Space Weather ~~Introductory~~ Course
Brussels, Belgium

SWIC

Radio communications & Ionosphere

A. Martínez Picar, C. Marqué, J. Magdalenić, and E. Tassan-Din

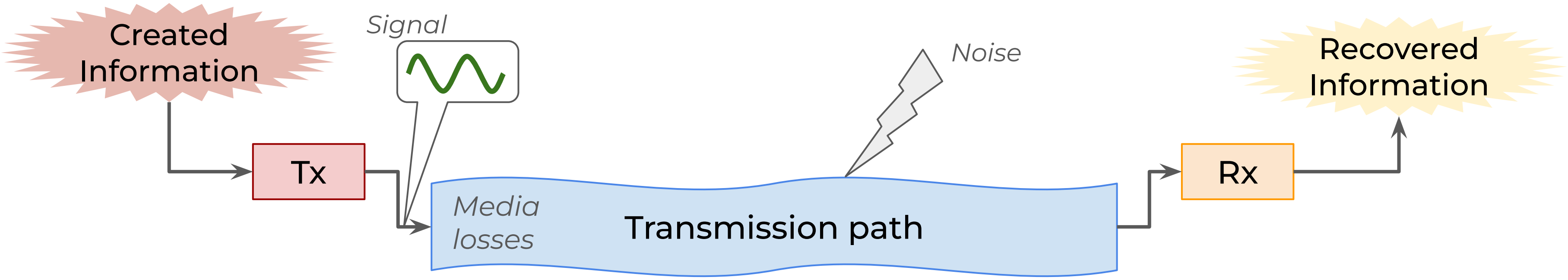
Solar-Terrestrial Centre of Excellence

Solar Influences Data analysis Center

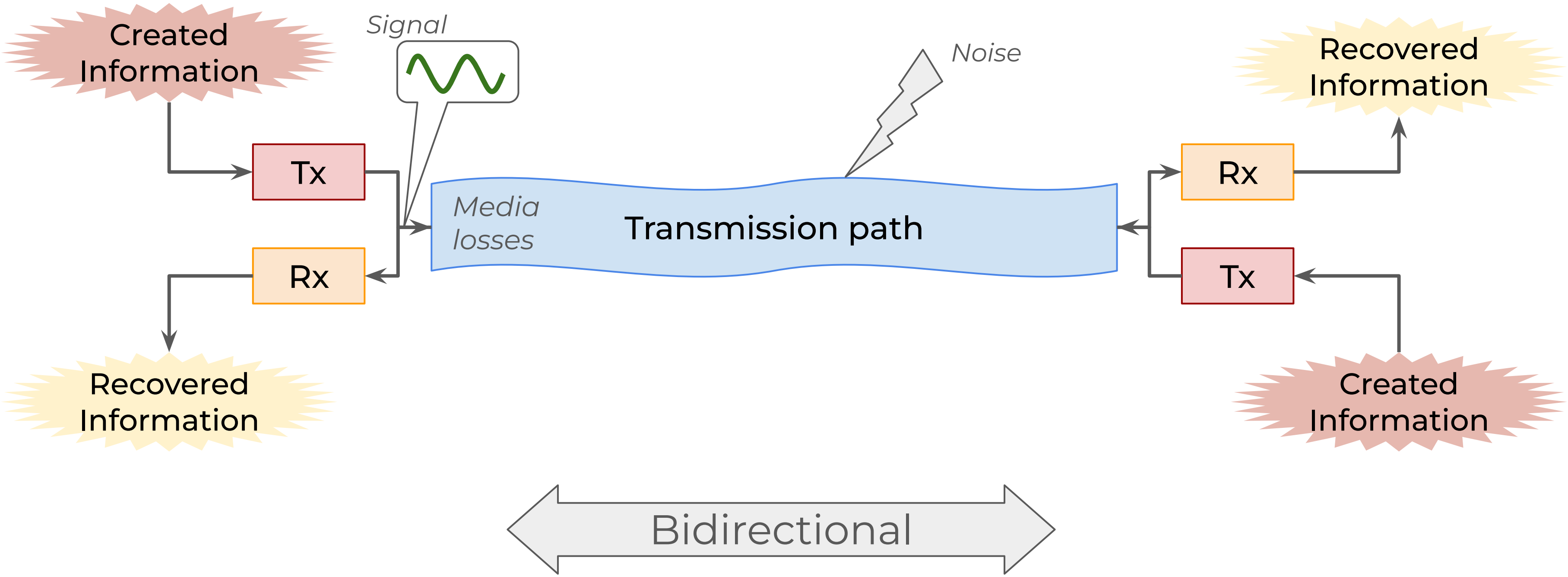
Royal Observatory of Belgium

Belgian Science Policy Office
belspo

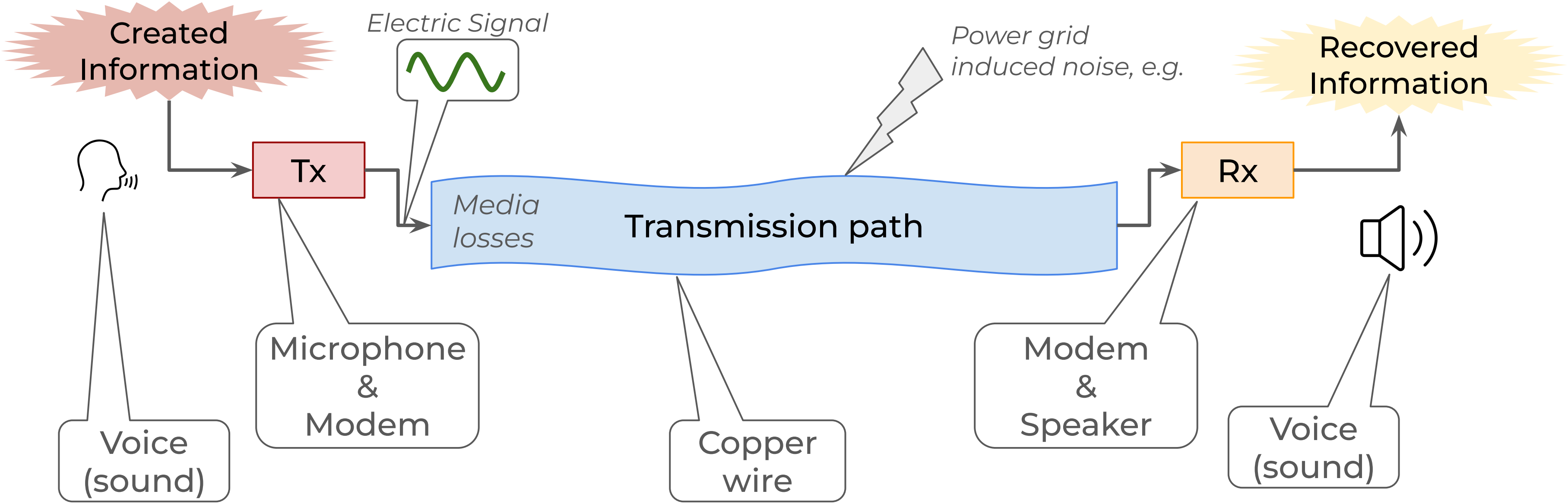
Telecommunication systems



Telecommunication systems

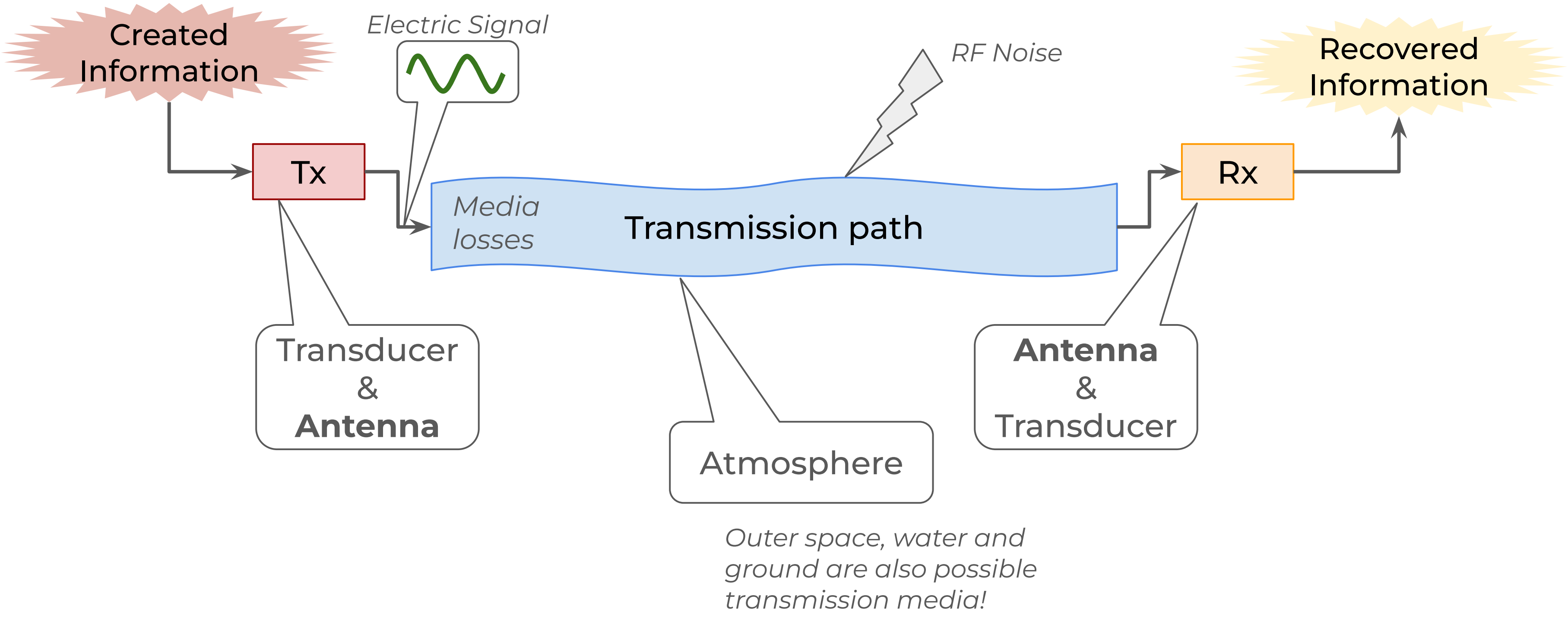


Telecommunication systems



Basic telephone system

Radio telecommunication systems

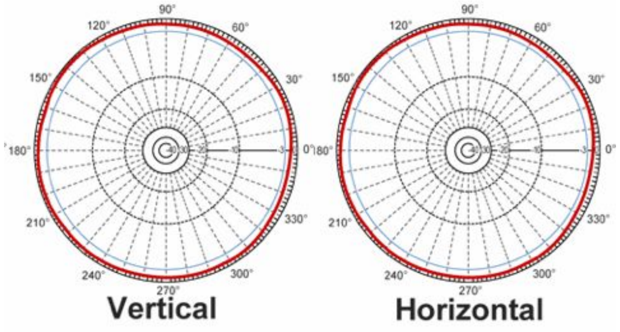


Royal Observatory of Belgium

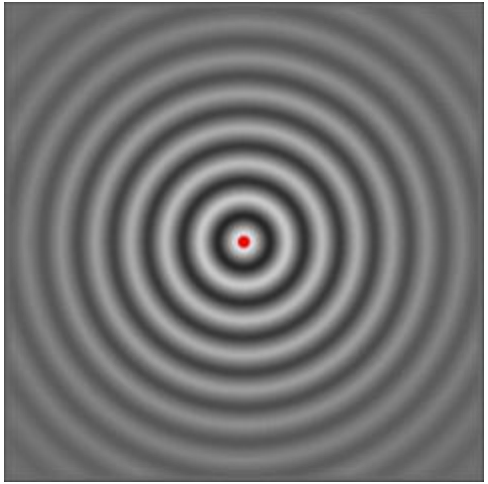
Antennas

Isotropic antenna: <u>theoretical</u> antenna that radiates equally in all directions with the same intensity

Has a "gain" of 1 (0 dB) in the spherical space all around it and has an efficiency of 100%



Antenna Pattern of an Isotropic Antenna



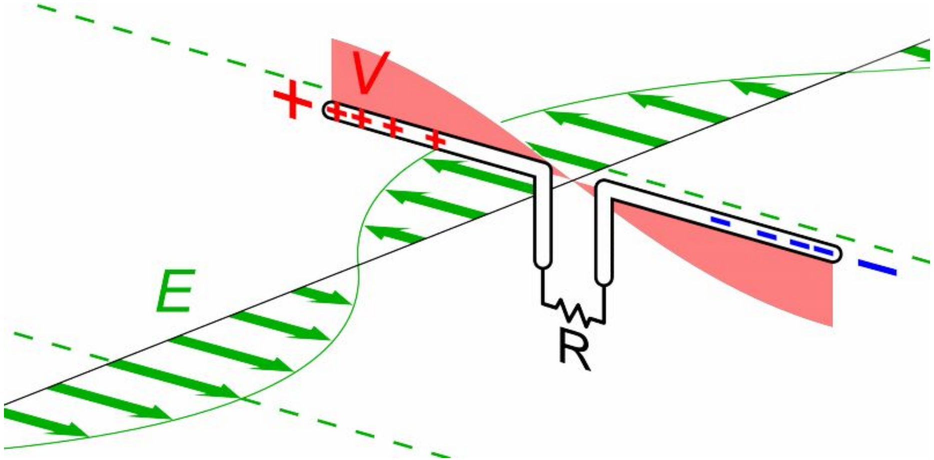
Animated diagram of waves from an isotropic radiator

An isotropic antenna is used as a reference to evaluate antenna "gain"

Antennas

Specialized transducers that converts electric current into electromagnetic waves or vice versa

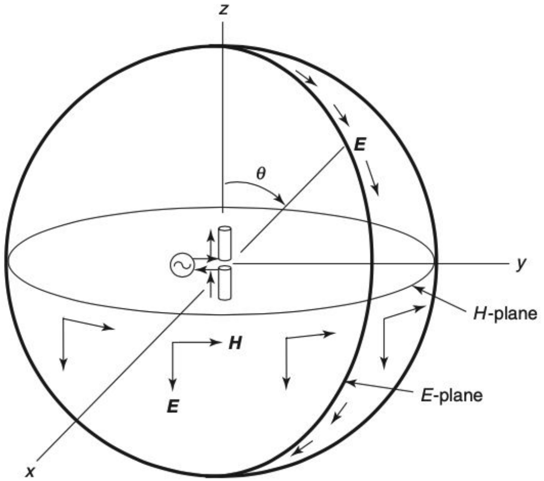
Reciprocity principle
(Tx ⇌ Rx)



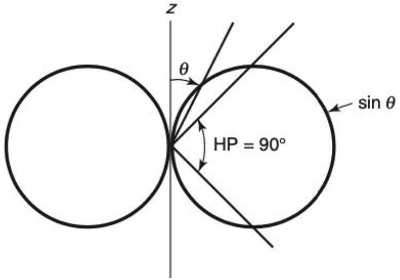
Half-wave dipole antenna receiving a radio wave

- Geometry (3D) plays an important role
- Dimension is linked to λ

Antennas
Idealized dipole

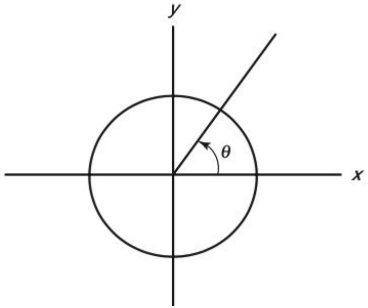


Field components

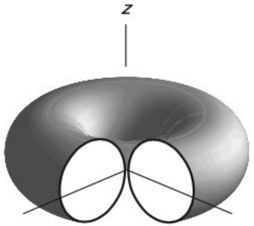


E-plane radiation pattern

- Geometry (3D) plays an important role
- Dimension is linked to λ

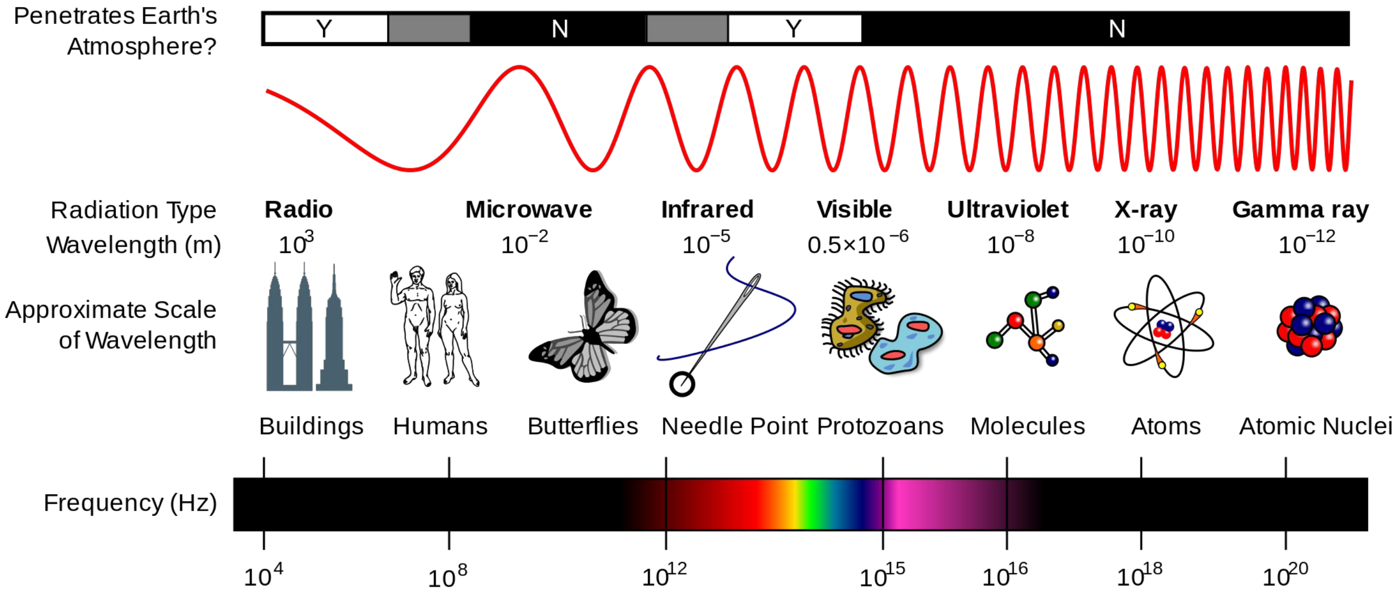


H-plane radiation pattern



3D pattern plot

Electromagnetic spectrum



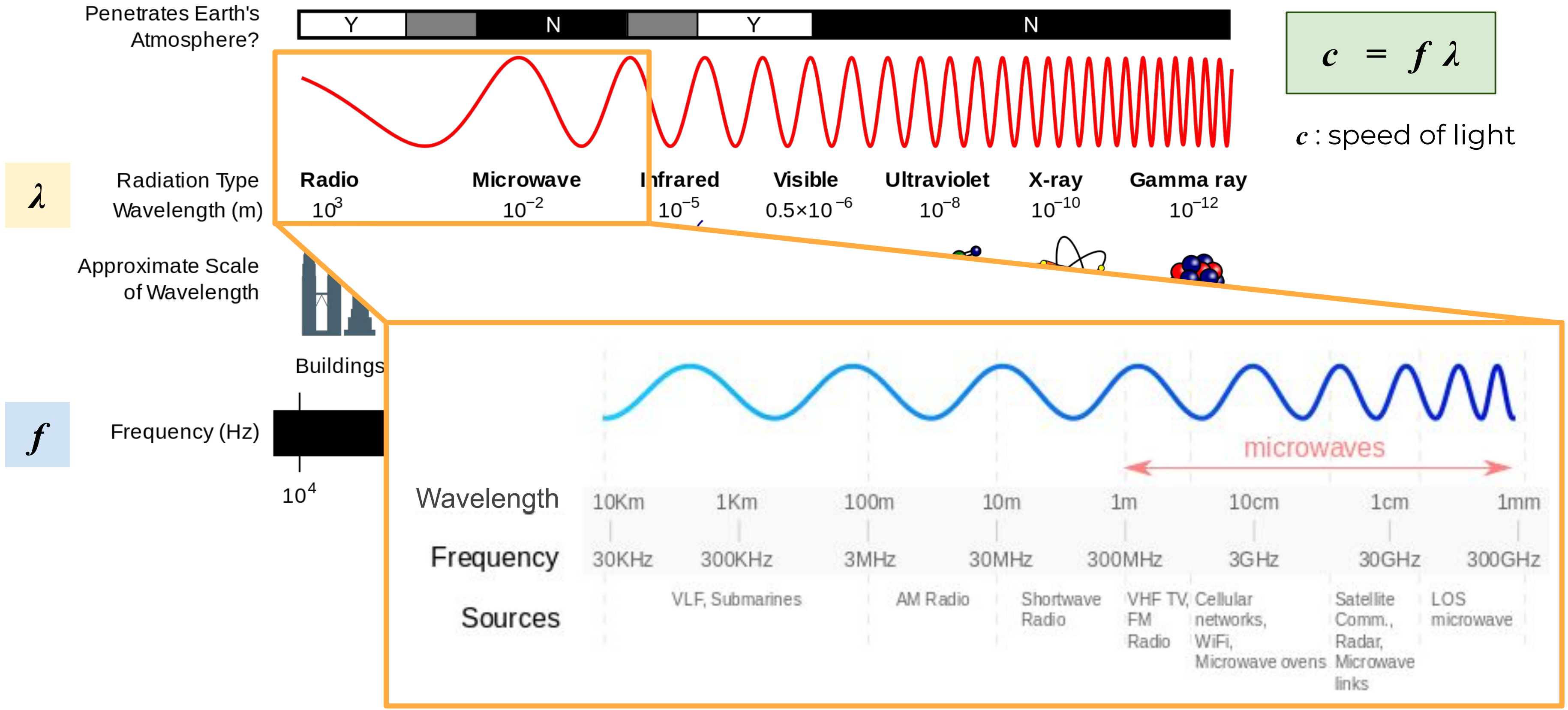
λ

f

$$c = f\,\lambda$$

c : speed of light

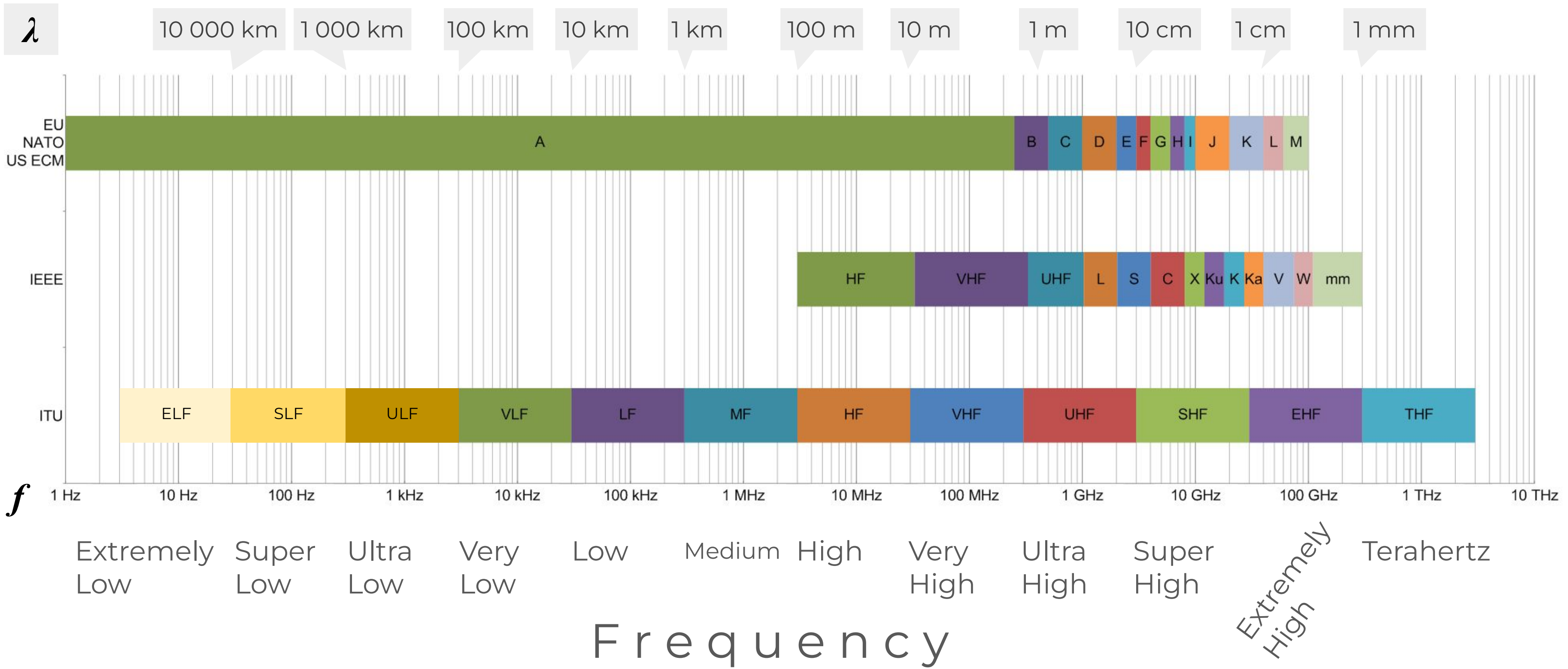
Electromagnetic spectrum



$$c = f\,\lambda$$

c : speed of light

Radio bands



λ
10 000 km
1 000 km
100 km
10 km
1 km
100 m
10 m
1 m
10 cm
1 cm
1 mm
EU
NATO
US ECM
A
B
C
D
E
F
G
H
I
J
K
L
M
IEEE
HF
VHF
UHF
L
S
C
X
Ku
K
Ka
V
W
mm
ITU
ELF
SLF
ULF
VLF
LF
MF
HF
VHF
UHF
SHF
EHF
THF
f
1 Hz
10 Hz
100 Hz
1 kHz
10 kHz
100 kHz
1 MHz
10 MHz
100 MHz
1 GHz
10 GHz
100 GHz
1 THz
10 THz
Extremely Low
Super Low
Ultra Low
Very Low
Low
Medium
High
Very High
Ultra High
Super High
Extremely High
Terahertz
Frequency

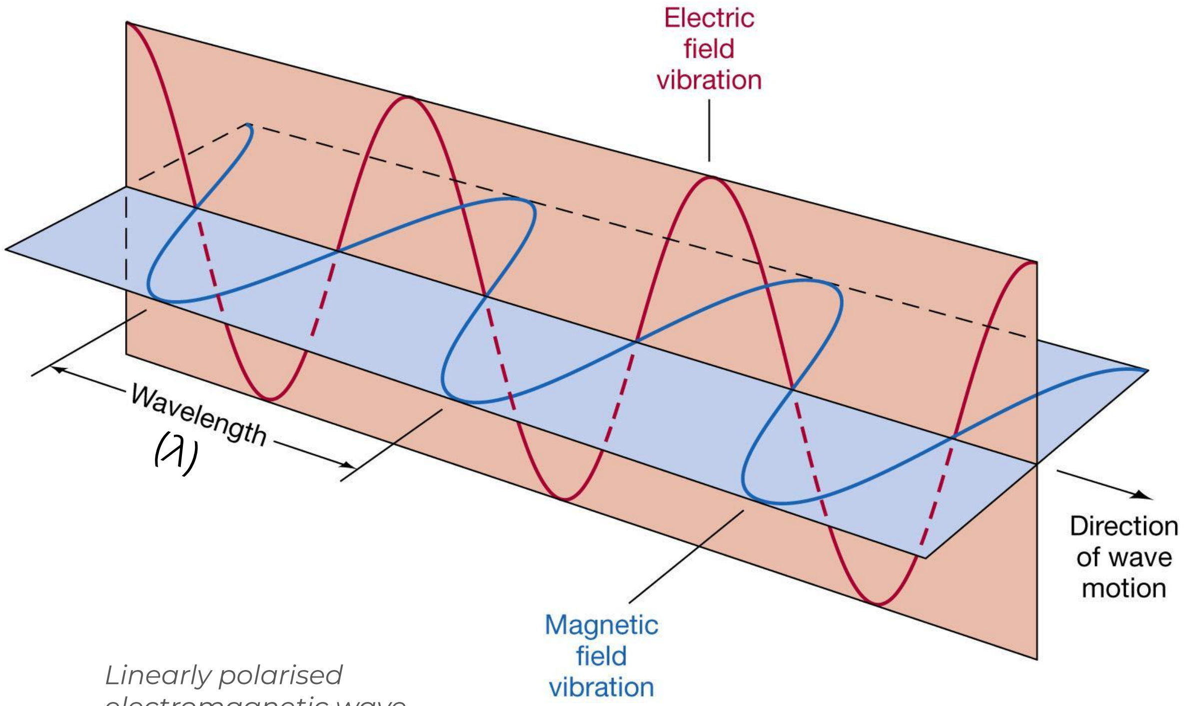
Primary modes of Propagation

Royal Observatory of Belgium

ITU Designation	Frequency Range	Principal Propagation Mode	Principal Uses
Extra low frequency (ELF)	30–300 Hz	Ground wave and Earth–ionosphere waveguide mode	Submarine communication
Very low frequency (VLF)	3–30 kHz	Same as above	Navigation, standard-frequency and -time dissemination
Low frequency (LF)	30–300 kHz	Same as above	Navigation LORAN-C
Medium frequency (MF)	300–3000 kHz	Primarily ground wave, but sky wave at night	AM broadcasting, maritime, aeronautical communication
High frequency (HF)	3–30 MHz	Primarily sky wave, some ground wave	Shortwave broadcasting, amateur, fixed services
Very high frequency (VHF)	30–300 MHz	Primarily LoS, some sky wave at lower VHF	FM broadcasting, television, aeronautical communication
Ultrahigh frequency (UHF)	300–3000 MHz	Primarily LoS, some refraction and scattering by the ionosphere	Television, radar, navigation, aeronautical communication
Superhigh frequency (SHF)	3–30 GHz	Same as above	Radar, space communication

Fundamentals of radio waves

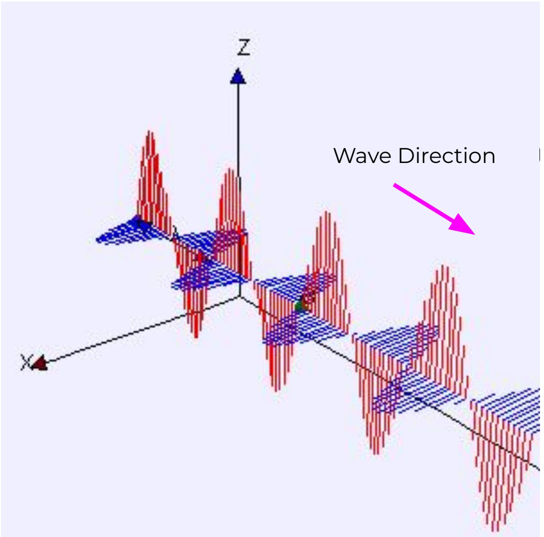
Electromagnetic wave



Linearly polarised electromagnetic wave

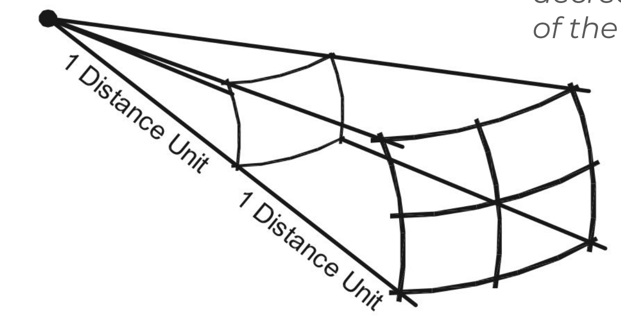
$$c = f\lambda$$

$c \cong$ 300 000 km/s
in a vacuum



Fundamentals of radio waves

Free Space Attenuation & Absorption



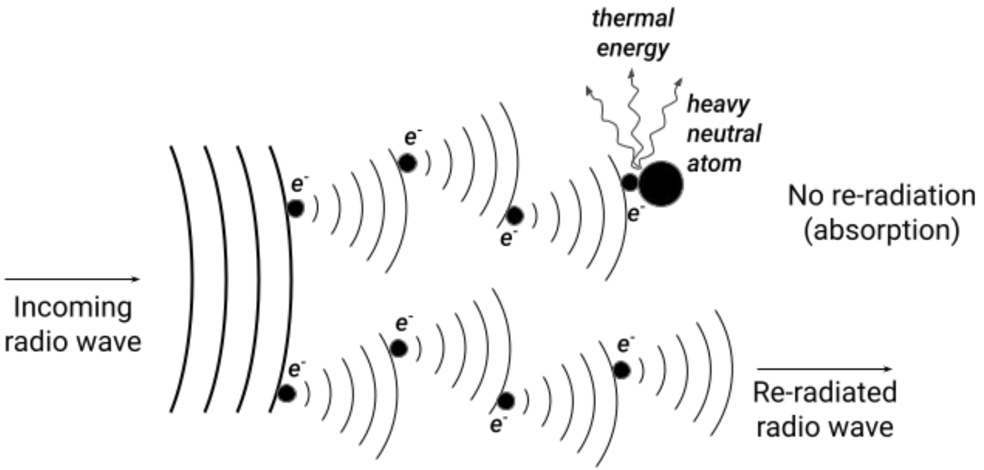
The signal's power density decreases with the square of the distance

$$L_{fs} = 32.45 + 20 \log d + 20 \log f$$

L_{fs} : Free space path loss [dB]

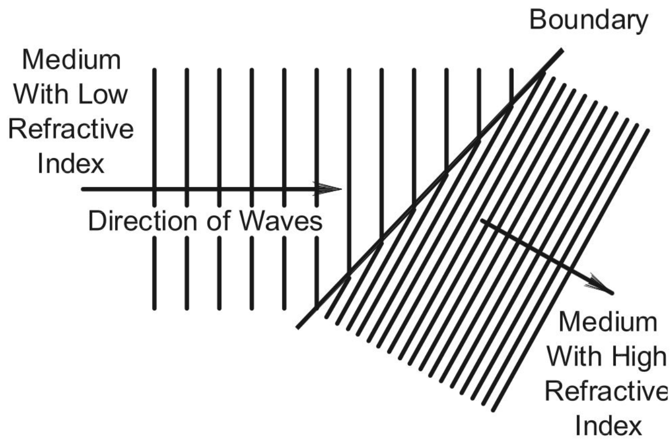
d : distance [km]

f : frequency [MHz]



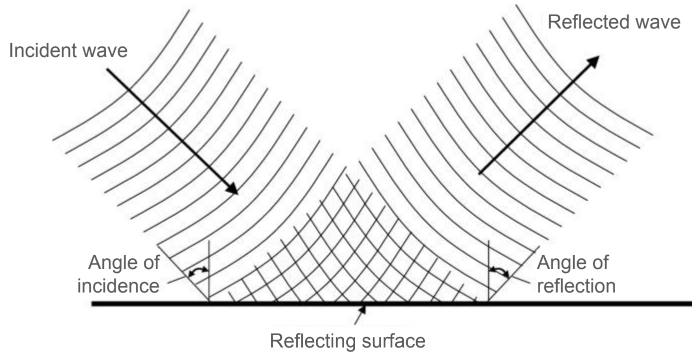
Electromagnetic wave propagation

Refraction, Reflection & (Diffuse) Scattering



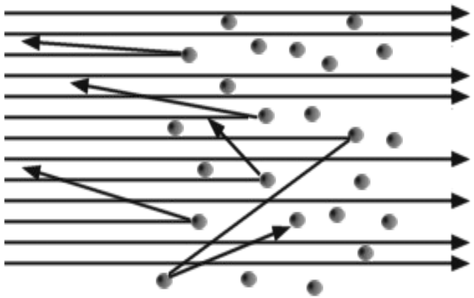
Radio waves bend at boundaries between media, as one part of the wave slows before the other

***Flat surface**: reflection angle = incidence angle*



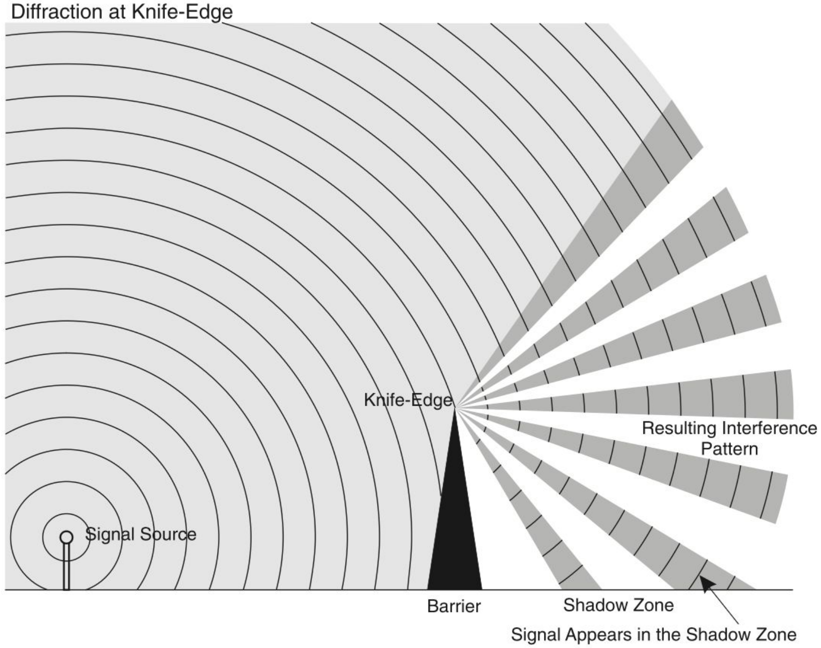
***Small particles**:*

waves scatter in all directions

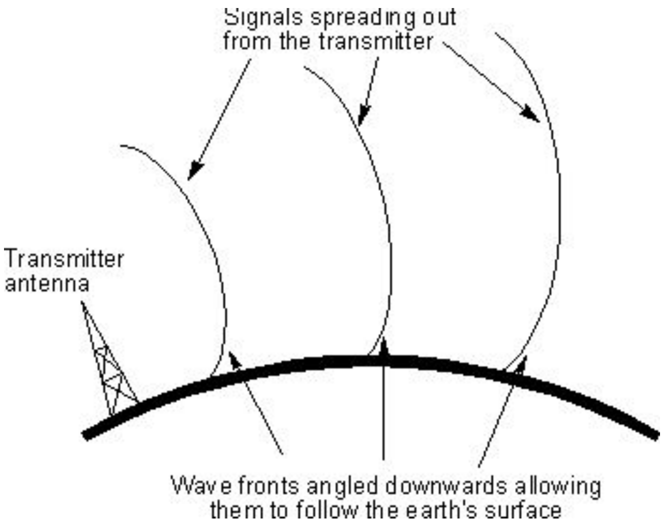


Electromagnetic wave propagation

Knife-edge Diffraction & Ground Wave



In free space, signals interfere uniformly, forming an expanding wave. A knife-edge obstacle disrupts this, creating a non-uniform pattern



Radio waves also "bend" over rounded edges. Over Earth's curved surface, the lower wave front slows, tilting the wave and allowing signals to travel beyond the horizon

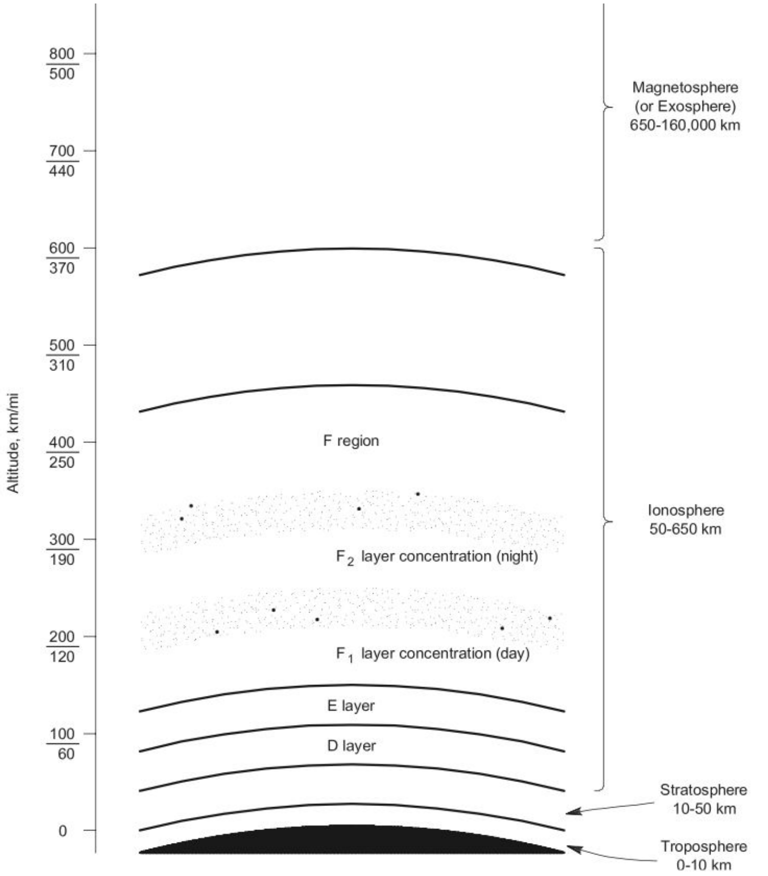
Royal Observatory of Belgium

Royal Observatory of Belgium

Sky-Wave Propagation and the Sun

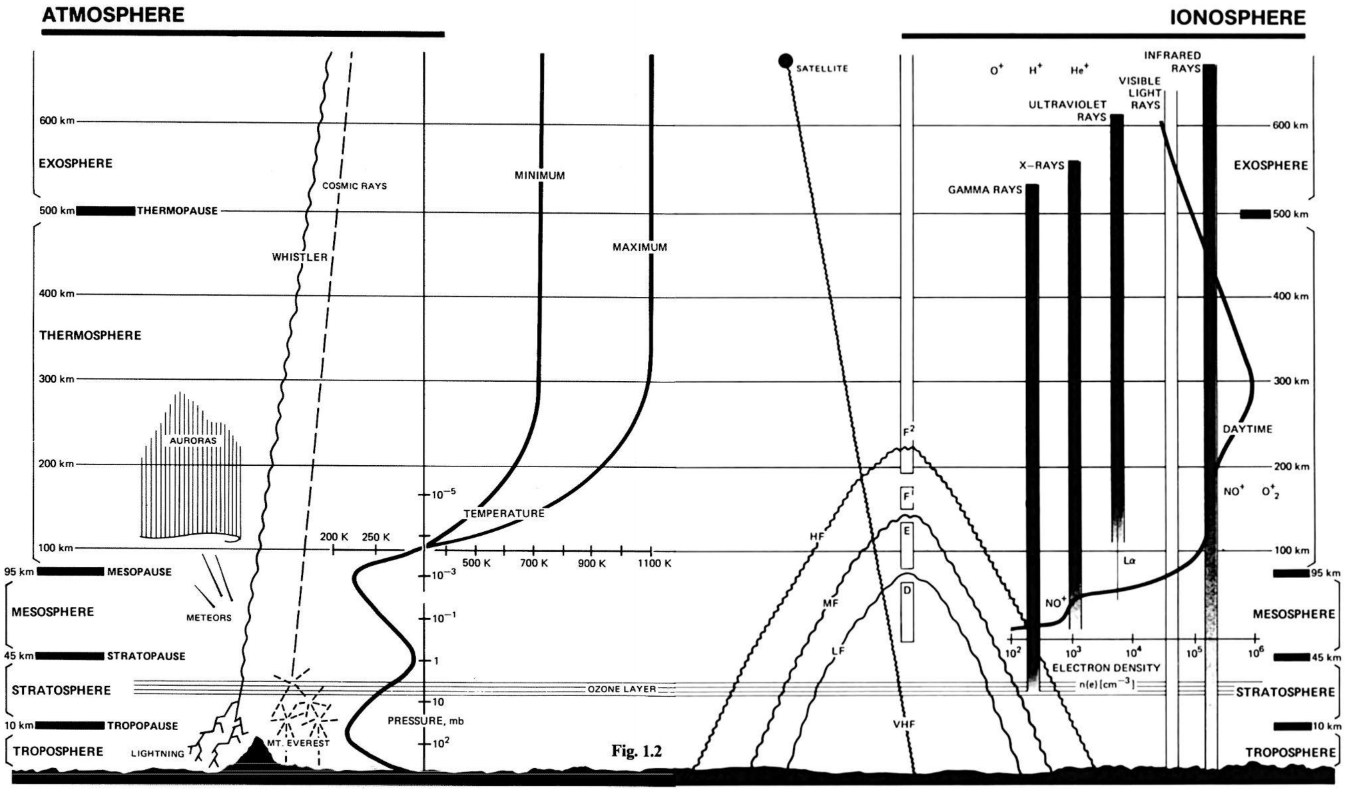
Structure of the Earth's Atmosphere

- Atmosphere reaches more than 600 km altitude
- Solar radiation affects all atmospheric layers
- Surface heating drives weather (**troposphere**)
- Solar ultraviolet (UV) radiation creates small concentrations of ozone (O_3) molecules at **stratosphere**
- Extreme UV (EUV) and X-ray radiation partially ionize atmospheric gases
- High altitudes: long-lasting ionization
- Low altitudes: fast recombination
- Continuous radiation sustain ionization



Sky-Wave Propagation and the Sun

The Ionosphere



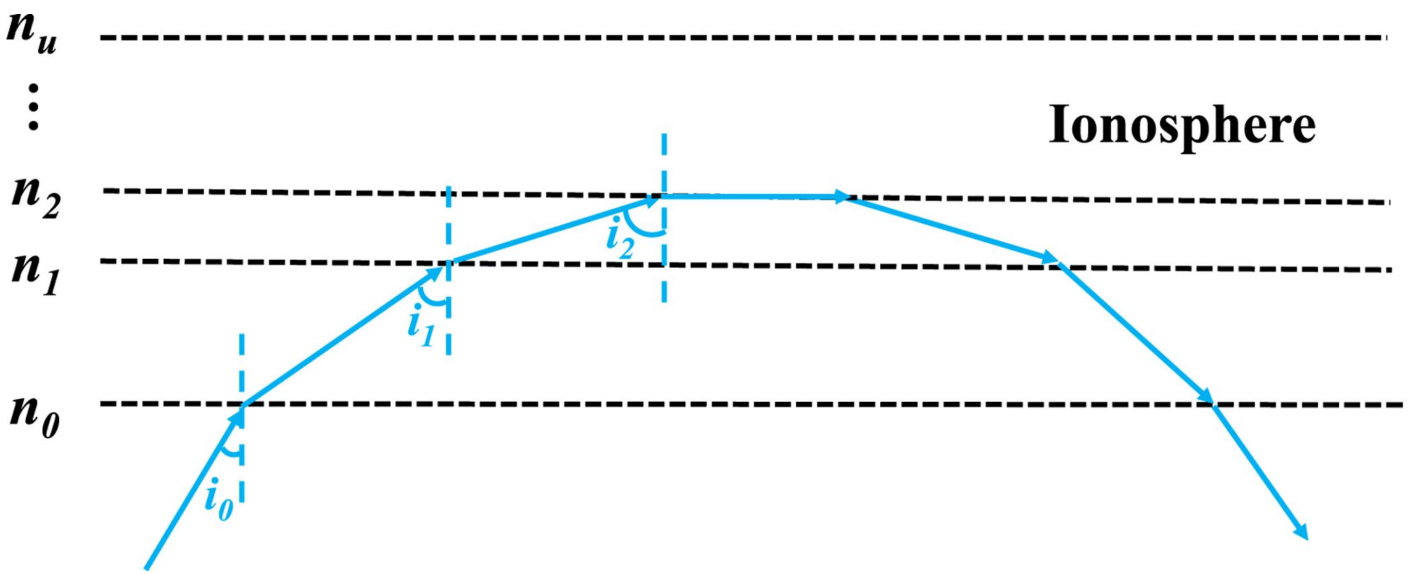
Source: Hunsucker, Radio Techniques for Probing the Terrestrial Ionosphere

- The ionosphere extends from ~50–600 km and strongly affects radio propagation
- It consists mainly of atomic/molecular oxygen, nitrogen, and nitric oxide at very low pressure
- Solar EUV and X-rays ionize these gases, forming a region rich in ions
- Is is divided into the **D**, **E** and **F** layers
- Enables *long-distance communication* at 1.8–30 MHz with weaker effects up to ~ 432 MHz

Royal Observatory *of* Belgium

Sky-Wave Propagation and the Sun

Oblique Propagation



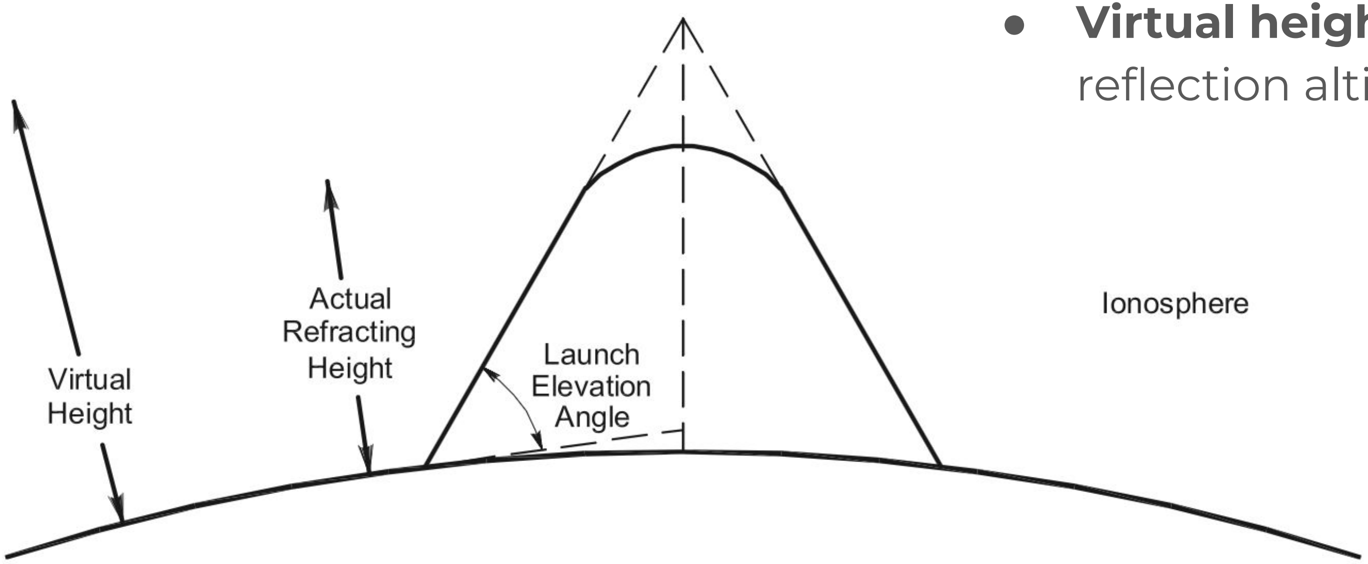
Radio waves become useful for terrestrial propagation only when they are refracted enough to bring them back to Earth

Sky-Wave Propagation and the Sun

Ionospheric Refraction

Royal Observatory *of* Belgium

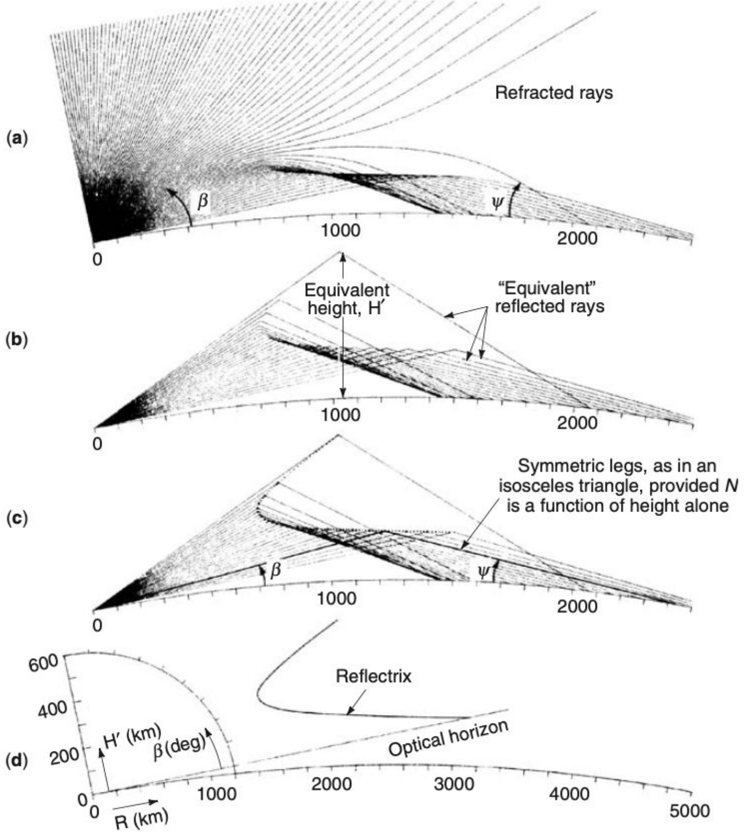
- Ionospheric *refraction* is often treated as ***reflection***
- **Virtual height** = equivalent reflection altitude



Sky-Wave Propagation and the Sun

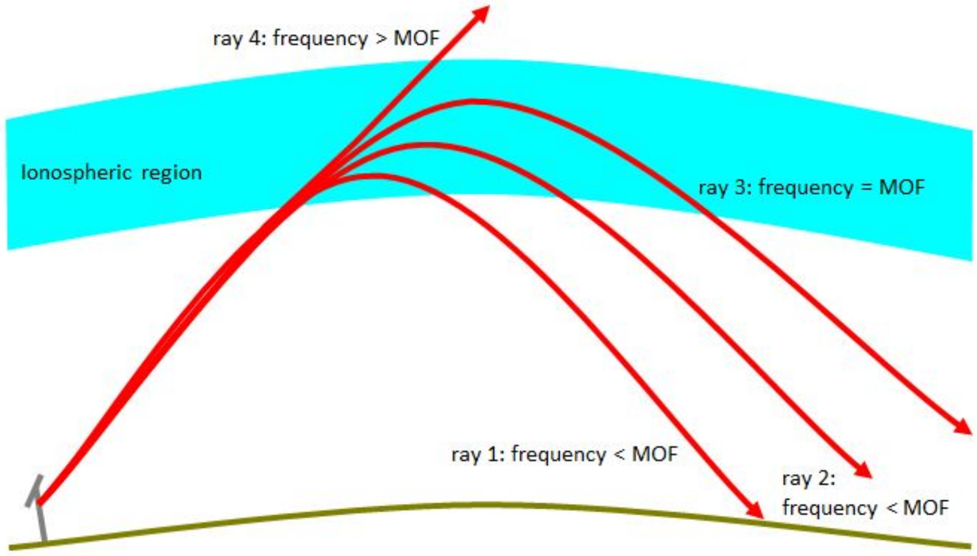
Ray Tracing

- Real ionospheric profiles require ***ray tracing*** (too complex for analytical formulas)
- Rays are traced from a transmitter by elevation and azimuth until *returning* or *escaping*
- Increasing elevation angle first reduces, then increases ground range (→ **skip zone**)
- Virtual ray paths form triangles with apexes on a **reflectrix** curve
- The *reflectrix* links virtual height and elevation angle



Sky-Wave Propagation and the Sun

Frequency, range and elevation angle

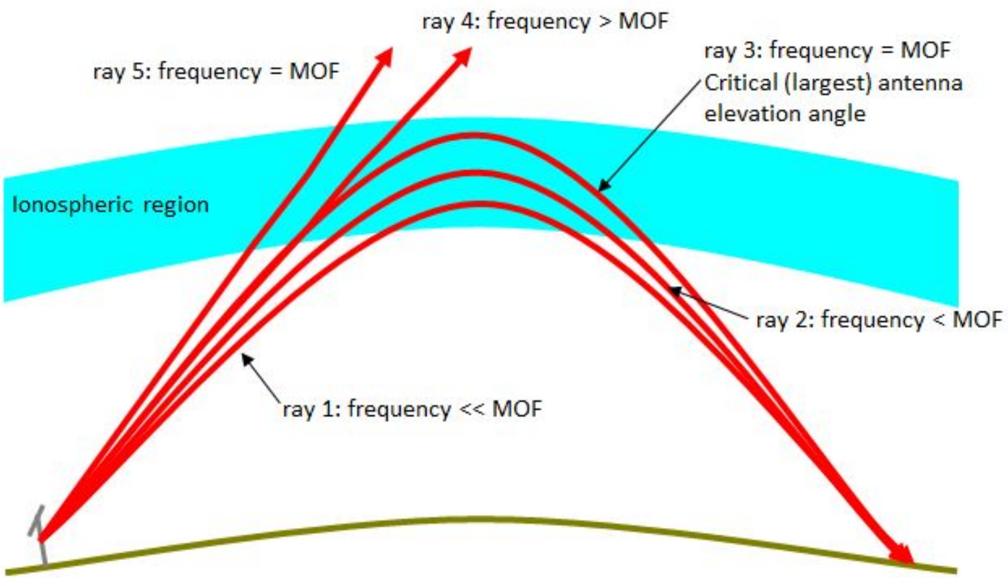


Elevation angle fixed, variable frequency (f):

- As f is increased, the wave is reflected higher in the ionosphere and the range increases (rays 1 and 2)
- Exactly at f = MUF maximum range is achieved (ray 3)
- If f > MUF, the wave penetrates the ionosphere

Sky-Wave Propagation and the Sun

Frequency, range and elevation angle

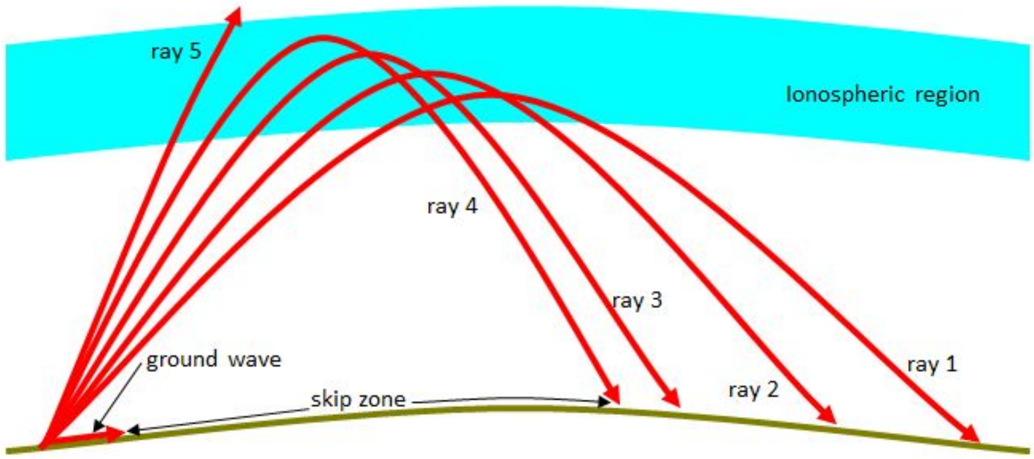


Path length fixed:

- As f is increased, the wave is reflected higher in the ionosphere ⇒ the elevation angle must increase (rays 1 & 2)
- At f = MUF, critical angle is reached (ray 3)
- If f > MUF, the wave penetrates the ionosphere

Sky-Wave Propagation and the Sun

Frequency, range and elevation angle



Frequency fixed, variable elevation angle:

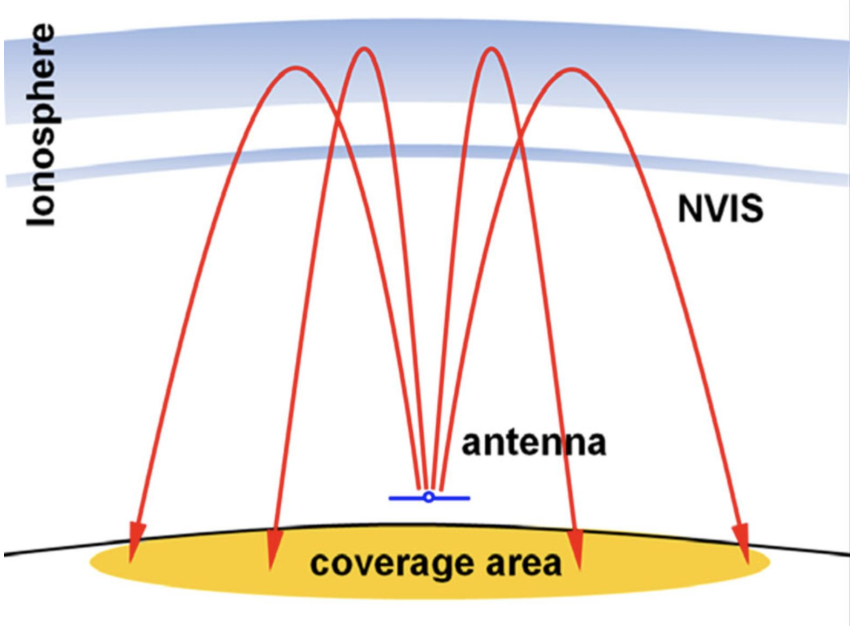
- At low elevation angles the range is greatest (ray 1)
- As elevation angle is increased, the range decreases and the ray is reflected in higher zones in the ionosphere (rays 2, 3 & 4)
- If the elevation angle is increased beyond the critical value for that frequency, then the wave penetrates the ionosphere (ray 5)

Royal Observatory *of* Belgium

Sky-Wave Propagation and the Sun

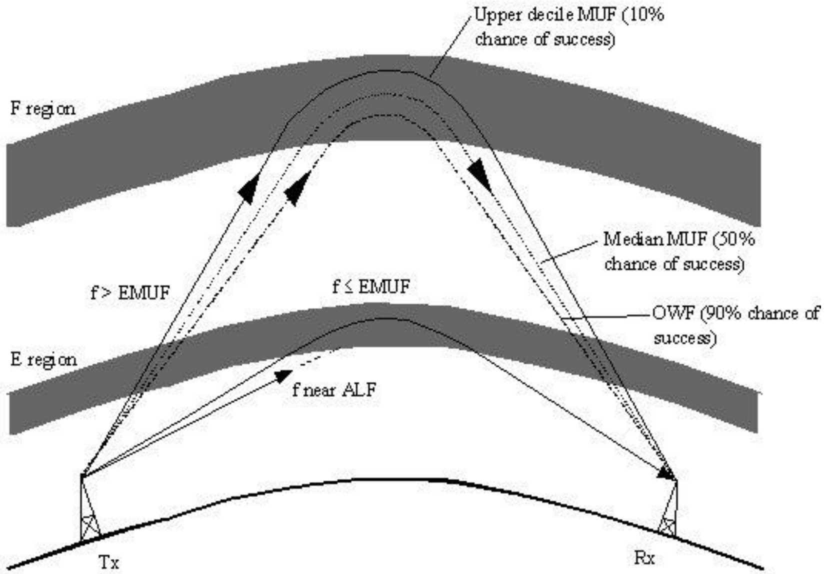
NVIS Propagation

- Radio stations within the skip zone may be able to communicate at a lower frequency, or by *ground wave* if they are close enough
- *Near Vertical Incidence Skywave* (**NVIS**) propagation usually bridge the gap between where ground wave is too weak and where the skip zone ends
- Propagation over short distances means high elevation angles



Sky-Wave Propagation and the Sun

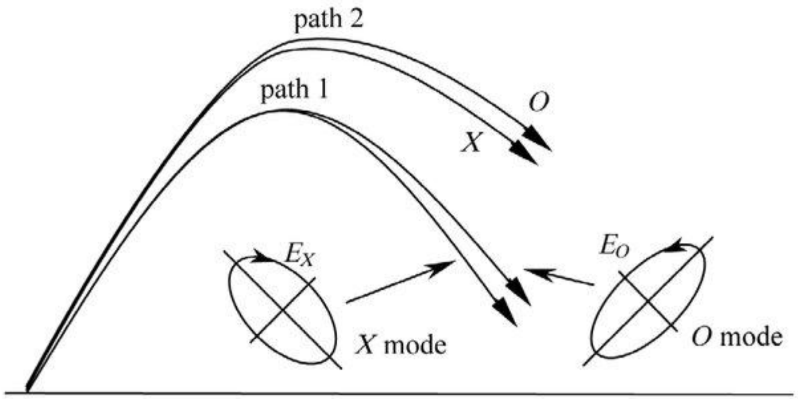
Ionospheric Fading



- Ionospheric changes cause phase shifts ↳ signal fading
- HF signal strength varies over seconds to minutes
- Fading sources include:
  - Multiple propagation paths
  - *O*– and *X*–wave interference (polarization fade)
  - Absorption changes
  - Focusing effects

Sky-Wave Propagation and the Sun

Polarization at HF

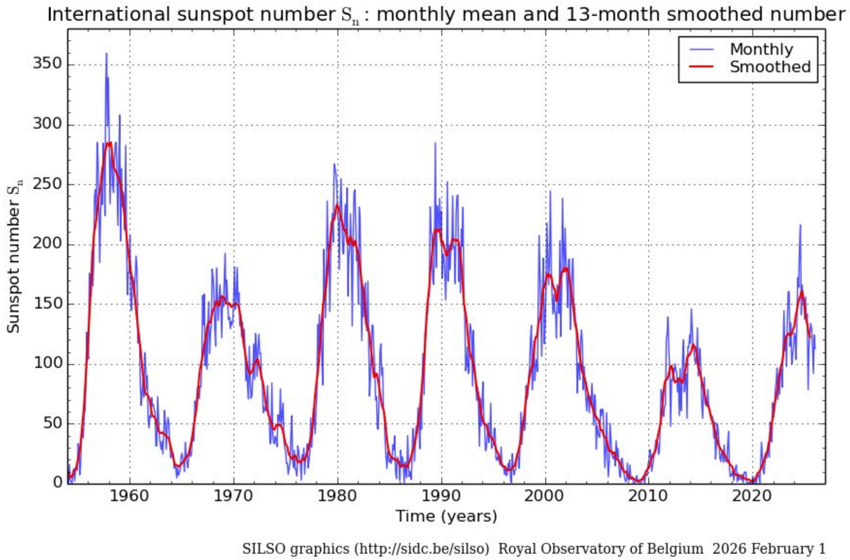


Multipath and multimode propagation in the ionosphere

- The ionosphere splits waves into *ordinary* (O) and *extraordinary* (X) modes
- O and X waves are orthogonal, counter-rotating, and elliptically polarized
- Antenna polarization controls coupling into O/X waves
- On HF ≥ 80 m, polarization choice is less critical
- On 160 m, the X-wave is strongly absorbed
- Vertical polarization usually performs best on 160 m

Sky-Wave Propagation and the Sun

The 11-year Solar Cycle – Sunspots

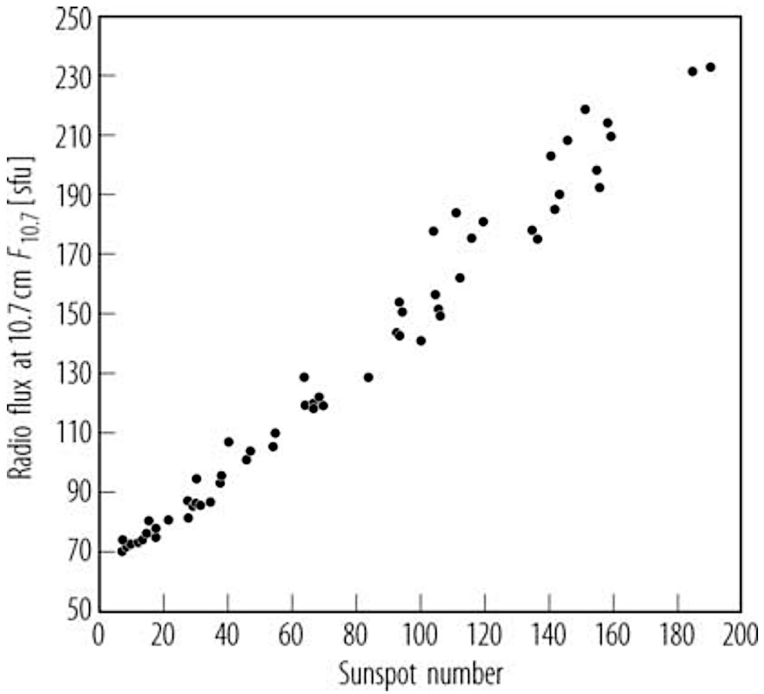


- The Sun shows periodic sunspot cycles of about 11 years
- Sunspots mark cool, magnetically active regions
- Solar maxima bring more radiation and flares
- Increased radiation strengthens ionospheric ionization
- This raises critical frequencies and improves long-distance HF propagation
- Sunspot number estimates overall solar activity

Royal Observatory *of* Belgium

Sky-Wave Propagation and the Sun

The 11-year Solar Cycle – Solar Flux

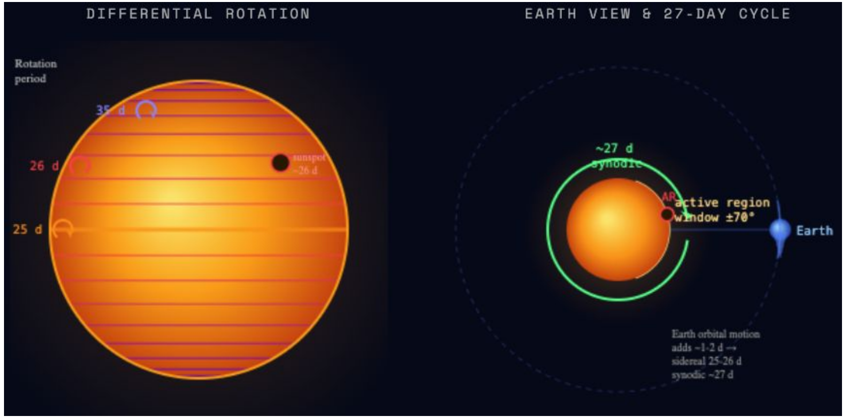


Annually averaged λ = 10.7 cm solar radio flux vs. sunspot number (1947–2009).

- Solar flux measures the Sun's 2800 MHz radio emission
- It estimates UV/X-ray activity, like sunspot numbers
- Typical values range 60–300
- Penticton solar flux is used in propagation predictions
- Higher flux usually means higher MUF
- Accurate MUF forecasts also depend on time, season, and path geometry

Sky-Wave Propagation and the Sun

The Sun's 27-Day Rotation

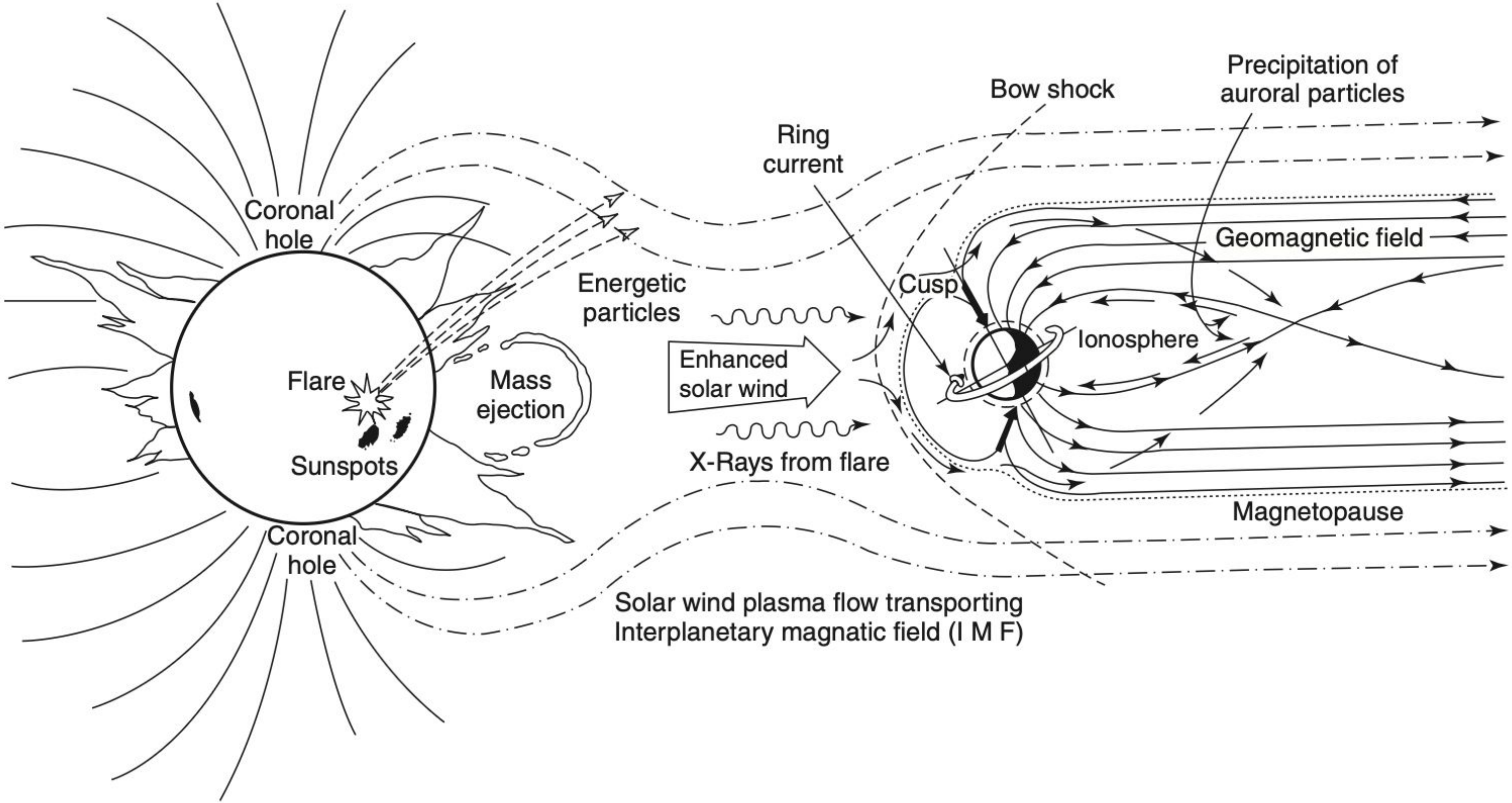


- Sun rotates unevenly (fluid body)
- Rotation ≈ 25 days at equator, ≈ 35 days at poles
- Earth-affecting sunspots rotate in ~26 days
- Apparent rotation from Earth is ~27 days
- Active regions must face Earth to affect the ionosphere
- Persistent regions create ~27-day activity cycles

Royal Observatory of Belgium

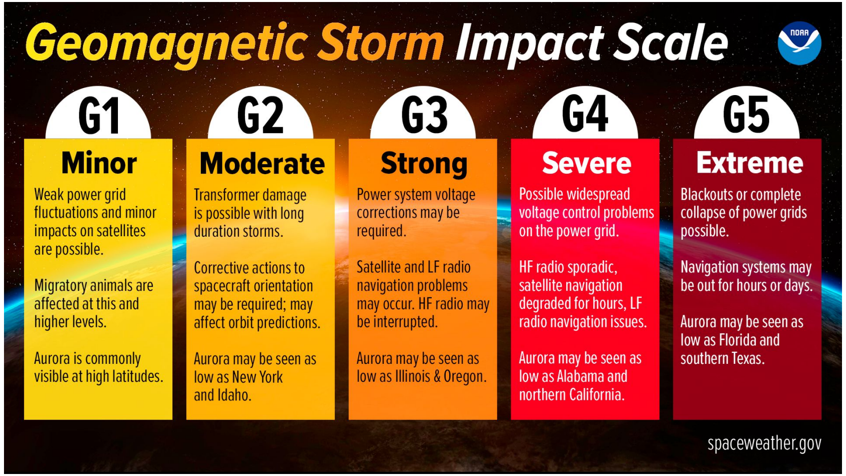
Sky-Wave Propagation and the Sun

Disturbances to Propagation



Sky-Wave Propagation and the Sun

Disturbances to Propagation – Geomagnetic Storms



- Geomagnetic storms near the equator raise LUF, lower MUF ➞ HF fadeouts
- In polar regions, storms can raise MUF ↳ unexpected VHF propagation

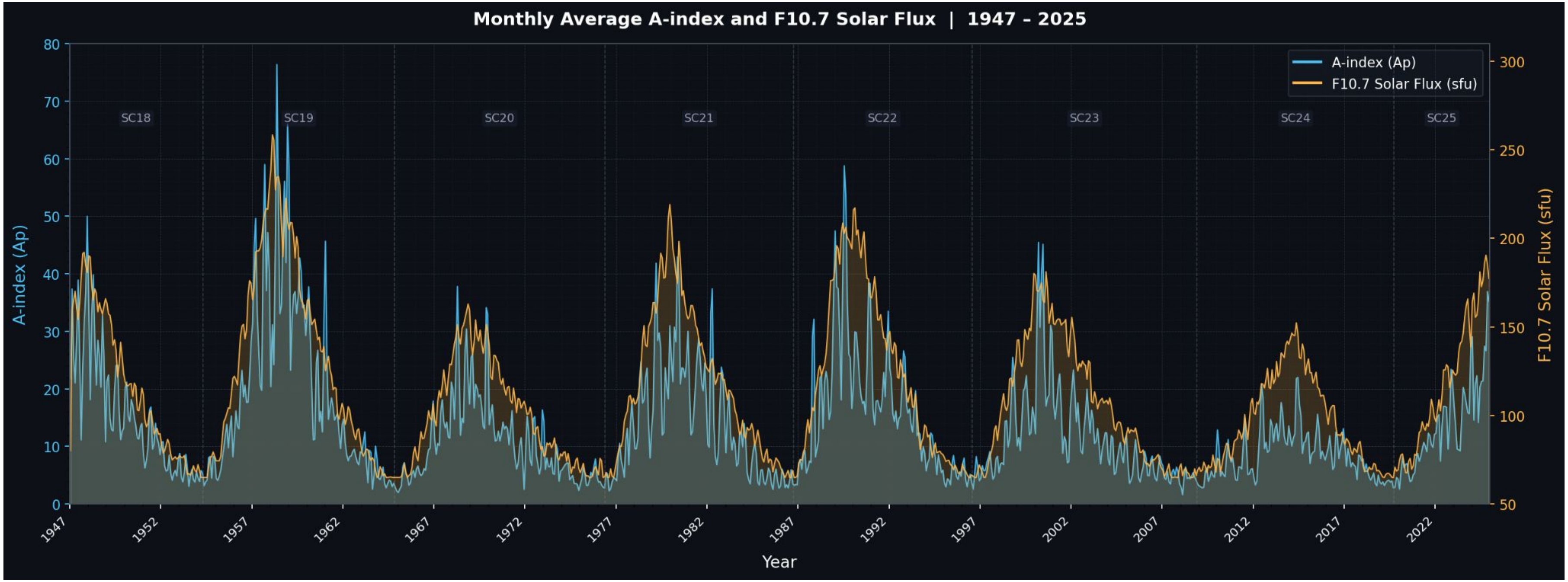
- Geomagnetic storms come from *Coronal Mass Ejections* (CMEs) and high-speed solar wind
- CMEs originate in the corona of the Sun
- Satellites observe CMEs using coronagraphs (artificial eclipses)
- Coronal holes release fast solar wind into space
- Earth-directed events cause major ionospheric disturbances
- Effects reach Earth after ~1–2 days

Royal Observatory of Belgium

Royal Observatory of Belgium

Sky-Wave Propagation and the Sun

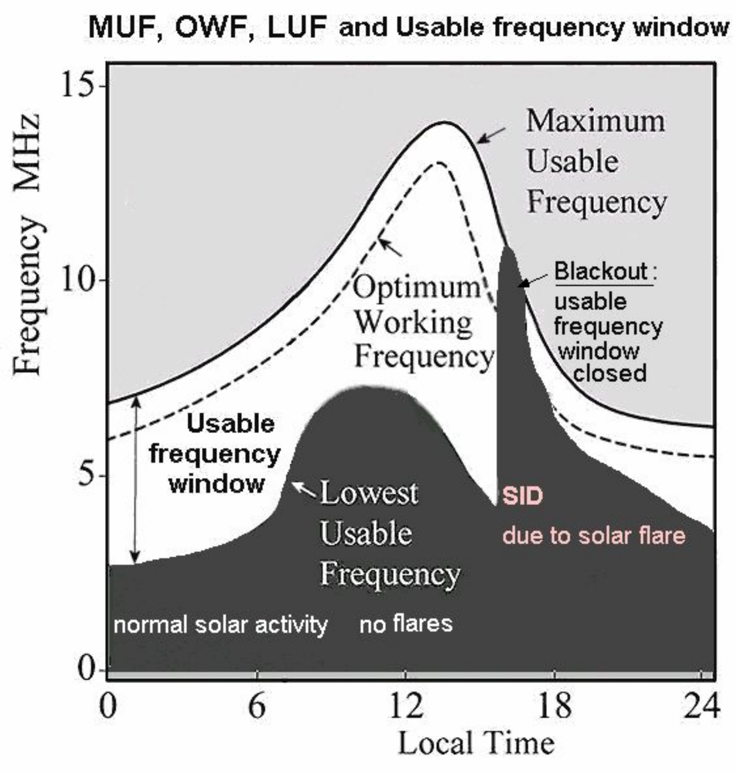
Disturbances to Propagation – Geomagnetic Storms



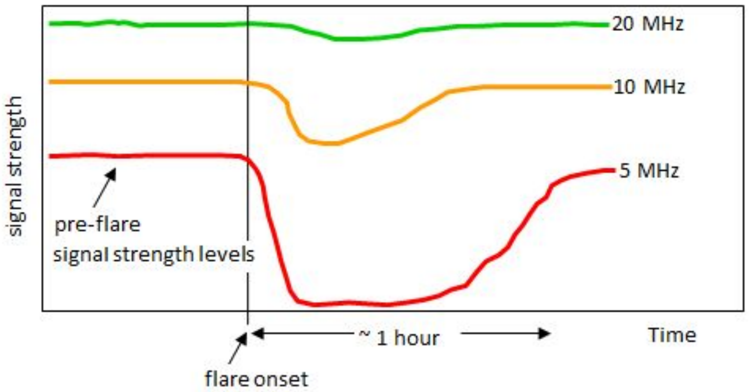
Geomagnetic storms peak near solar maxima

Sky-Wave Propagation and the Sun

Disturbances to Propagation – Radiation Storms & Radio Blackouts

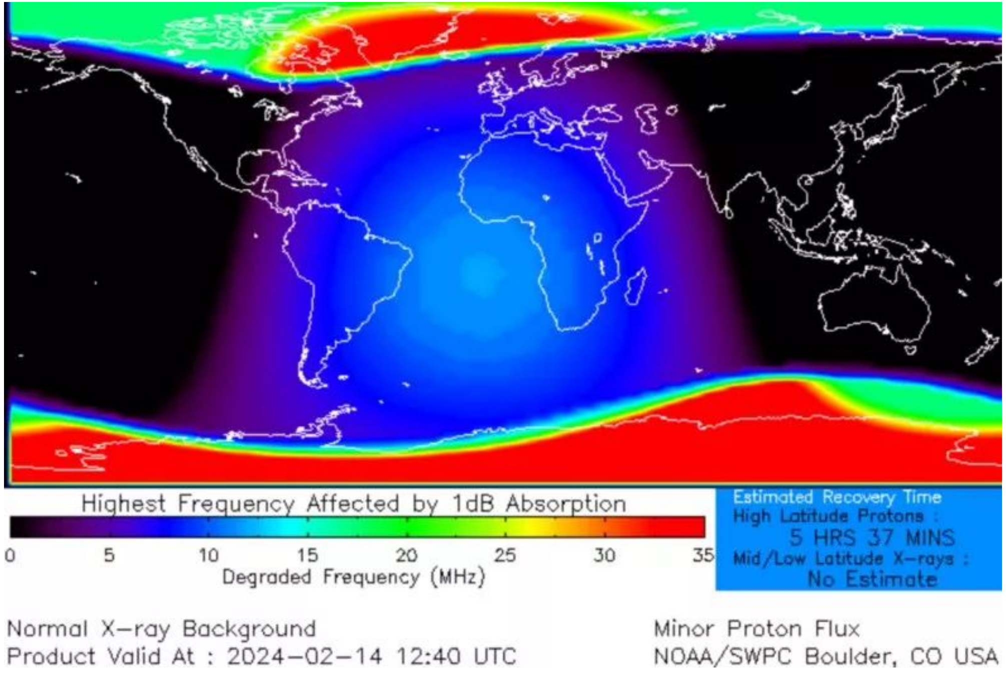


- Large solar flares on the Sun emit intense radiation
- X-rays trigger *Sudden Ionospheric Disturbances* (SID) → radio blackouts
- SIDs mainly affect lower HF and last up to ~1 hour



Sky-Wave Propagation and the Sun

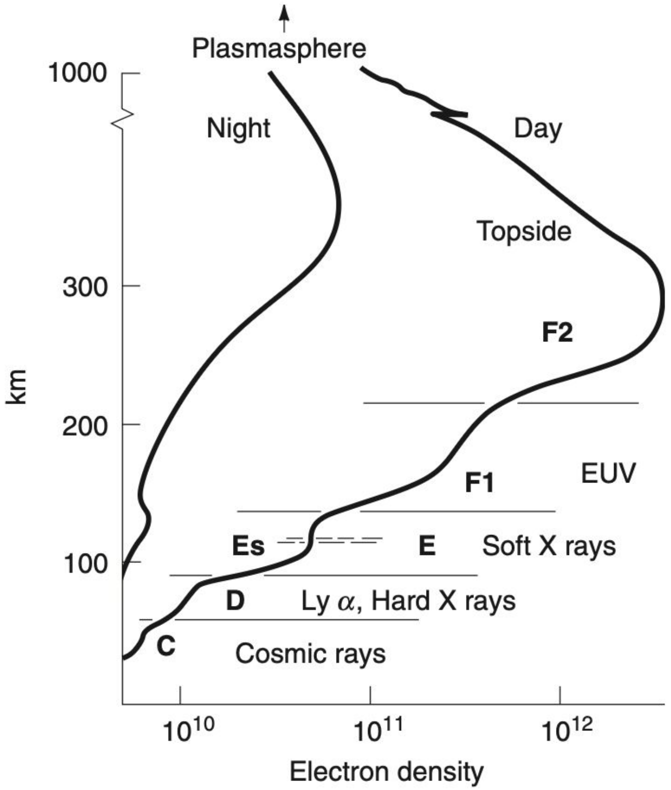
Disturbances to Propagation – Polar Cap Absorption



- Energetic protons cause *Polar Cap Absorption* (PCA) events
- PCAs disrupt polar HF propagation for days
- Solar flares and CMEs are independent

Sky-Wave Propagation and the Sun

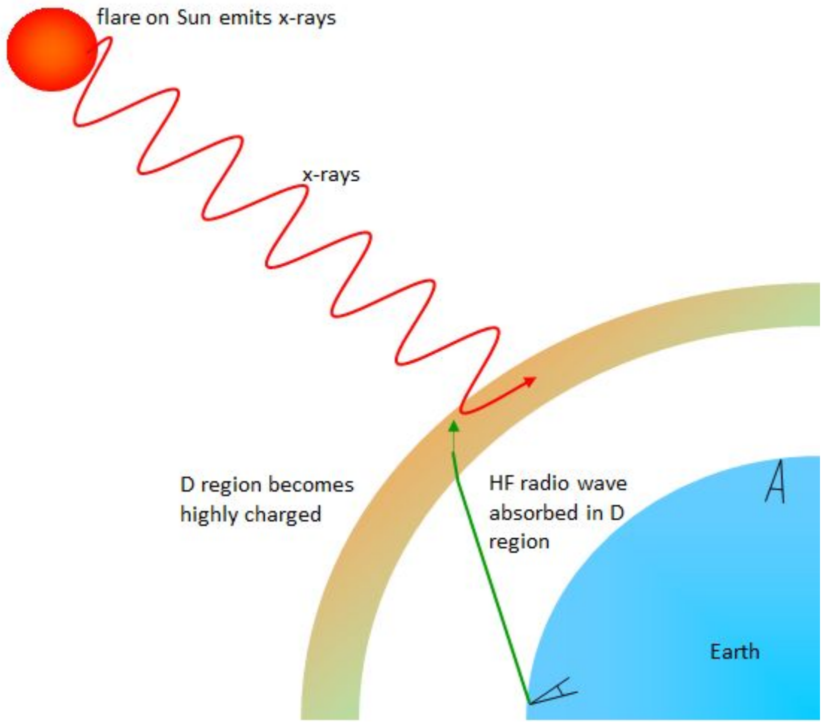
D Layer Propagation



- The D layer lies at ~55–90 km altitude
- It is ionized by UV and hard X-rays from the Sun
- It exists mainly during daylight
- The D layer absorbs MF/HF signals, not refracts them – Refraction works in VLF though
- Absorption is strongest below ~5 MHz in daytime
- At night, ionization drops and low HF bands propagate farther

Sky-Wave Propagation and the Sun

D Layer Propagation

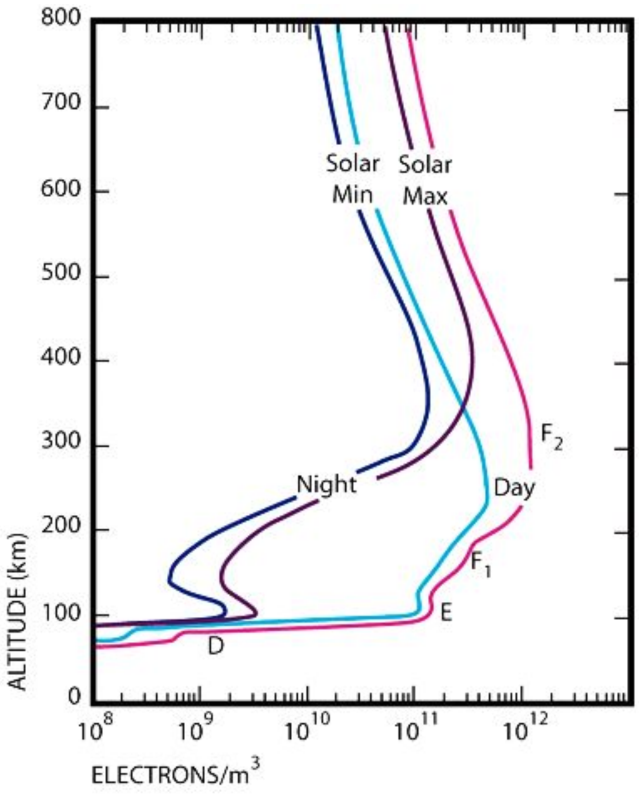


- The D layer lies at ~55–90 km altitude
- It is ionized by UV and hard X-rays from the Sun
- It exists mainly during daylight
- The D layer absorbs MF/HF signals, not refracts them – Refraction works in VLF though
- Absorption is strongest below ~5 MHz in daytime
- At night, ionization drops and low HF bands propagate farther

Sky-Wave Propagation and the Sun

E Layer Propagation

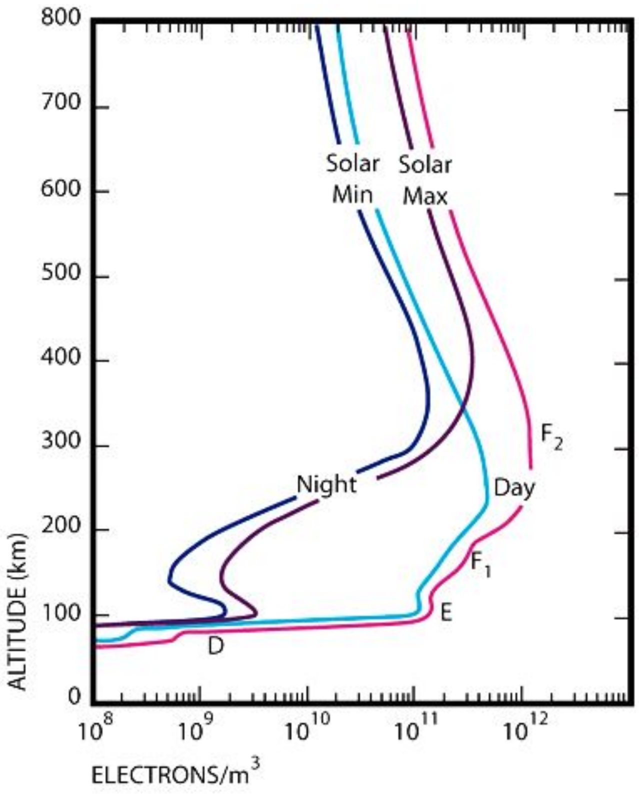
Royal Observatory *of* Belgium



- The E layer lies at ~90–150 km altitude
- Ionized by UV and soft X-rays from the Sun
- Exists mainly during daylight
- Has less absorption than the D layer
- Daytime critical frequency: ~3–4 MHz
- At night it weakens but can still refract low-band signals

Sky-Wave Propagation and the Sun

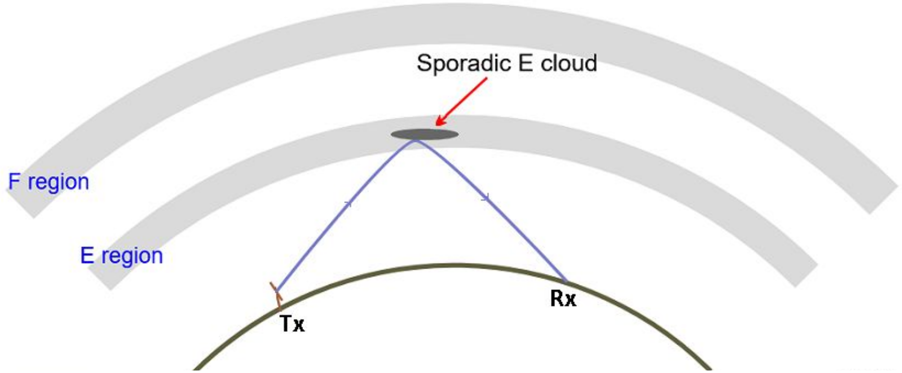
E Layer Propagation – Daytime E Layer

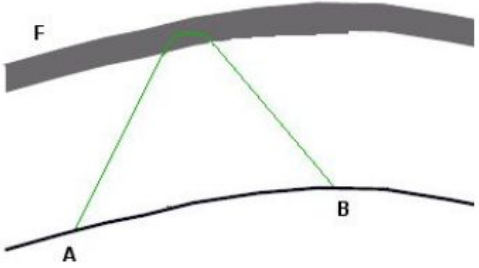


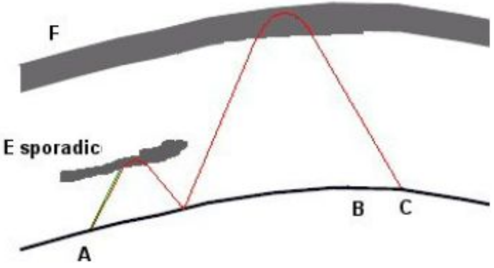
- The E layer has limited HF propagation role
- Daytime D-layer absorption restricts E-layer skip
- Low-angle 7–10 MHz signals are mostly absorbed
- High-angle E skip is limited to ~1200 km
- At 14 MHz, E and F propagation may be hard to distinguish
- Supports special modes: sporadic E, aurora, meteor scatter
- Mainly useful on upper HF and low VHF

Sky-Wave Propagation and the Sun

E Layer Propagation – Sporadic E



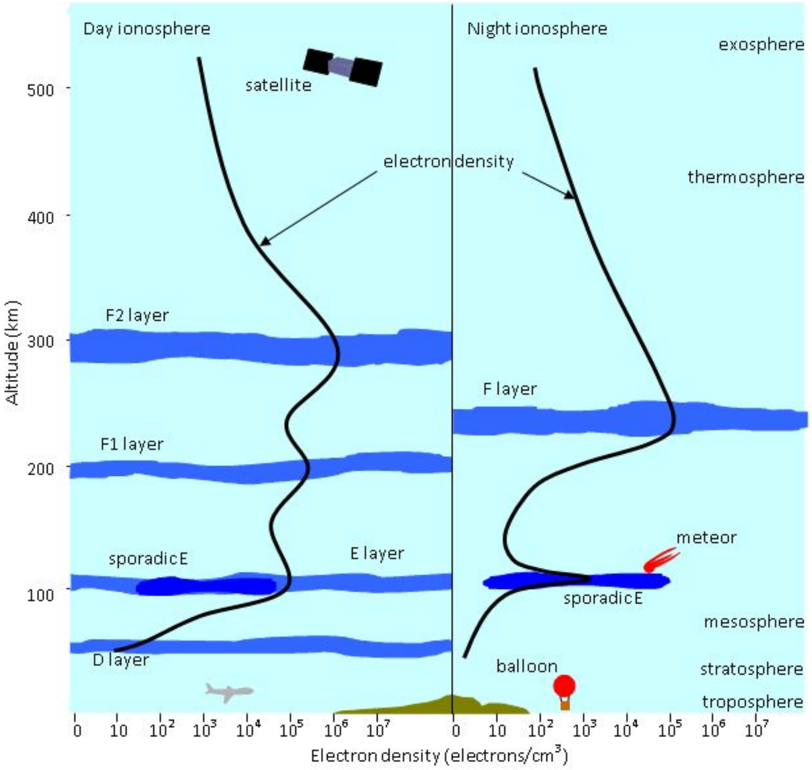




- Sporadic E (*Es*) = dense ionized clouds at ~90–140 km
- Occurs **unpredictably**, lasting minutes to hours
- Can reflect high frequencies like the F layer
- May block or replace F-layer propagation (*Es blanketing*)
- Causes signal fading or intermittent reception
- Most common in summer and daytime (mid-latitudes)

Sky-Wave Propagation and the Sun

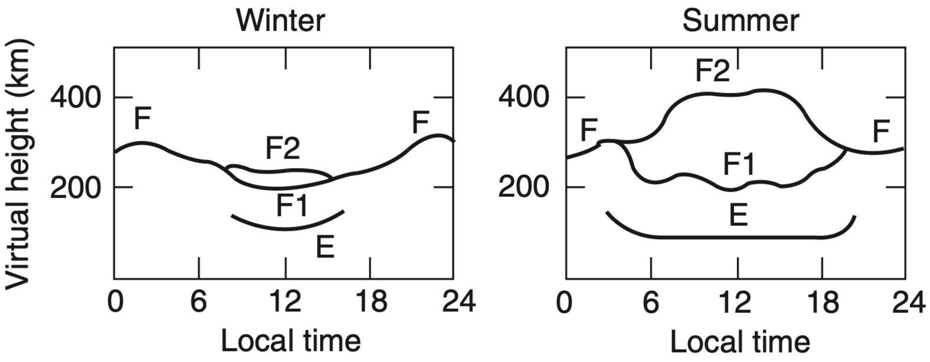
F Layer Propagation



- The F region (~150–400+ km) enables long-distance HF propagation
- Ionized mainly by UV radiation from the Sun
- Daytime splits into F_1 (150–250 km) and F_2 (>250 km) layers
- F_1 disappears at night
- F_2 persists and supports long-range propagation
- Ionization varies with time, season, and solar cycle

Sky-Wave Propagation and the Sun

F Layer Propagation – F_1 Layer



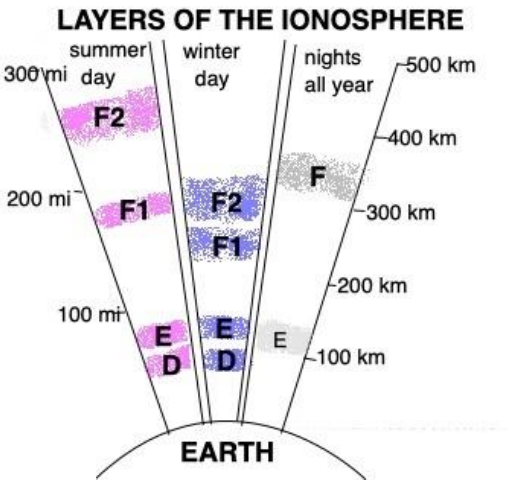
Average variation of ionospheric layer height as a function of season and local time. Note the large change in height of the F_2 layer in summer.

- The F_1 layer exists only during daytime
- It has limited importance for HF propagation
- Signals < 10 MHz rarely reach it
- Signals > 20 MHz usually pass through it
- Some propagation occurs at 10–20 MHz (summer, ~3000 km range)
- Most long-distance HF relies on the F_2 layer

Sky-Wave Propagation and the Sun

F Layer Propagation – F_2 and Nighttime F Layers

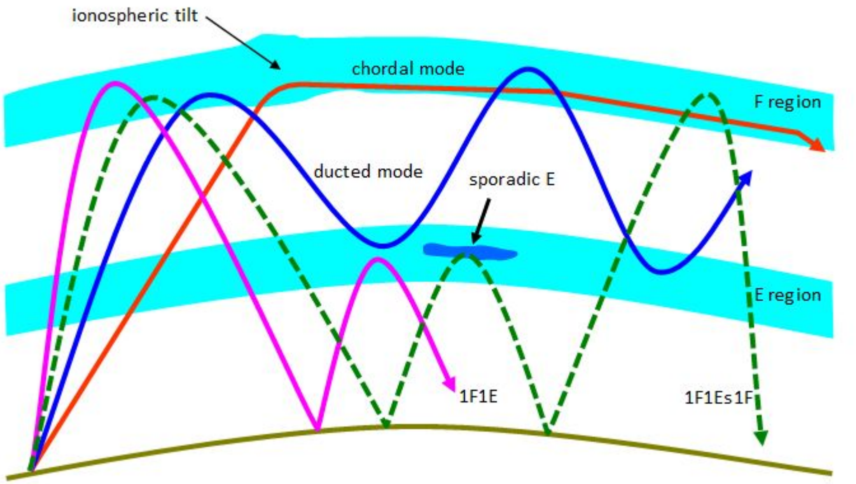
Royal Observatory *of* Belgium



- F_2 (~250–400 km) is the key layer for long-distance HF
- Present day and night (merges into single F region at night)
- Has the highest electron density
- MUF closely follows solar UV and the solar cycle
- One-hop range ≈ 4000 km
- NVIS enables short-range (~200–300 km) coverage below critical frequency
- MUF rises after sunrise, peaks after noon, drops at night
- Highest MUFs near the equator (transequatorial paths)
- Winter anomaly: winter daytime MUF often higher than summer

Sky-Wave Propagation and the Sun

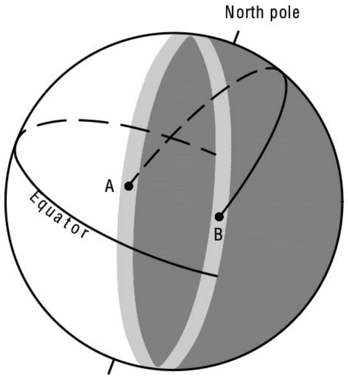
F Layer Propagation – Multihop

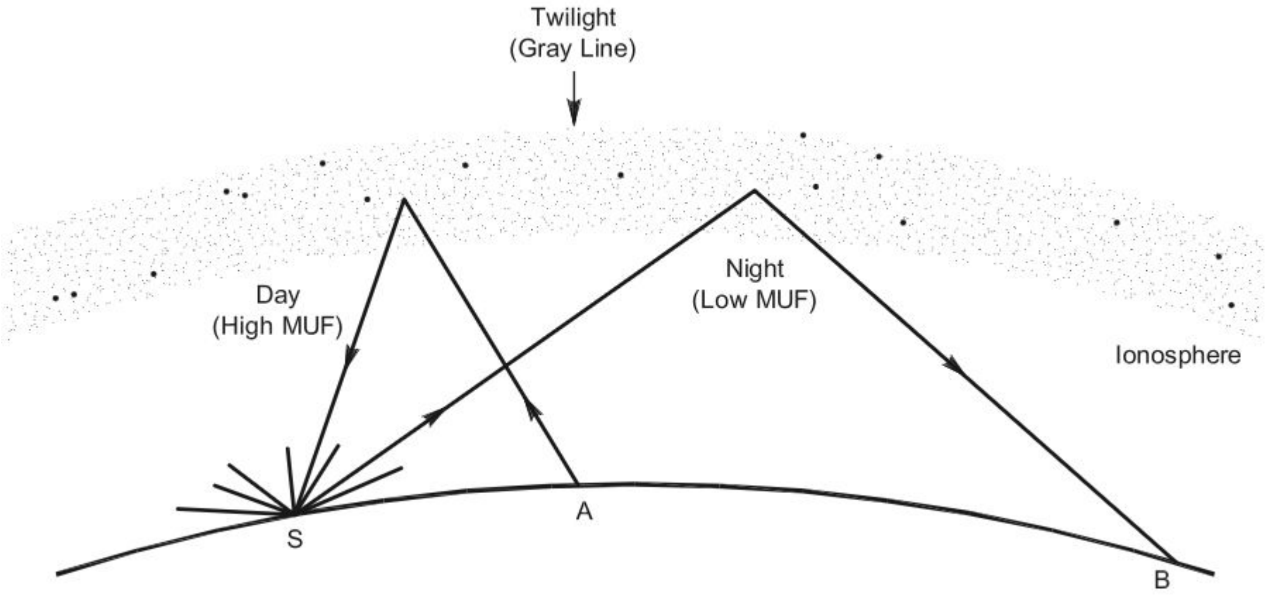


- HF paths > 4000 km use multiple ionospheric hops
- Each hop adds *attenuation and absorption*
- Signals can travel halfway or fully around the world
- Chordal hops (within *F* layer) reduce ground-loss
- Mixed *E*, *Es*, and *F* hops are common
- Multi-path arrival increases fading

Sky-Wave Propagation and the Sun

F Layer Propagation – Grayline & Backscatter





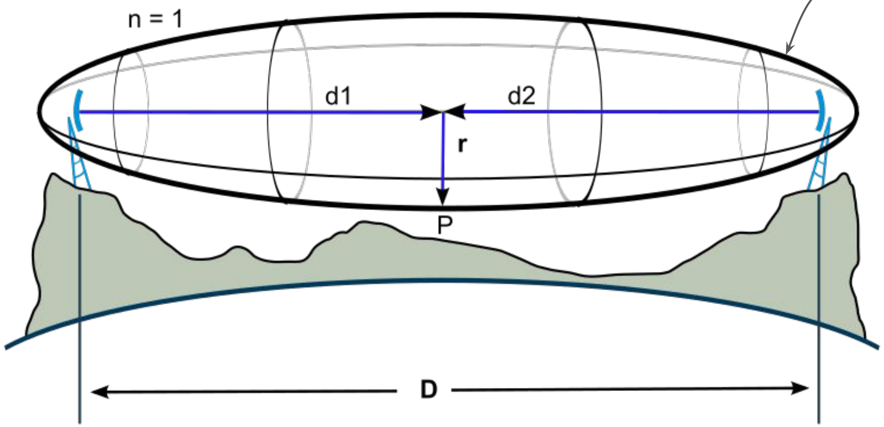
Propagation in the Troposphere

Royal Observatory of Belgium

- All radio waves pass through the troposphere, where refraction and scattering affect propagation
- Effects are minor $f < 30$ MHz, but significant $f > 50$ MHz
- Long-distance links in VHF/UHF/microwave often relies on it
- Driven by terrestrial weather rather than solar or geomagnetic activity

Propagation in the Troposphere

Line of Sight (LOS)



1st Fresnel Zone → *70–90% of signal energy*

$$r = 8.66\,(D / f)^{1/2}$$

D : distance between antennas [km]

f : frequency [GHz]

Because of refraction (Beyond LOS = BLOS)

$$D' = (17\,h)^{1/2}$$

D' : distance to the radio horizon [km]

h : height above average terrain [m]

Clearance

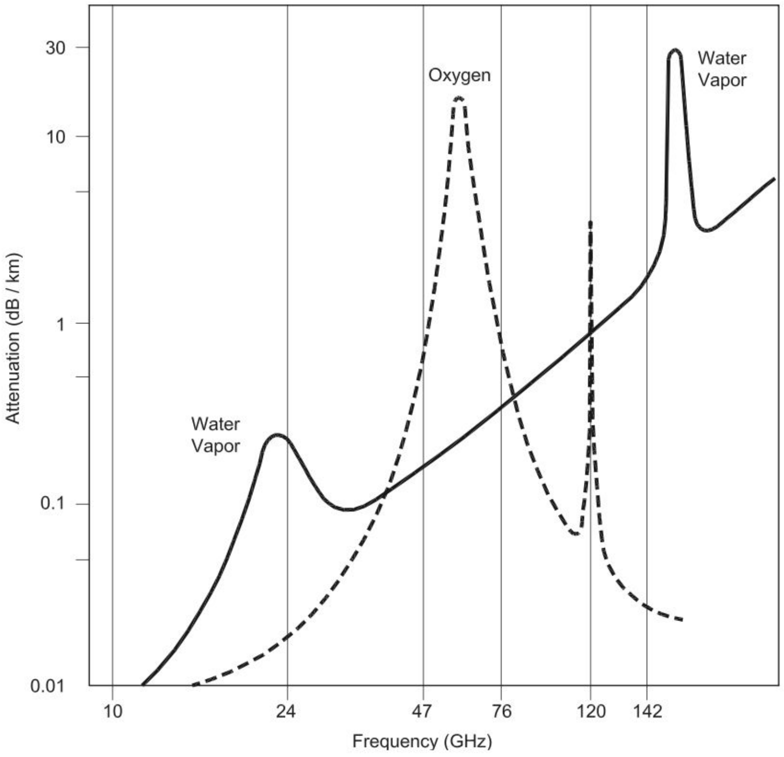
Maximum obstruction allowable is 40%

Recommended is 20% or less

Propagation in the Troposphere

Atmospheric Absorption

- Atmospheric gases cause minor loss below 10 GHz
- Rain attenuation becomes significant above ~3 GHz
- Losses increase rapidly with frequency
- Heavy fog affects signals mainly above ~5.6 GHz

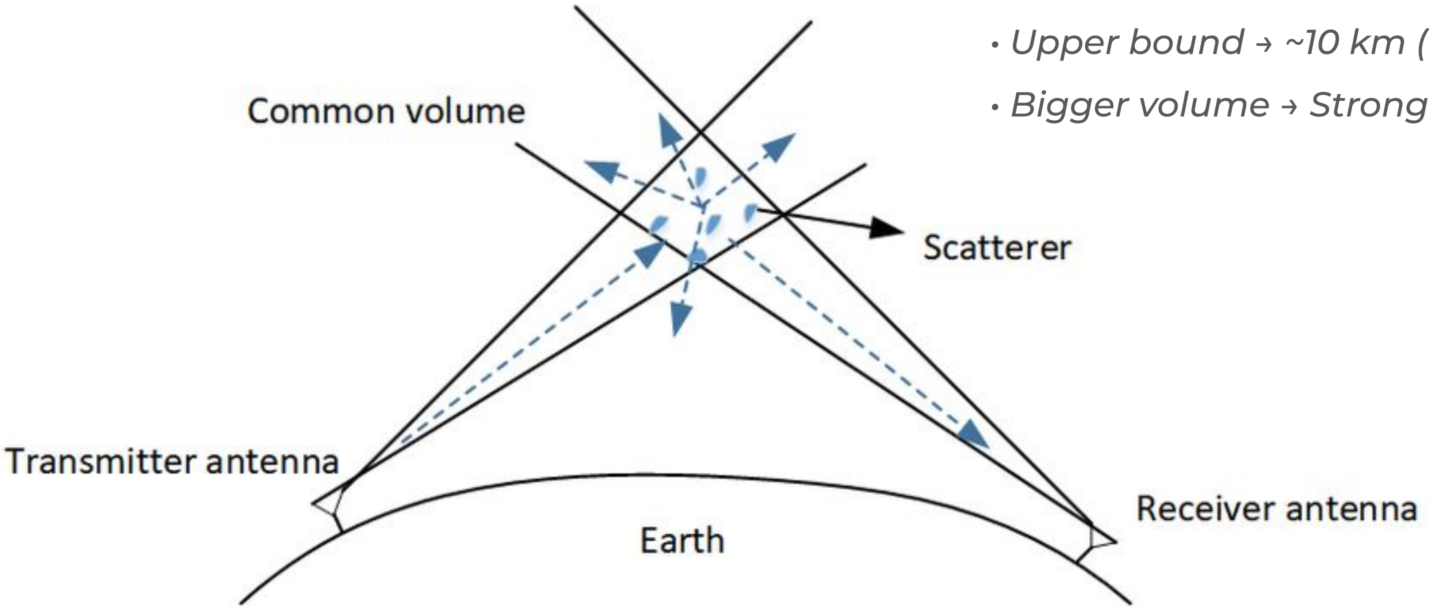


Attenuation caused by O_2 and water vapor at 10 g/m^3 (equivalent to 40% humidity at 25 °C).

Propagation in the Troposphere

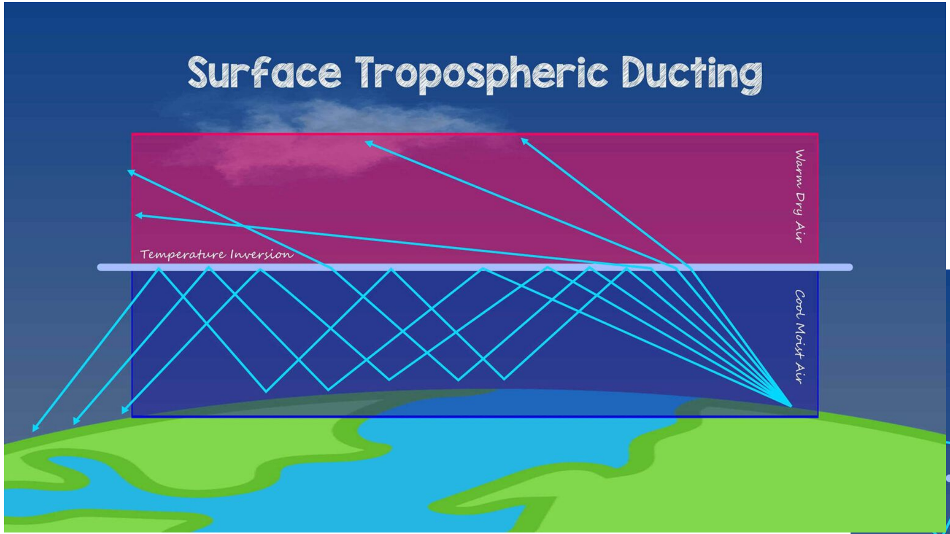
Troposcatter

- *Lower bound → Station take-off angle*
- *Upper bound → ~10 km (troposcatter limit)*
- *Bigger volume → Stronger signal*



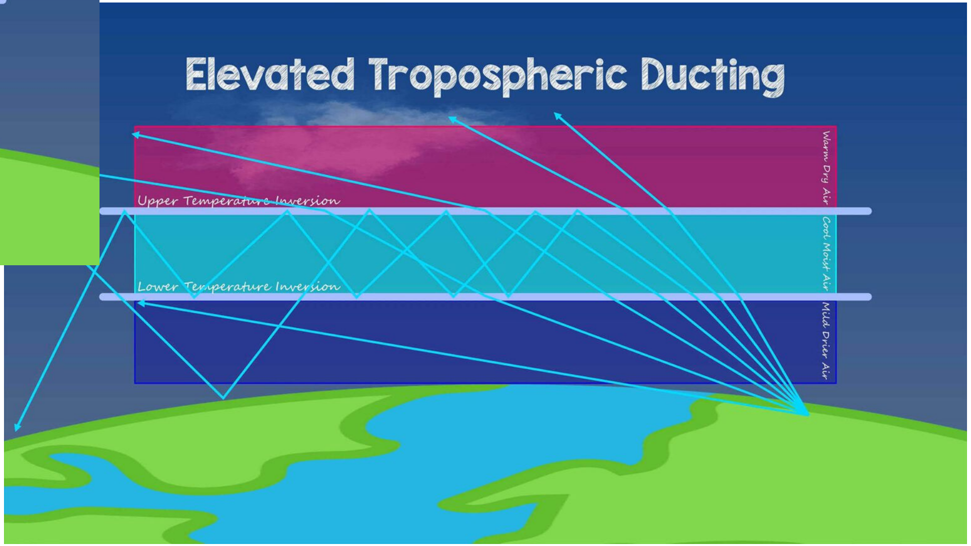
Propagation in the Troposphere

Surface- and Elevated-Ducting



Tropospheric Refraction

- Caused by gradients in refractive index (temp., RH, press)
- Extends radio horizon beyond visual line of sight
- Higher frequencies (microwave bands) show effects first



Tropospheric Ducting

- Refraction bends radio waves back to Earth's surface
- Enables very strong signals up to 1500 km
- Caused by temperature inversions (temp. ↗ with alt.)
- Enhanced by a drop in humidity → higher refractivity

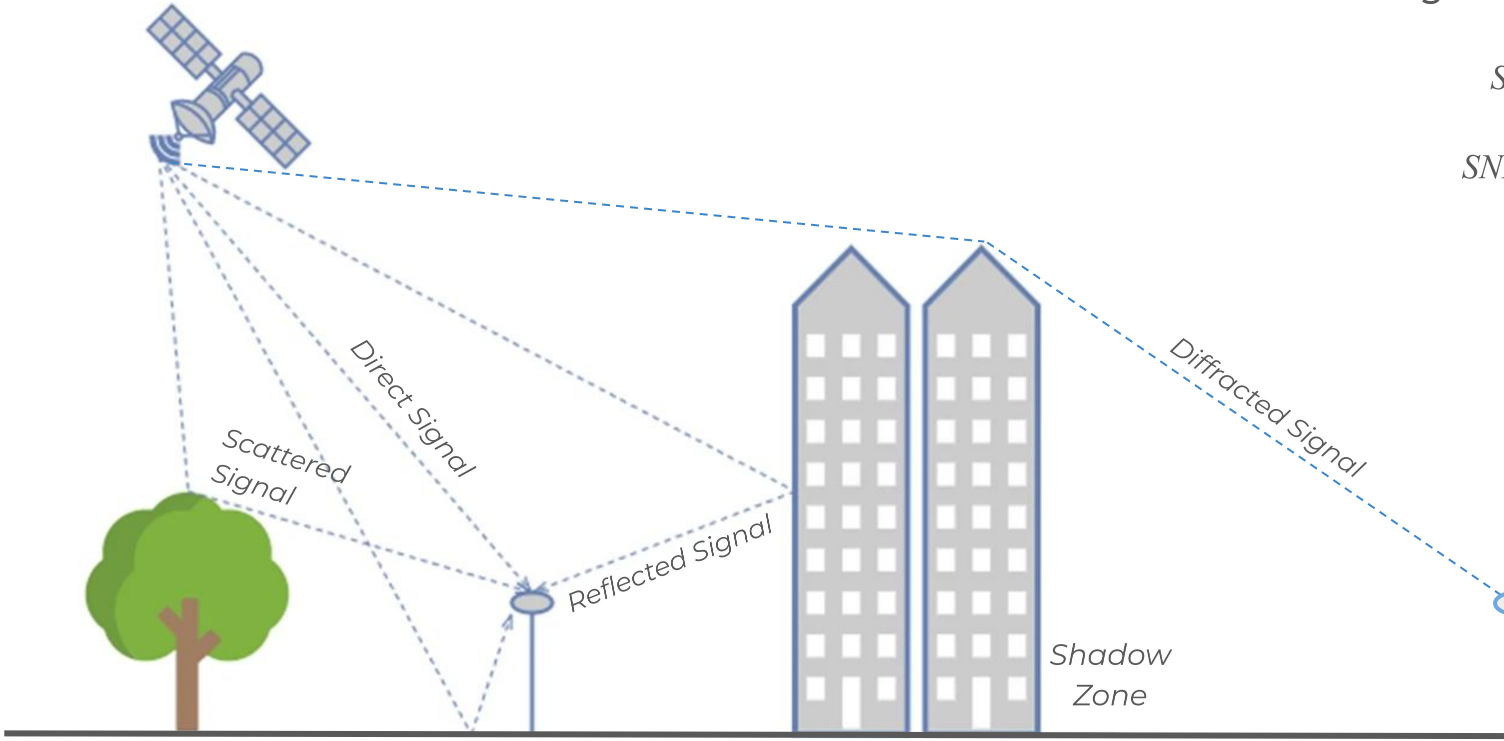
Propagation in the Troposphere

Tropospheric fading

- Atmospheric varies (density & humidity) → Signal refraction
- Multiple paths → Addition or cancellation
- Wind → Changing paths → Scintillation fading
  ↳ Stars twinkle = same process
- Effect increases with frequency & distance
- Minor for VHF/UHF, major for microwave links

Earth-Space Propagation

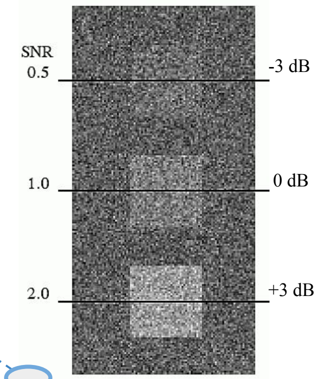
Satellite LOS, Non-LOS, Multi-Path environment



Signal-to-Noise Ratio

$$SNR = \frac{P_{signal}}{P_{noise}}$$

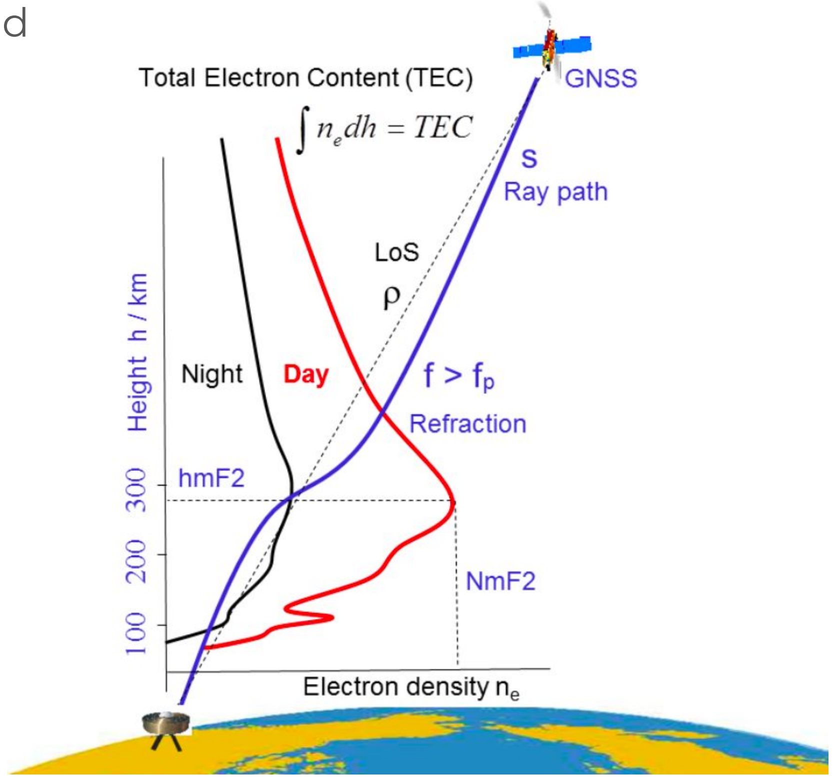
$$SNR_{[dB]} = 10 \log(SNR)$$



Earth-Space Propagation

Trans-ionospheric propagation

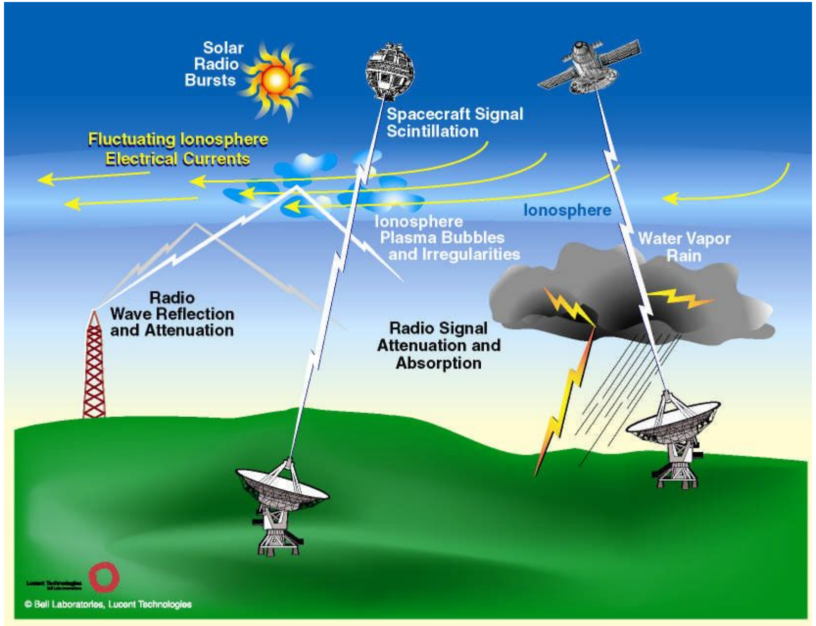
- Ionospheric refractive index is dispersive and depends on electron density
- First-order delay/range error ∝ TEC; dual-frequency GNSS estimates and mitigates it
- Geomagnetic field causes anisotropy
  ↳ double refraction and Faraday rotation
- Refraction bends ray paths, impacting low-elevation positioning
- Irregularities (e.g., plasma bubbles) cause scintillation, degrading signals $f < 10$ GHz



Space Weather Impacts on Radio

Ionospheric Scintillation

- Ionospheric scintillation causes signal fading, dominant below ~2 GHz (troposphere dominates above 2 GHz)
- Caused by anisotropic, magnetically aligned irregularities in the ionosphere
- Depends on location, local time, season, solar cycle, and geomagnetic storms.
- Fade rates: ~1–2 Hz for slow-moving sources (Moon/GEO); faster for LEO satellites.

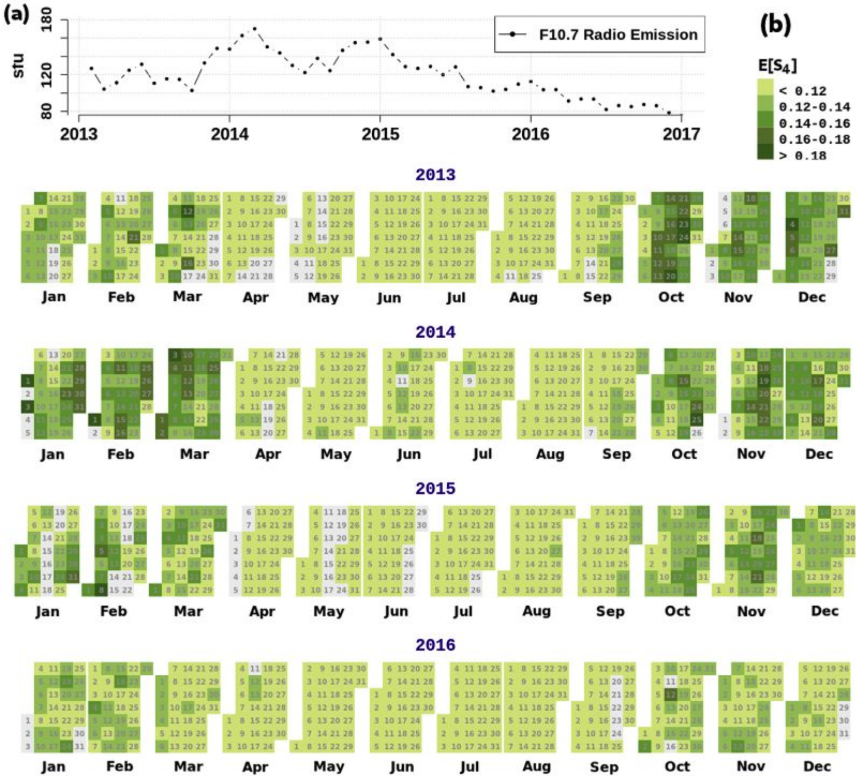


Royal Observatory *of* Belgium

Space Weather Impacts on Radio

Ionospheric Scintillation

- Degrades measurements and receiver tracking performance
- May cause loss of lock and reduced positioning availability
- Disrupts GNSS-based services (agriculture, surveying, navigation)
- Can impair GBAS and aviation safety services

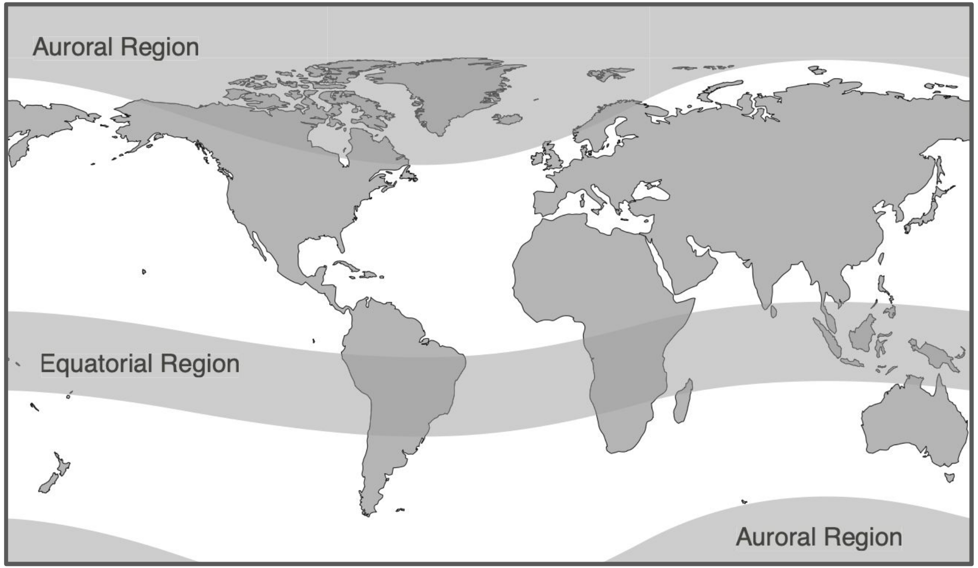


(a) F10.7 index for the 2013–16 period. (b) Daily averaged S_4 index for PRU station (Brazil) in the same period

Space Weather Impacts on Radio

Ionospheric Scintillation

- Strongest within ±20° of the magnetic equator (up to 20–30 dB fades); common near poles (≤10 dB); rare at mid-latitudes
- Equatorial events typically occur after sunset; polar events can occur anytime



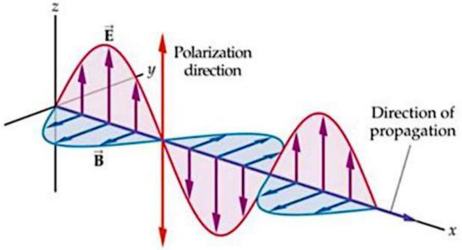
Regions of the world (shaded) where scintillation fading effects can be especially severe.

Royal Observatory of Belgium

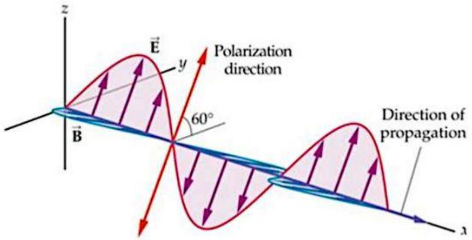
Earth-Space Propagation

Electromagnetic wave Polarization

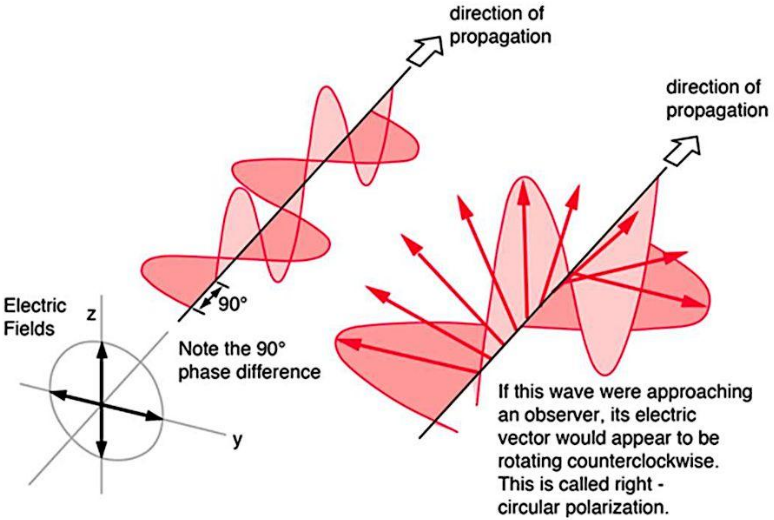
- Polarization: direction of the electric field ($\bar{\boldsymbol{E}}$) oscillation.
- Linear: E-field oscillates in a fixed direction.
- Circular: E-field rotates at constant rate (RHCP/LHCP).
- Elliptical: E-field traces an ellipse.



This wave **is polarized** in z -direction



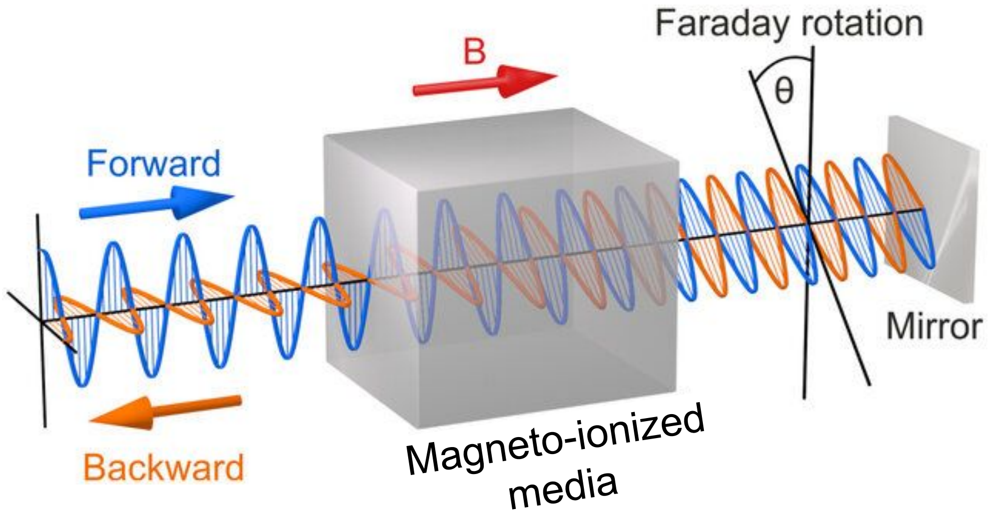
This wave **is polarized** in a direction at an angle of 60º with y-axis



Earth-Space Propagation

Faraday Rotation

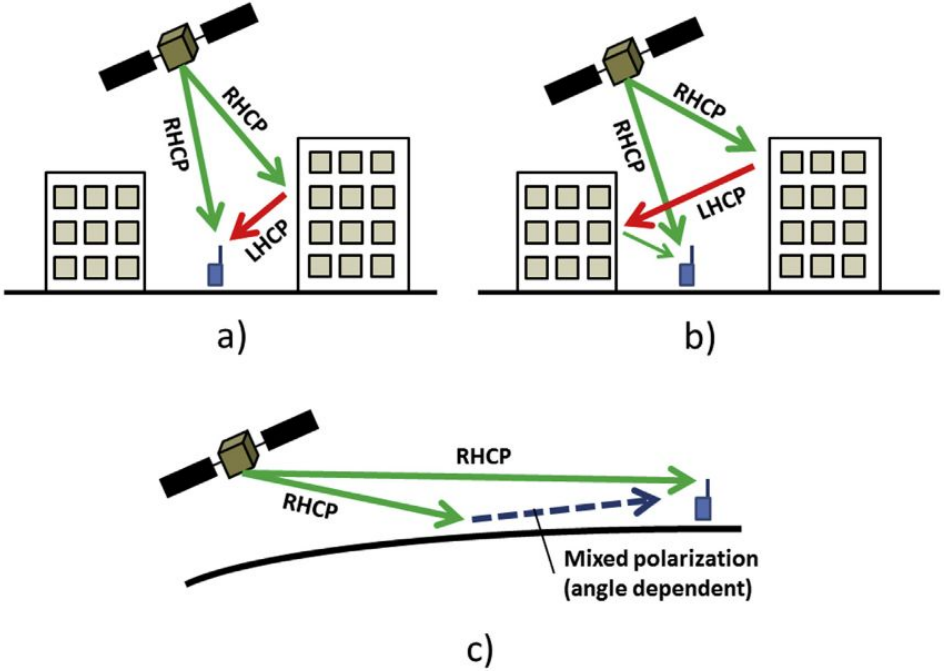
- The ionosphere can rotate wave polarization
- Polarization mismatch (e.g., 90° shift) increases path loss and causes fading
- Rotation is time- and frequency- dependent, and hard to predict



Earth-Space Propagation

Faraday Rotation

- Reflections reverse polarization sense
- Circular polarization avoids rotation effects, but reflections reverse polarization sense, requiring both LHCP and RHCP systems
- At 144 MHz, realignment may occur in minutes; at 432 MHz, it can take 30+ minutes



Questions?

Panorama of the Humain Radio-Astronomy Station

https://sidc.be/humain/home

Antonio Martínez Picar
antonio.martinez@oma.be