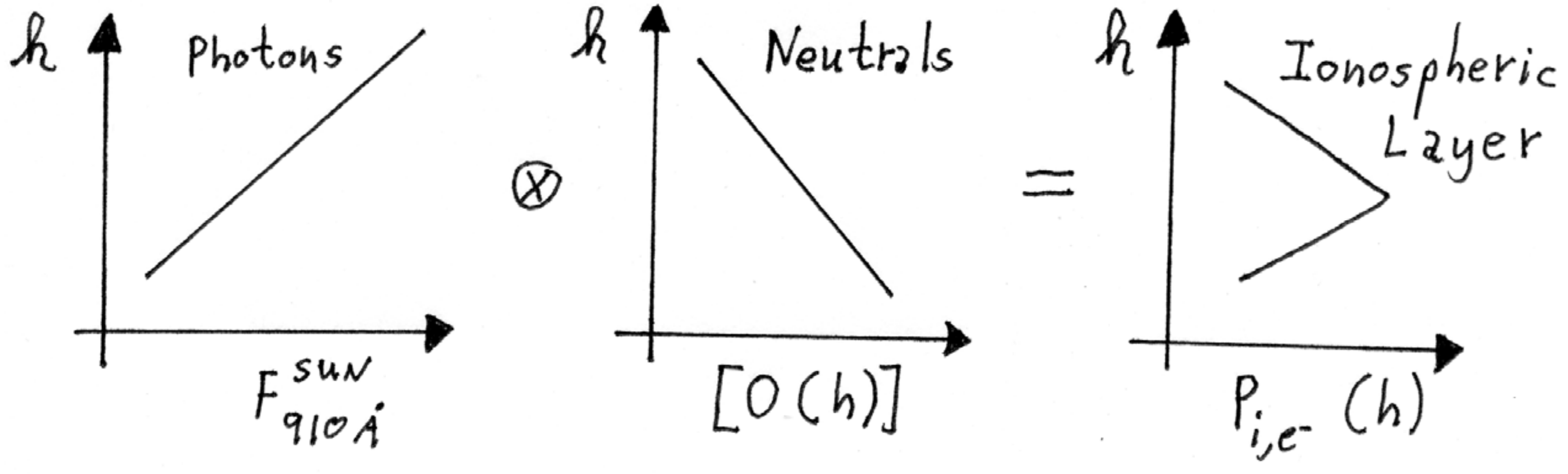
- Photon energy, $E = h\nu = hc/\lambda$

$$\text{or } \lambda(\text{Å}) \approx \frac{12345}{E(ev)}$$

Thus, Photon (910 Å) + O $\rightarrow$ O^+ + e^-

Knowing
$$\underbrace{F_{910}^{SUN}(h) + \left[O(h)\right] = \left[O^{+}(h)\right] + \left[e^{-}(h)\right]}_{\substack{\text{Production Function (P)} \\ \text{for monochromatic ionizing radiation} \\ \text{(called "Chapman Theory")}}}$$

How should P (h) look?



Algebraically, $P_{i,e^-}(h) = F^{\text{sun}}_{\lambda_{\text{ion}}}(h) \cdot \underbrace{\sigma_{\text{ion}}}_{\substack{\textit{ionization}\\ \textit{cross-section}}} \cdot [O(h)]$

What happens if photon

- $\lambda > \lambda_{\text{ion}}$? → *No ionization*
- $\lambda < \lambda_{\text{ion}}$? → *Extra Energy*

i.e., Photon ($\lambda < \lambda_{\text{ion}}$) + O → $O^+ + e^{-*}$ (energetic photo-electron)

If e^{-*} Kinetic Energy > Ionization Potential
collisions can cause additional ionizations

$e^{-*} + O \rightarrow O^+ + e^-$ ("secondary ionization")

Thus, a very energetic photon can lead to several ion-electron pairs.

For a complete model of Photo-Ionization, the flux of solar photons at all relevant λs is needed:

$$P_{\text{Total}}(\text{h}) = \sum_{\lambda=0}^{\lambda_{\text{ion}}} \text{F}_{\lambda}^{\text{sun}}(\text{h}) \cdot \sigma_{ion}(\lambda) \cdot [\text{N(h)}]$$

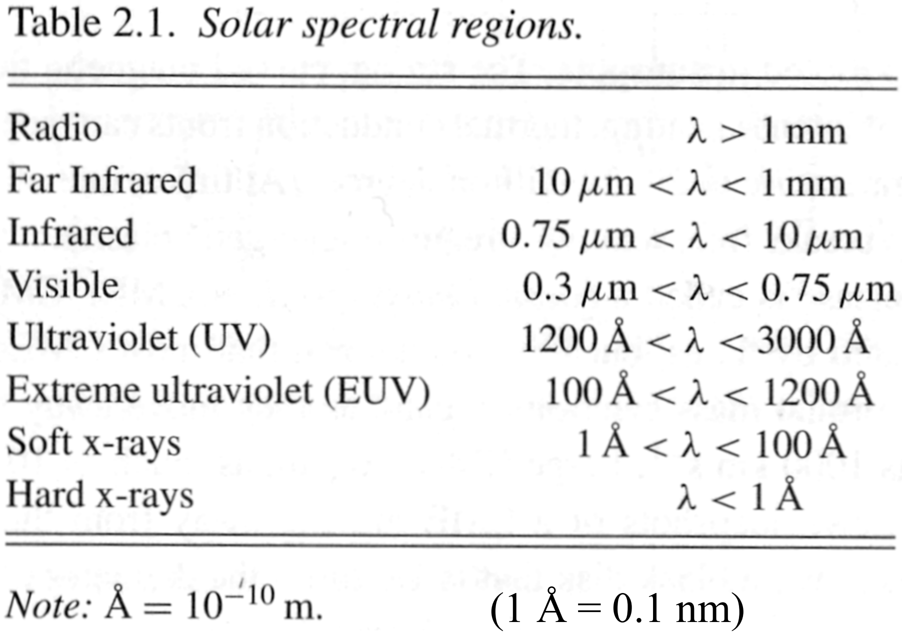
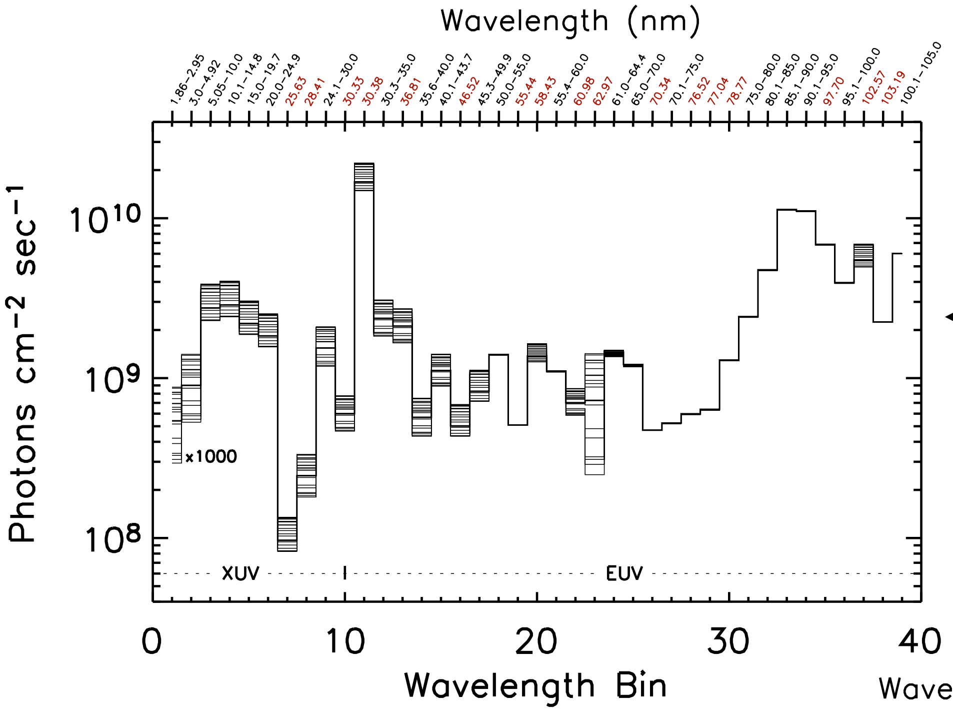


Table 2.1. *Solar spectral regions.*

Radio	$\lambda > 1$ mm
Far Infrared	$10\,\mu\text{m} < \lambda < 1$ mm
Infrared	$0.75\,\mu\text{m} < \lambda < 10\,\mu\text{m}$
Visible	$0.3\,\mu\text{m} < \lambda < 0.75\,\mu\text{m}$
Ultraviolet (UV)	$1200\,\text{Å} < \lambda < 3000\,\text{Å}$
Extreme ultraviolet (EUV)	$100\,\text{Å} < \lambda < 1200\,\text{Å}$
Soft x-rays	$1\,\text{Å} < \lambda < 100\,\text{Å}$
Hard x-rays	$\lambda < 1\,\text{Å}$

Note: $\text{Å} = 10^{-10}$ m. (1 Å = 0.1 nm)



SOLAR2000 IRRADIANCES

- Flux in 39 wavelength bins (bands + lines)

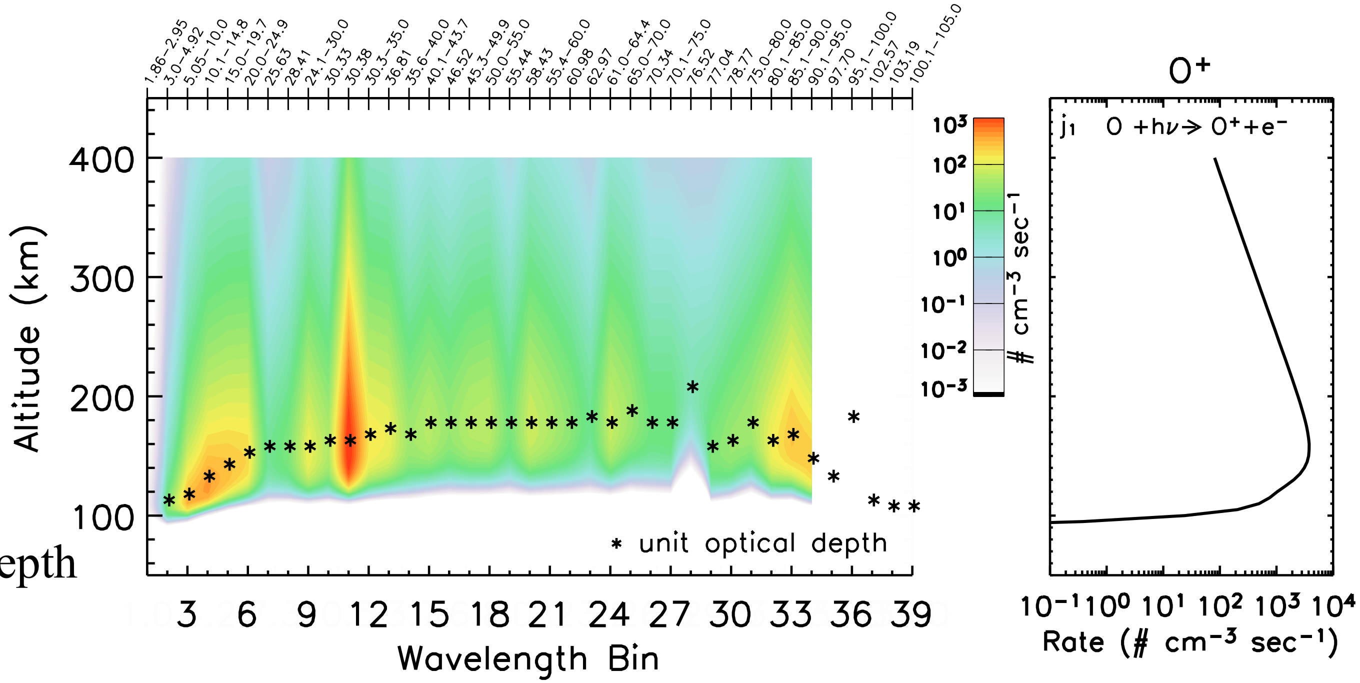
- Shown here are for 15 consecutive days to portray variability

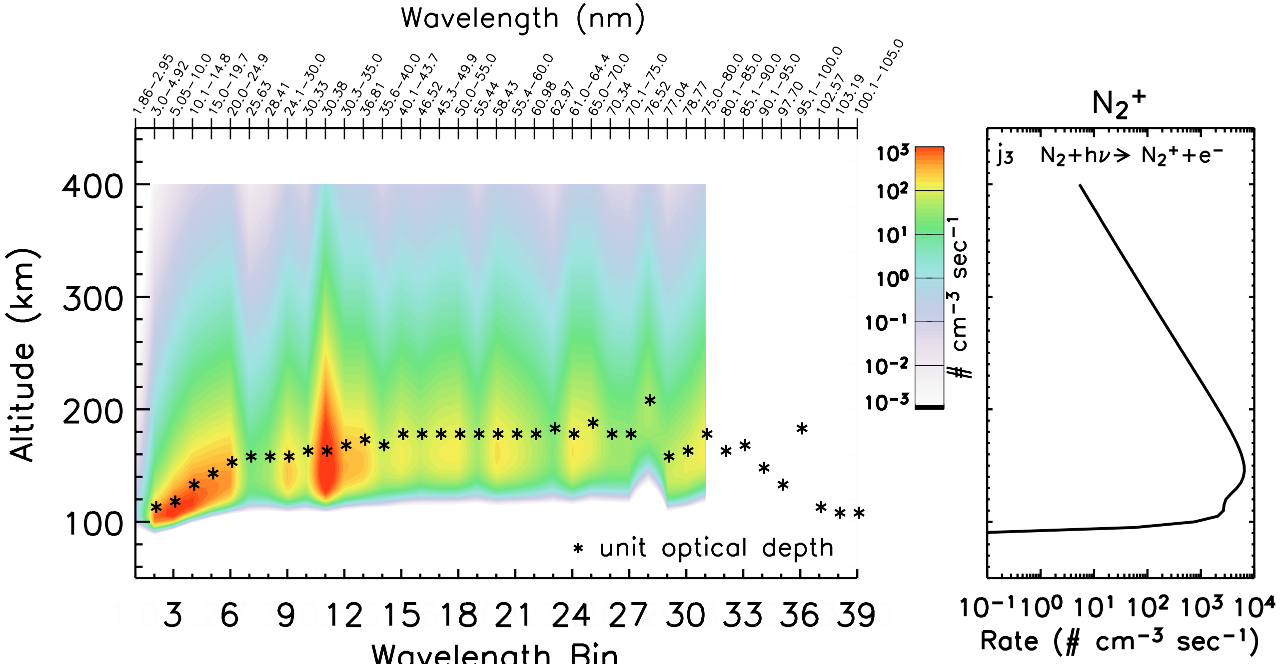
Sample results:

Oxygen

Photons + O →O^+ + e^-

* = unit optical depth

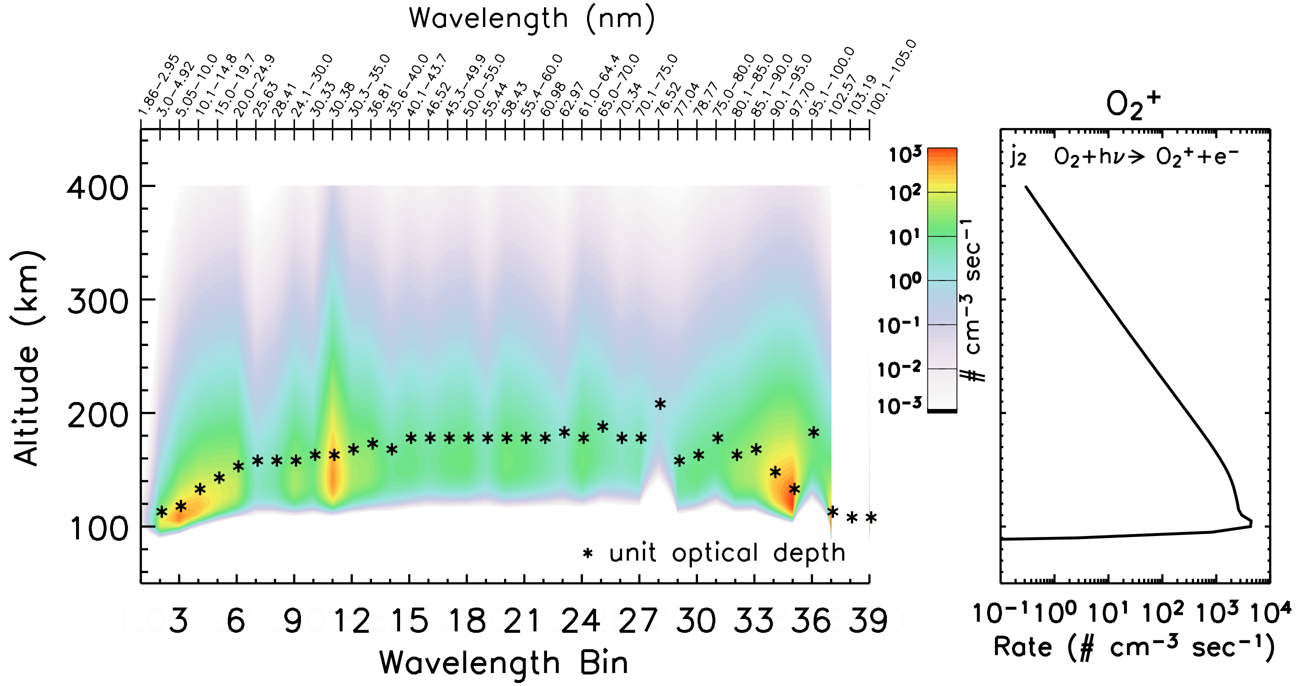




Sample results:

Molecular Nitrogen

Photons + $N_2 \rightarrow N_2^+ + e^-$



Sample results:

Molecular Oxygen

Photons + $O_2 \rightarrow O_2^+ + e^-$

2. Ionospheric Transformations

- What does “production only” imply? Use peak P (O^+, e^-)

e.g., use P(O^+) value from graph:

P_{max} = 4000 $e^-/cm^3/sec$ x 3 hours ($\approx 10^4$ sec)

gives $N_{max} \approx 4 x 10^7 e^- / cm^3$ ***Never Measured!!!***

Message: Something happens to these ions and electrons

Answer: Chemistry → Plasma recombination

Answer: Chemistry → Neutral-Plasma Processes

CASE # 1: Atomic ions + electrons

$$O^{+} + e^{-} \xrightarrow{\alpha} O$$

[very rare due to precise energetics
needed for electron capture]

CASE # 2: Molecular ions + electrons [Loss= αN_e^2]

$$O_2^{+} + e^{-} \xrightarrow{\alpha} O + O$$

[fast due to excess energetics
used for dissociation]

CASE #3: Transform Atomic ions to Molecular ions

$$O^{+} + \begin{bmatrix} N_2 \\ O_2 \end{bmatrix} \xrightarrow{k} \underbrace{\begin{bmatrix} NO^{+} \\ O_2^{+} \end{bmatrix}}_{\text{followed by CASE \#2 (quick)}} + \begin{bmatrix} N \\ O \end{bmatrix} \quad \text{(slow)}$$

The 2-stage recombination process governed by slower step, e.g.,

$$\boxed{\frac{dN_e}{dt} = -k[N_2]N_e = -\beta N_e}$$

3. Photochemical Equilibrium

- Continuity Equation for electron density (N_e)

$$\frac{dN_e}{dt} = \mathrm{Production} - \mathrm{Loss} + \nabla \cdot \mathrm{Motion}$$

IF, temporal changes small (e.g., near noon) AND/OR dynamics slow

$$\frac{dN_e}{dt} + \nabla \cdot \mathrm{Motion} \approx 0 \text{ and } P = L$$

Photoionization rate = chemical loss rate

(a) $F_{sun}\sigma_{ion}N_{neutrals} = \alpha N_e^2$ (case #1 and #2) → $N_e = \sqrt{\frac{F_{sun}\sigma_{ion}N_n}{\alpha}}$

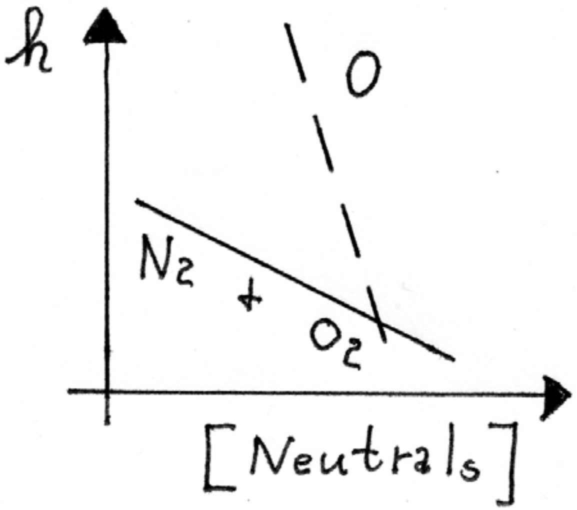
(N_e depends on neutral gas to be ionized)

(b) $F_{sun}\sigma_{ion}N_{neutrals} = \beta N_e$ (case #3) → $N_e = \frac{F_{sun}\sigma_{ion}N_n}{\beta} = \frac{F_{sun}\sigma_{ion}[O]}{k[N_2]}$

(N_e depends on ratio of neutral gases for ionization and loss)

Messages from Simple Photochemical Equilibrium Theory

- Plasmas should be ionized form of dominant neutral



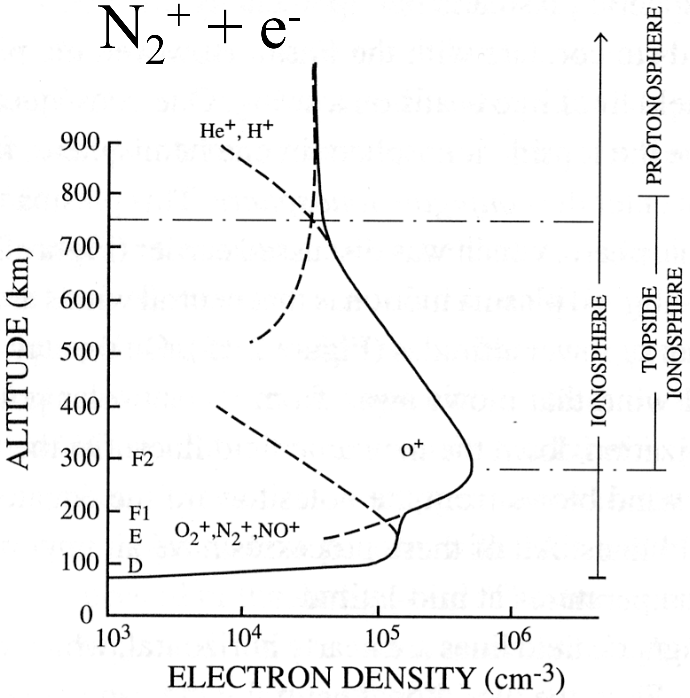
→ CASE #1 : $O^+ + e^-$

→ CASE #2 : $O_2^+ + e^-$
$N_2^+ + e^-$

- The actual case:

— some chemical transformations
to form NO^+ and H^+

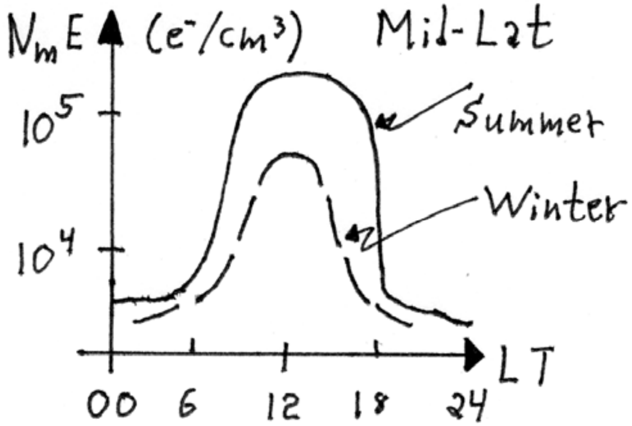
- Two main layers: F-layer and E-layer

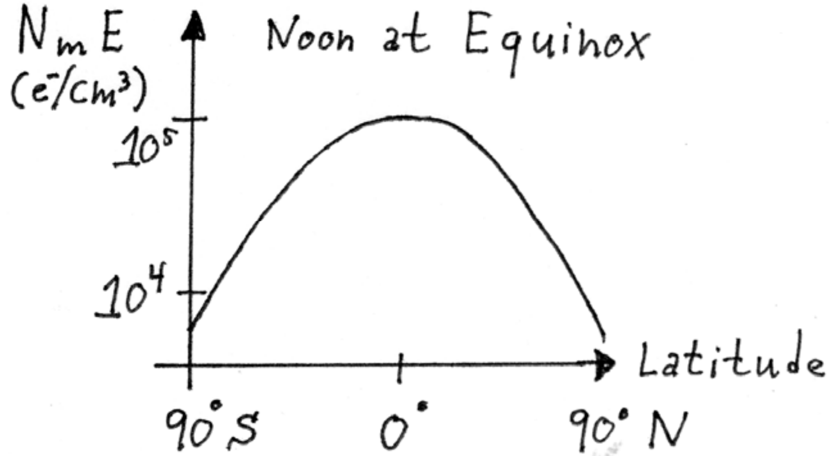


Some E-layer Characteristics

- In regions of a dense neutral atmosphere ($h \leq 150$ km) all ions are molecular (rapid chemistry) and the ions + electrons stay where produced (too many collisions to move away).

- Example of diurnal behavior

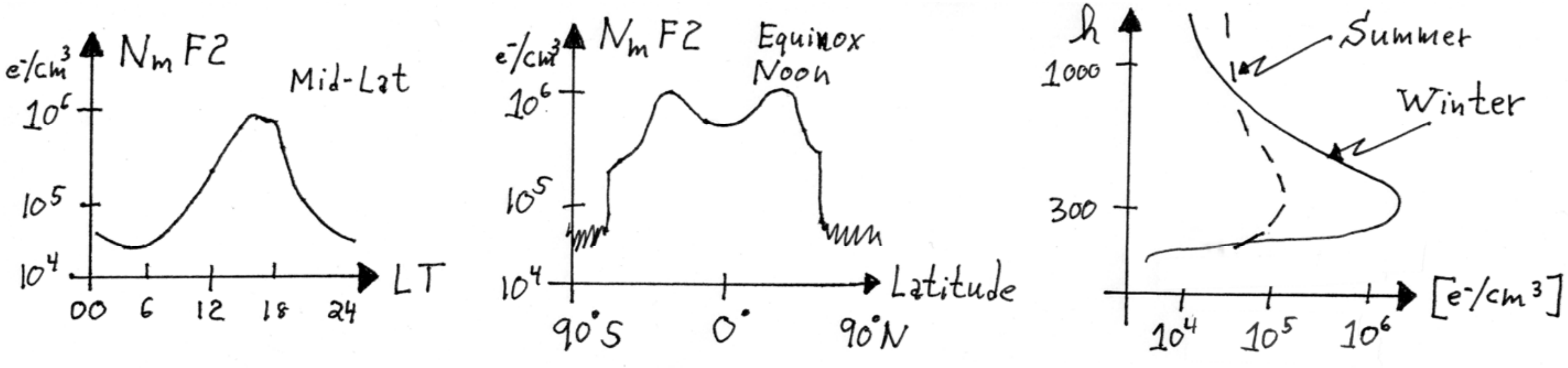




The E-layer is controlled by the Sun's flux and its position (dec + $\chi_\odot$)

4. Photochemistry-Plus-Dynamics

- Some F-layer Characteristics



The F-layer is produced by sunlight BUT its behavior does not follow $\chi_\odot \Rightarrow$ "Anomalies"

- At h > 200 km atomic ions (O^+, H^+ , He^+) have “slow chemistry” (CASE #3) ⇒ ions and electrons can move “ between/during” episodes of chemical loss.

$$\frac{dN}{dt} = P - L - \underbrace{\nabla(N\vec{V})}_{\frac{d}{dh}(Nw)} \qquad \vec{V} = \underset{\text{horizontal}}{v\,(\hat{x},\hat{y})} + \underset{\text{vertical}}{w\,(\hat{z})}$$

- Given solar-produced nature of the ionosphere, it varies more dramatically in vertical direction vs. horizontal

$$\nabla_z \text{ [parameter]} > \nabla_{x,y} \text{ [parameter]}$$

What are the causes of vertical motions?

- GRAVITY

- For neutral gas, $\frac{dP}{dh} = -\rho g \Rightarrow \frac{d(NkT)}{dh} = -Nmg$

(Prof. Forbes'Lecture)

Solution: Hydrostatic Law

$$N(h) = N_o(h_o)\exp[-(h-h_o)/H_n)$$

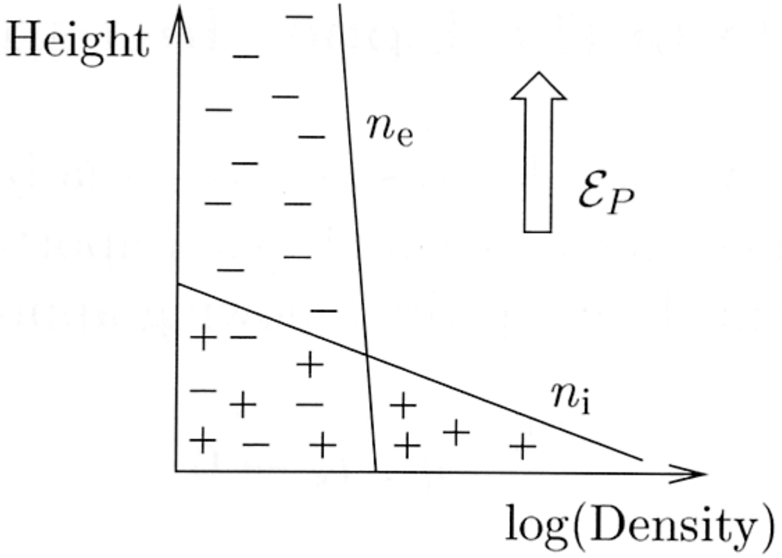
neutral scale height $H_n = \frac{kT}{mg}$

- For plasma → ions + electrons

$m_i \gg m_e$

Gravity tends towards “charge separation”

$\Rightarrow$ Polarization $\vec{E}$-field (ε_p)



(from Prölss, ’04)

$$\frac{dP_i}{dh} = -\rho_i g + N_i e \varepsilon_p \qquad \frac{dP_e}{dh} = -\rho_e g - N_e e \varepsilon_p$$

Adding, with $N_i = N_e = N$ and $m_e \approx 0$

$$\frac{d(P_i + P_e)}{dh} \approx -Nm_i g$$

- Solution $N(h) = N_o(h_o)exp[-(h-h_o)/H_p)$

Plasma scale height $H_p = \dfrac{k(T_e + T_i)}{mg}$

$$H_p \geq 2H_n$$

Called “Ambipolar diffusion”

electrons “pull” ions upward

ions “pull” electrons downward

- What else cause Vertical Motions?

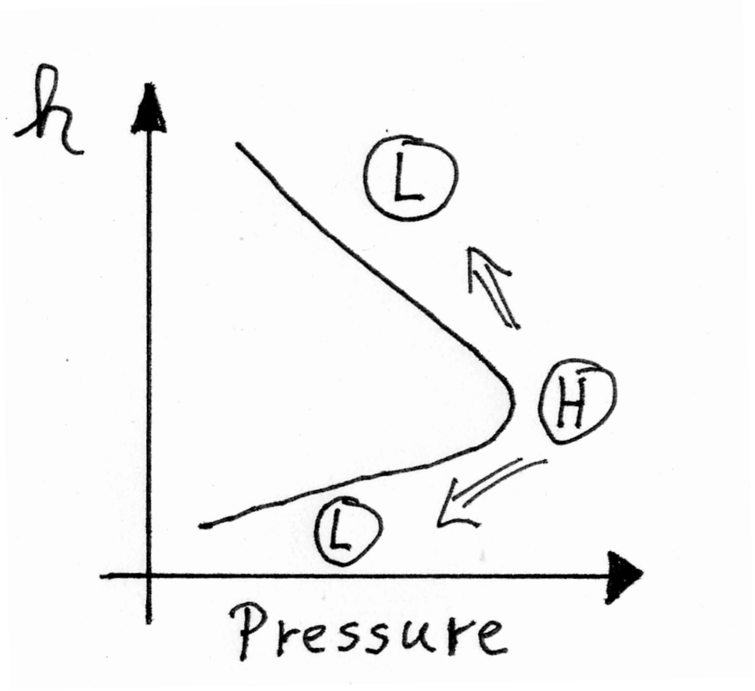
Other E-fields (Prof. Heelis' lecture

Pressure Gradients

$P_1 = NkT_1$, $P_2 = NkT_2$

ΔP from ΔN and/or ΔT

$$\frac{dP}{dh} \approx \frac{dN}{dh} + \frac{dT}{dh}$$



- $\underbrace{\text{Vertical Flux}}_{\text{Response to Pressure gradient}} \equiv$ Number density ($\#/\text{cm}^3$) x vertical speed (cm/sec)

$$F \equiv Nw \propto \frac{dP}{dh} \propto \frac{dN}{dh}$$

$$Nw = D\frac{dN}{dh}$$

D diffusion coefficient,
depends on collisions between
Ions and neutrals ν_{in}

- Solution:

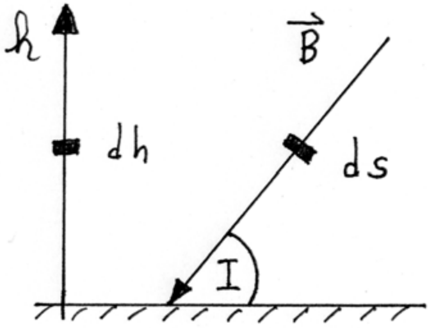
$$w_D = -D\left[\underbrace{\frac{1}{N}\frac{dN}{dh}}_{\text{vertical gradient}} + \underbrace{\frac{1}{T}\frac{dT_p}{dh}}_{\text{vertical gradient}} + \underbrace{\frac{1}{H_p}}_{\text{gravity}}\right]$$

$$T_p = \frac{1}{2}\left(T_e + T_i\right) \qquad H_p = \frac{2kT_p}{m_i g} \qquad D = \frac{k(T_e + T_i)}{m_i \nu_{in}}$$

- Discussion: roles of parameters

- Influence of Geomagnetic field

- Midlatitudes (local):



vertical gradient → field-aligned ($\vec{B}_{\parallel}$) gradient

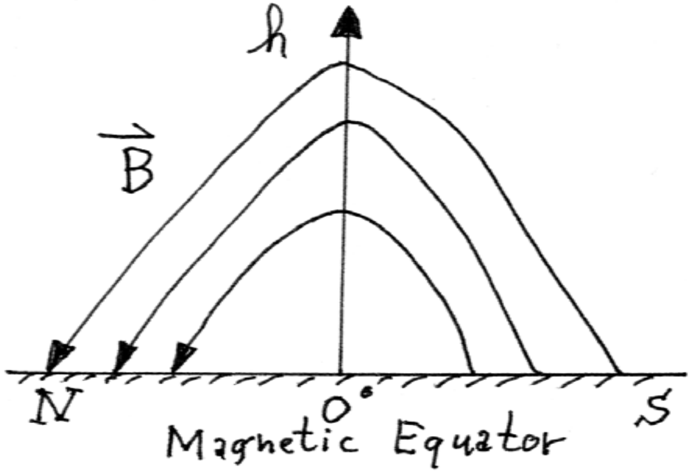
$$\frac{d}{dh} \rightarrow \frac{d}{ds}$$

$$V_{\parallel}^{plasma} = w_D \sin I \text{ and } w_z = w_d \sin^2 I$$

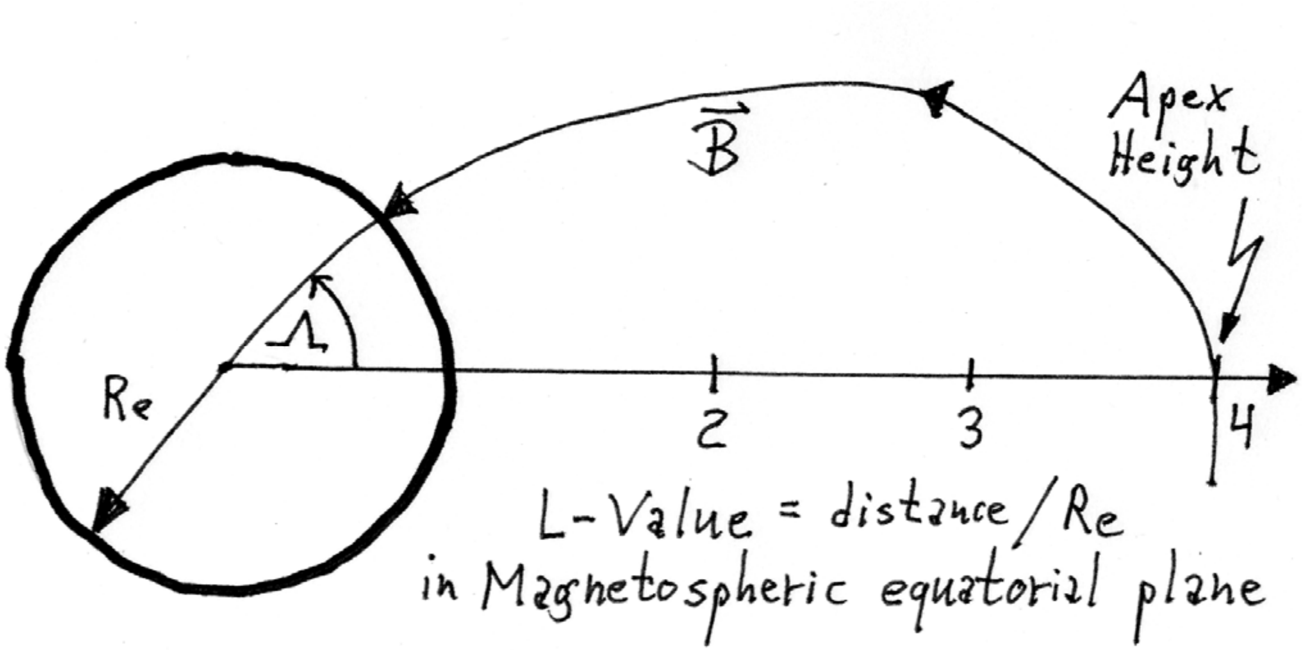
- Special case at equatorial latitudes:

$\vec{E}$-field needed for vertical motion

(Prof. Heelis' Lectures)

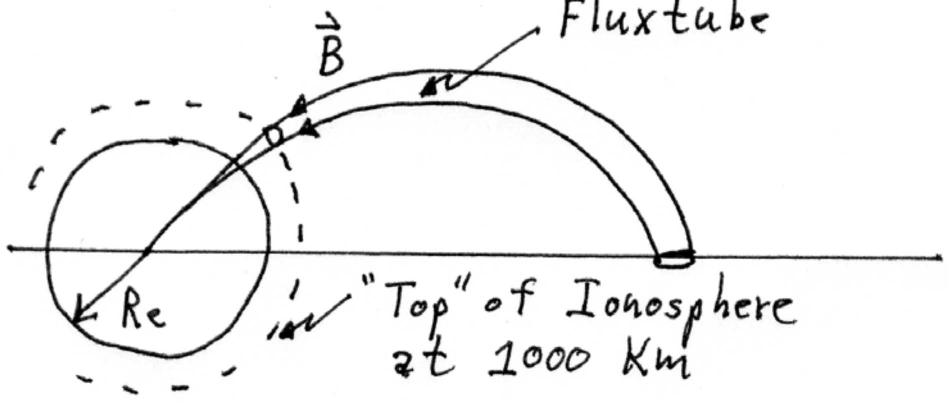


- Midlatitudes (extended)



Magnetic Latitude (Λ), $\cos^2\Lambda = 1/L$ (e.g., $L=4 \Rightarrow \Lambda = 60^o$)

What happens to ionospheric plasma diffusing upwards?



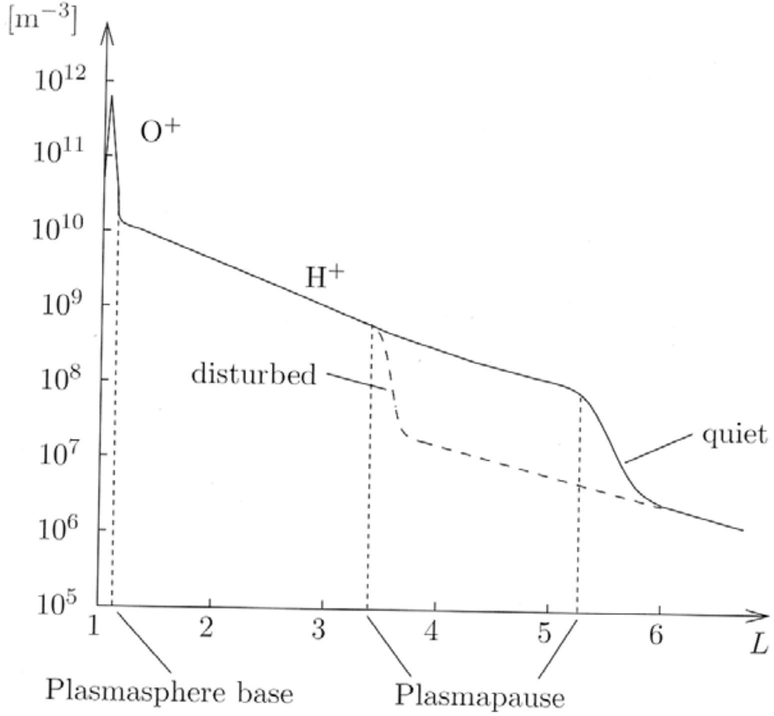
Diffusion affected by reduced gravity, $F_{\text{centripetal}}$, light ions

$$\frac{dP}{ds} \rightarrow \text{large } H_p$$

$\longrightarrow$ fluxtubes of plasma of ionospheric origin

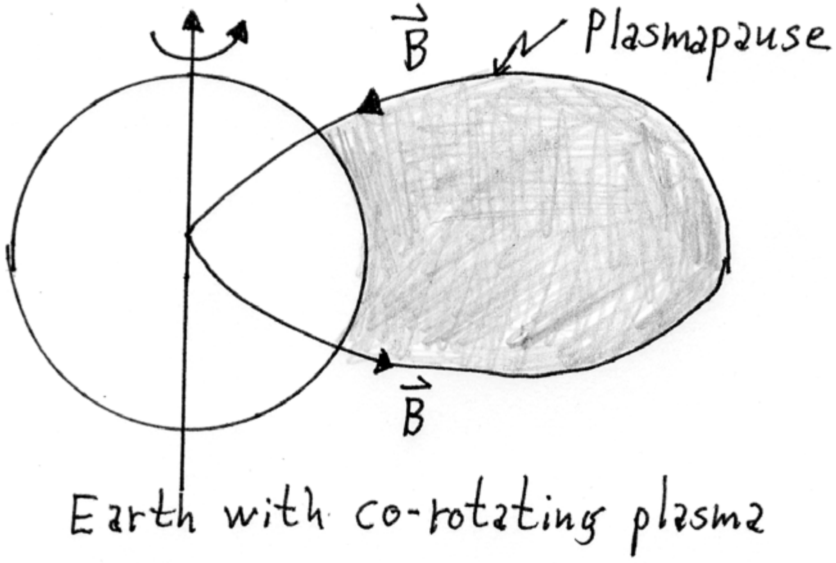
"Charge Exchange"

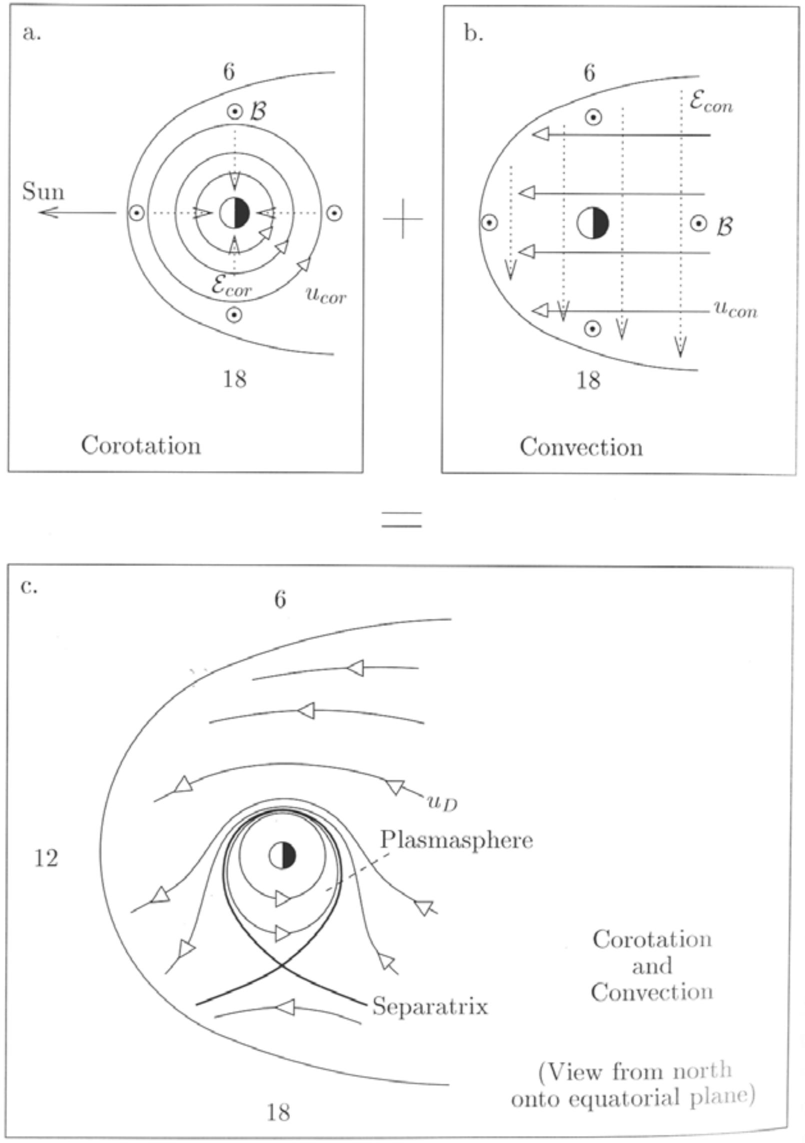
$$\underbrace{O^+}_{\text{heavy ion}} + H \Leftrightarrow \underbrace{H^+}_{\text{light ion}} + O$$



(from Prölss, '04)

The Plasmasphere in 3-dimensions:

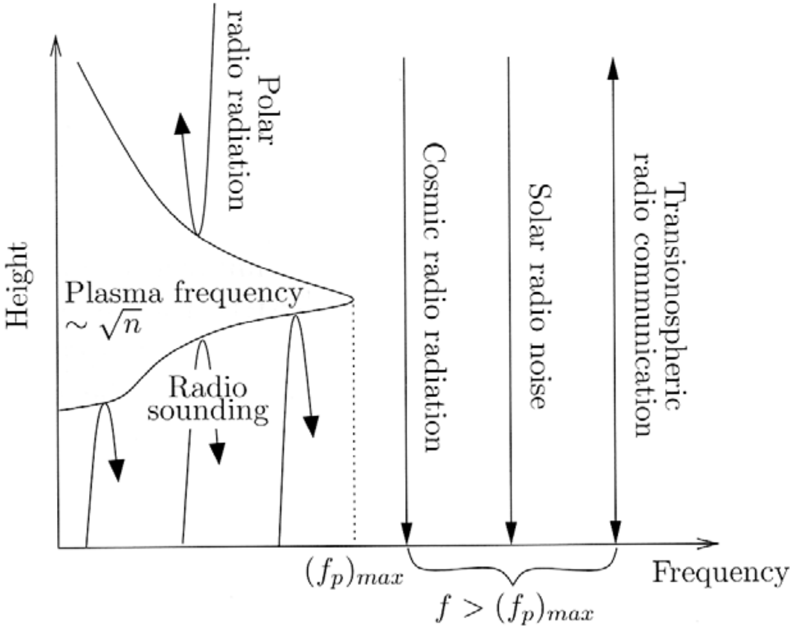


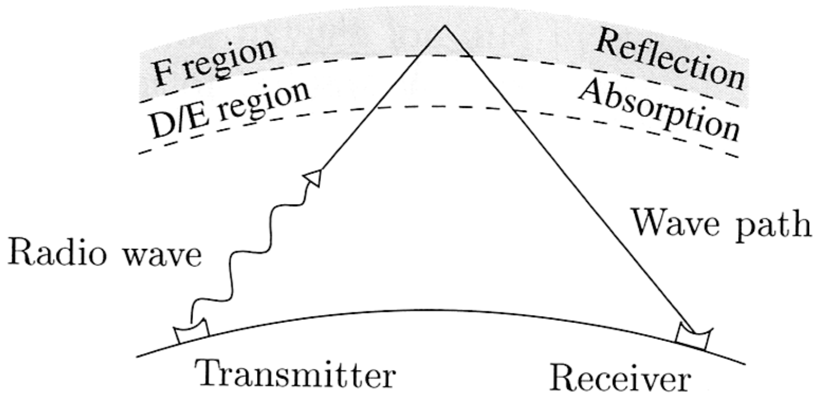


(from Prölss, '04)

5. Ionospheric Measurements

- Reflection of radiowaves (f_{HF} ~ 3-30 MHz)



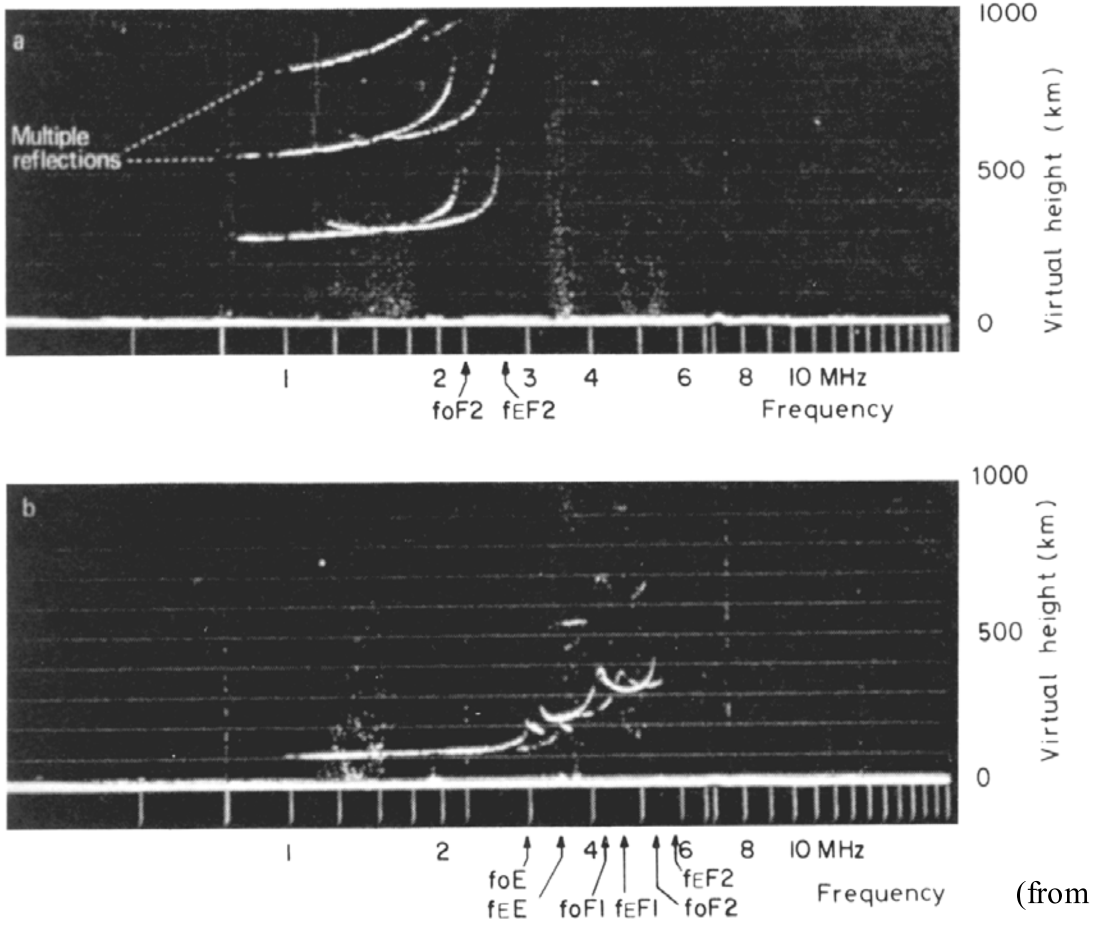


(from Prölss, ’04)

Plasma frequencies → Layer peak densities

$[f_p \text{ (Hz)}]^2 = 80.5 \ N_e \ (m^{-3})$

Example of Ionogram

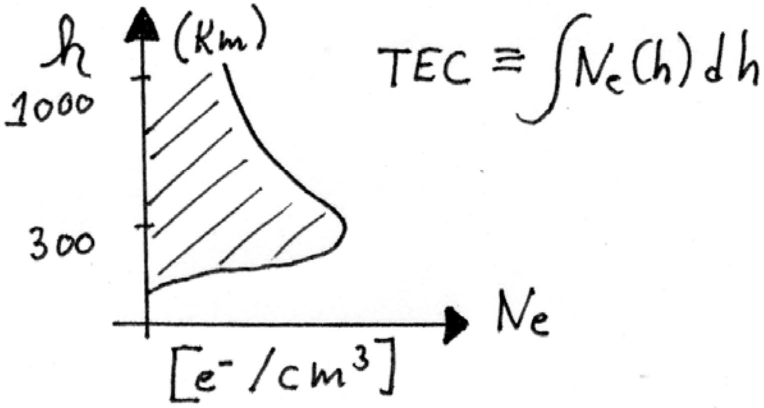


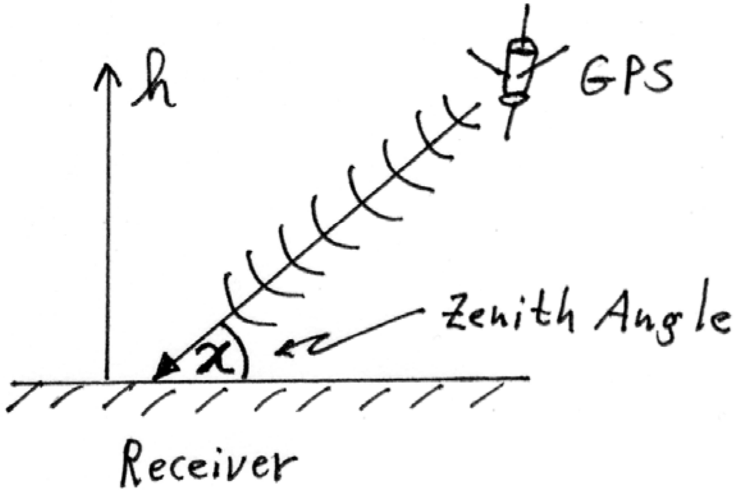
(from Hargreaves,'92)

The worldwide network of ionosondes

SPIDR: http://spidr.ngdc.noaa.gov/spidr/index.jsp

* Trans-Ionospheric Radiowaves (f_{VHF} ~ 30-300 Mhz)





Index of refraction (phase):

$$n^2 = 1 - \frac{\omega_p^2}{\omega^2}; \text{ if } \frac{\omega_p^2}{\omega^2} << 1 \text{ then } \quad n \approx \underbrace{1}_{\text{vacuum}} - \underbrace{\frac{40.3\mathrm{N_e}}{\mathrm{f}^2}}_{\text{effect of ionosphere}}$$

(N_e in m^{-3} and f in Hz)

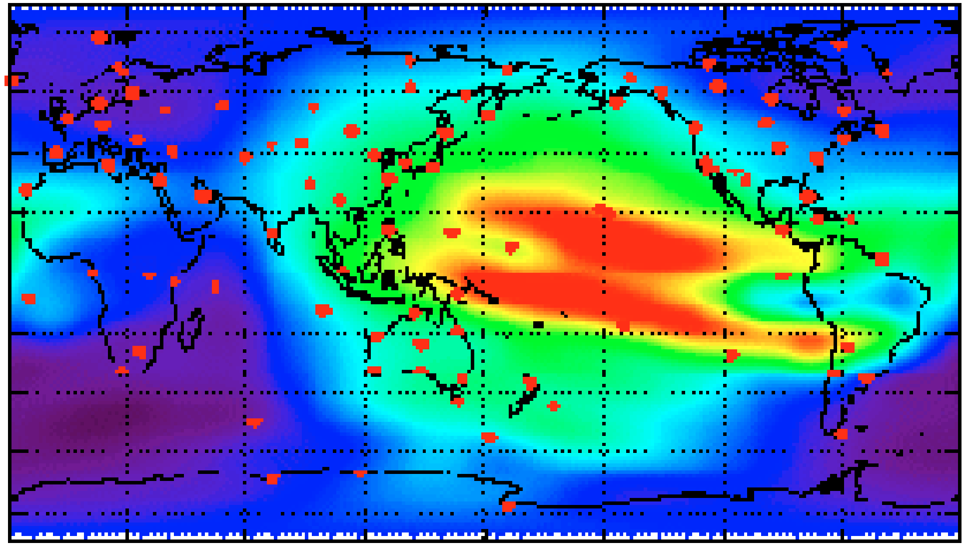
End result: wave is slowed down by plasma → Group Delay

The effect is cumulative → $\int N_e(s)ds$ → SLANT TEC

By measuring total group delay → STEC

Equivalent Vertical (for small spatial gradients) TEC

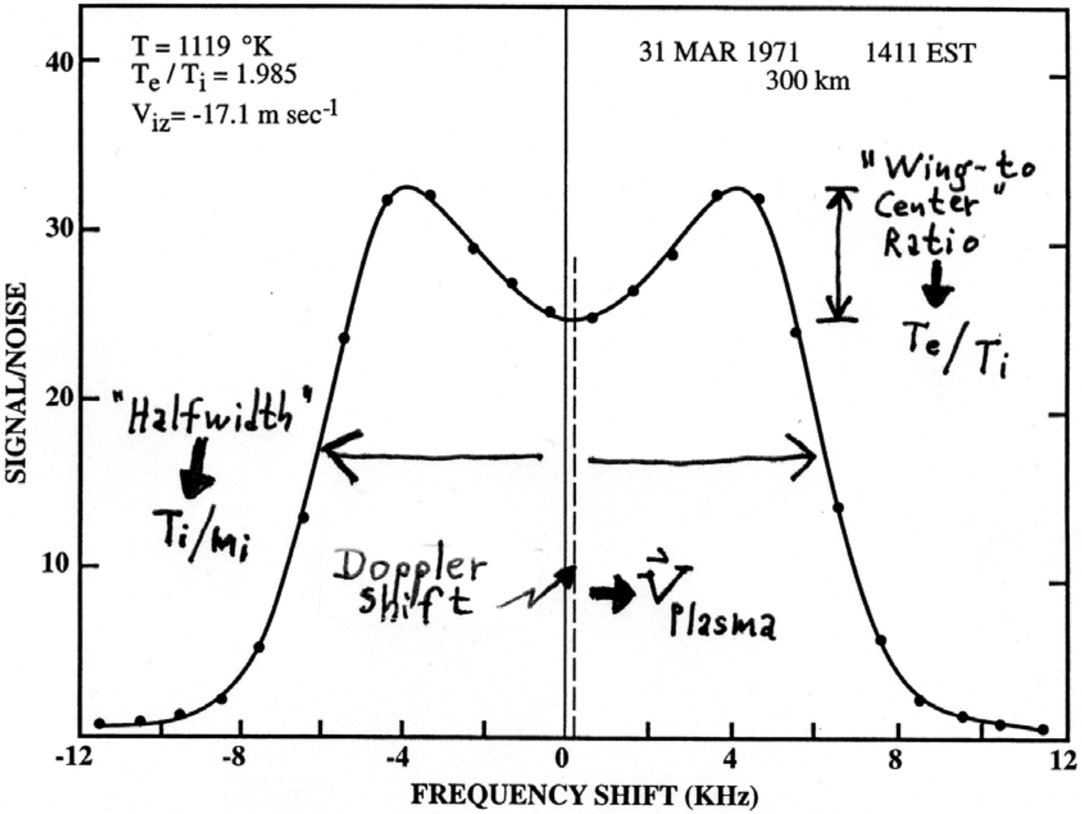
$$\text{TEC} = \text{STEC} \cos \chi$$



From GIM/JPL (http://iono.jpl.nasa.gov/gim.html)

- Back-scattering of Radiowaves
  - Incoherent scatter Radars (ISRs)

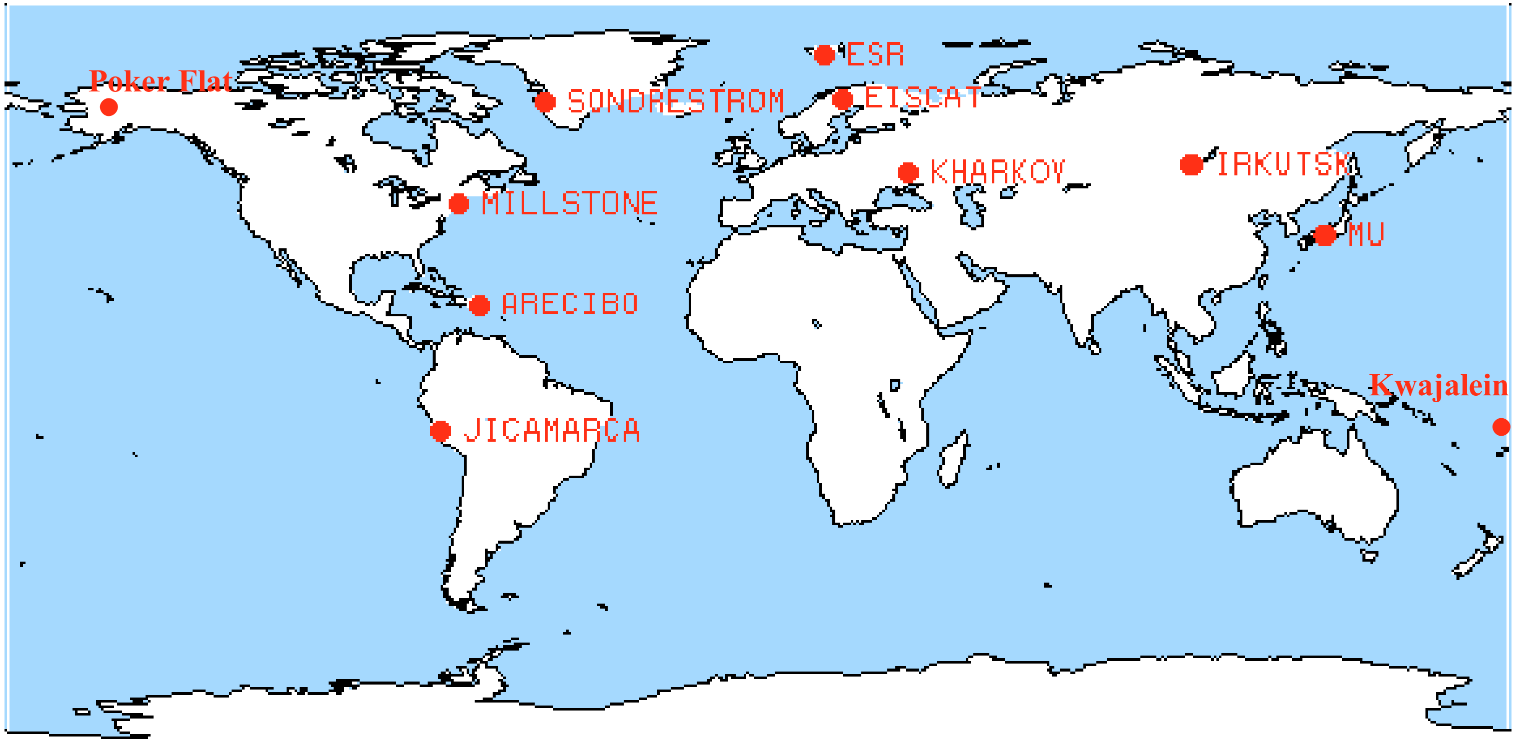
    The transmitted signal returns with a “spread in frequency” → ISR spectrum



(Adapted from Hunsucker, ’91)

Physical parameters at each height:

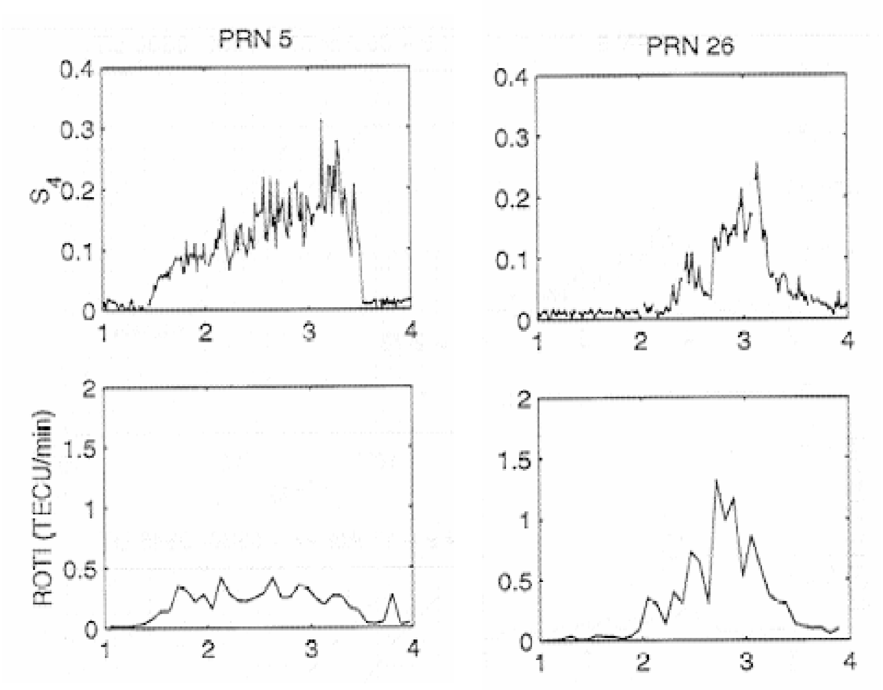
- Total power→ N_e
- Peak/center spectrum→ T_e / T_i
- width of spectrum → T_i / m_i



Data base at MADRIGAL site (http://madrigal.haystack.mit.edu/madrigal/)

6. Ionospheric Effects on Technological Systems

Example #1 : GPS signal *Amplitude* and *Phase Scintillations*
impact radio communications



amplitude

phase

(from Beach and Kintner, RS'99)

Cause: *small-scale* ionospheric irregularities $\Delta N_e / \langle N_e \rangle$ along raypath
cause diffraction patterns (scale sizes from cm to 10's km)

Effect: "Loss of Lock" for signal by receiver. Inability to use
GPS reliably for continuous position determinations

Example # 2 : Group Delay and Ranging Errors

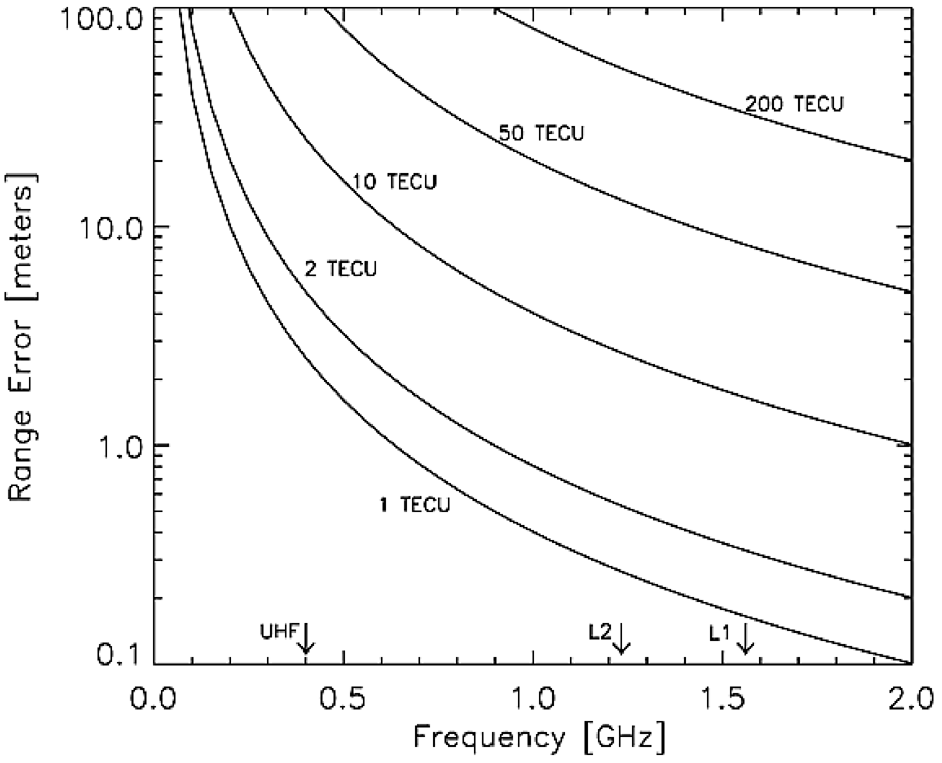
- In vacuum, R = c x t (Range = speed of light x time)
- For trans-ionospheric radio path , v < c. So R' = v x t

$\Delta R = R - R' \rightarrow$ "Ranging Error". ΔR thus depends on N_e along path $\rightarrow$ TEC (and χ)

$$\Delta R = 0.403 \text{ TEC}/f^2$$

where TEC is in TECU (10^{16} el m^{-2}), f is in GHz, and ΔR is in meters.

TEC can vary between ~ 2 to 200 TECU depending on LT, LAT, season and solar cycle



Solutions:

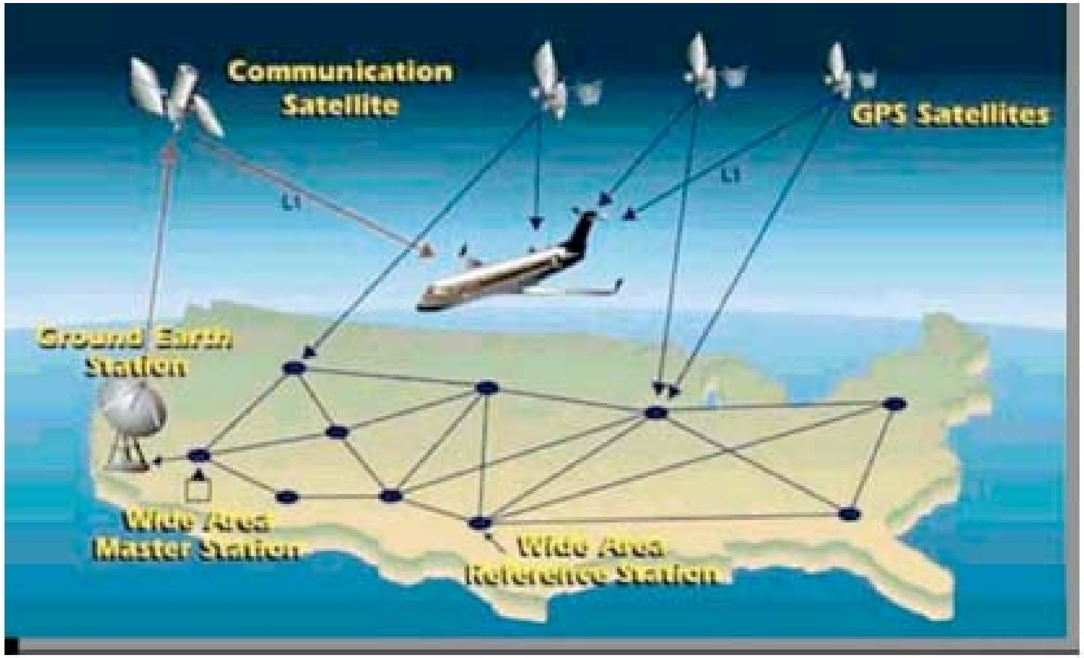
(a) TEC everywhere in real time from GPS receiver networks

(b) TEC from models → data assimilation models

Major concern: ΔTEC during storms with strong spatial gradients in TEC

→ Positive Phase

→ Negative Phase



“ How far down is the runway?”… “Look out the window !”