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Solar-Terrestrial
Center of Excellence

Space Weather Impact on Radio Communications

Solar-Terrestrial Center of Excellence

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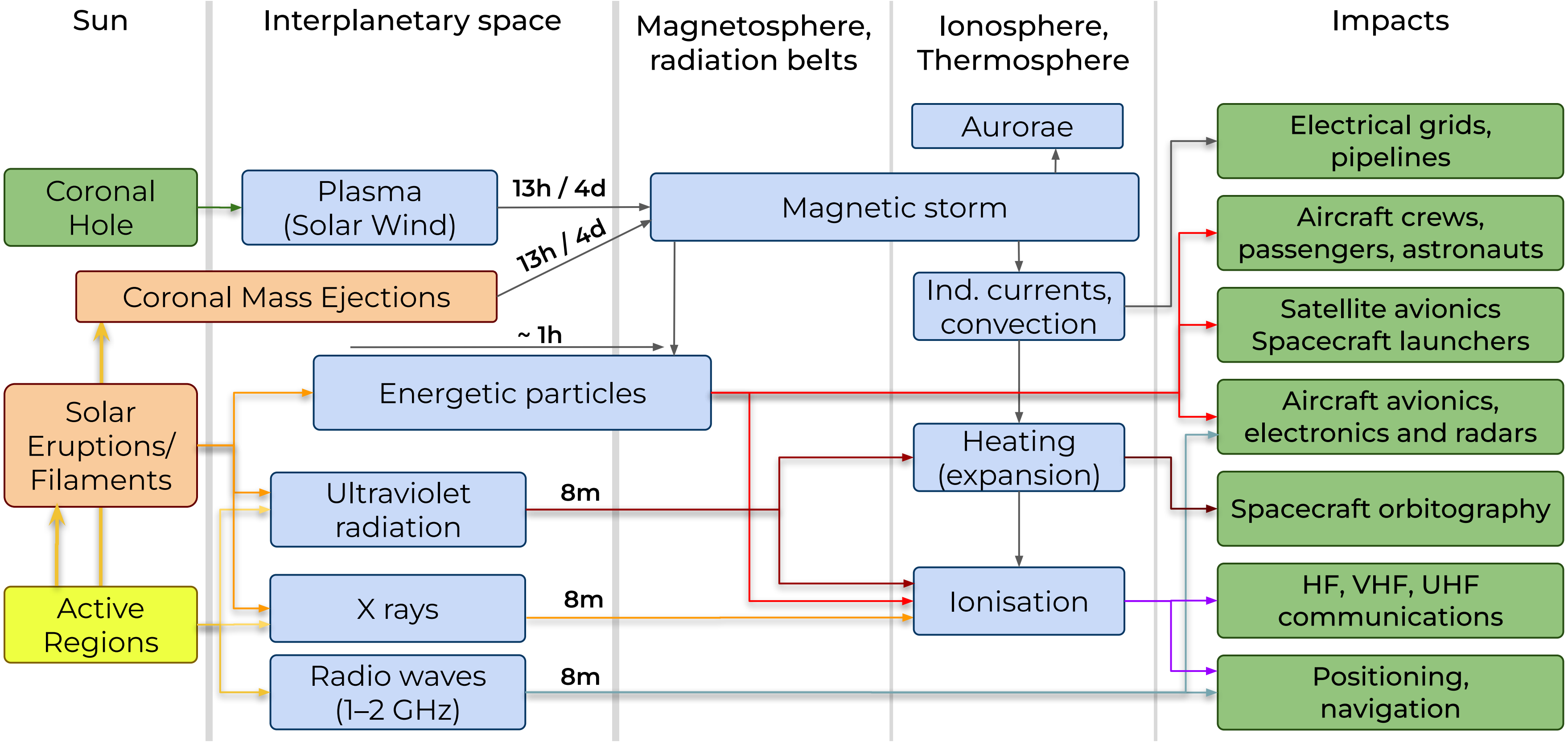
Space Weather from the Sun to the Earth



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Electromagnetic wave propagation fundamentals

Maxwell Equations

$$\nabla \times \mathbf{H}_0 = \mathbf{J} + \partial \mathbf{D}_0/\partial t$$

$$\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t$$

Time derivatives

$$\nabla \cdot \mathbf{D}_0 = \rho$$

$$\nabla \cdot \mathbf{B} \equiv 0$$

Spatial structure of the fields

E : Electric field intensity

D : Electric flux density

H : Magnetic field

B : Magnetic flux density

J : Conduction-current density

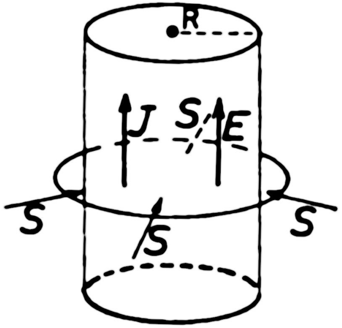
Material Equations

$$\mathbf{D}_0 = \varepsilon_0 \mathbf{E}$$

$$\mathbf{B} = \mu_0 \mathbf{H}_0$$

$$\mathbf{J} = \sigma \mathbf{E}$$

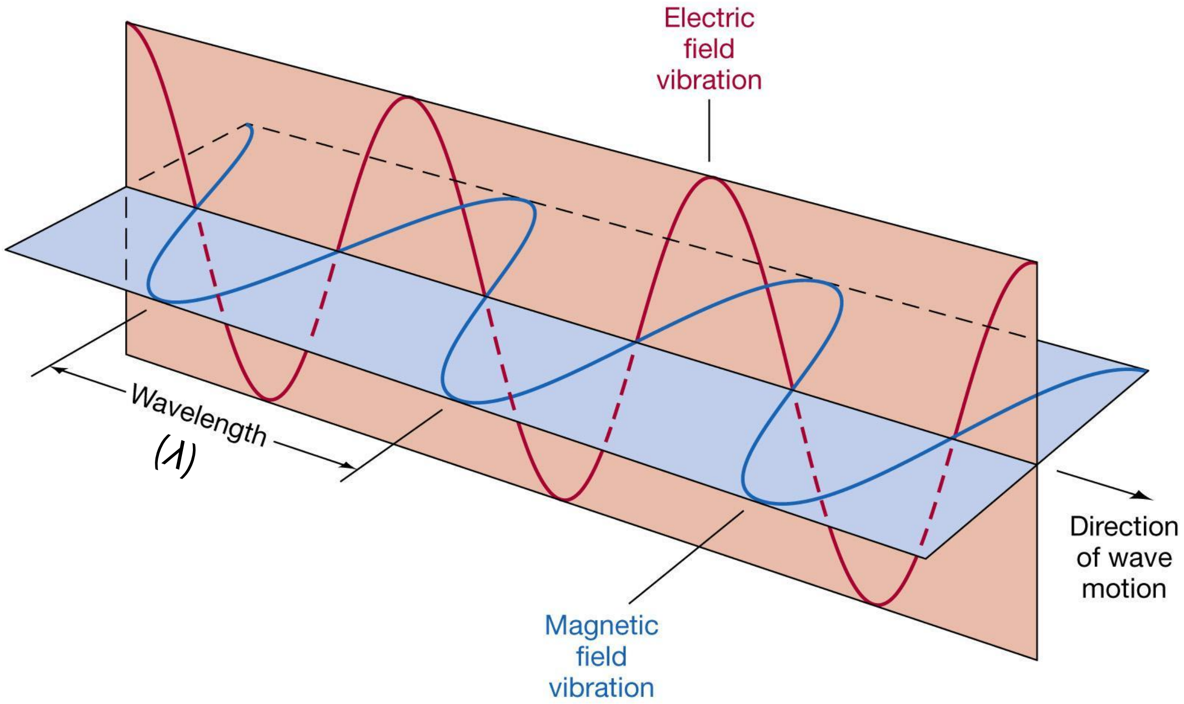
Energy Conservation



Poynting vector for a circular straight wire carrying a steady current density produced by the electric field

See, e.g. Elliot, R.S. (1981) *Antenna Theory & Design*, Wiley-IEEE Press

Electromagnetic wave propagation



Linearly polarised electromagnetic wave

Wave Equations

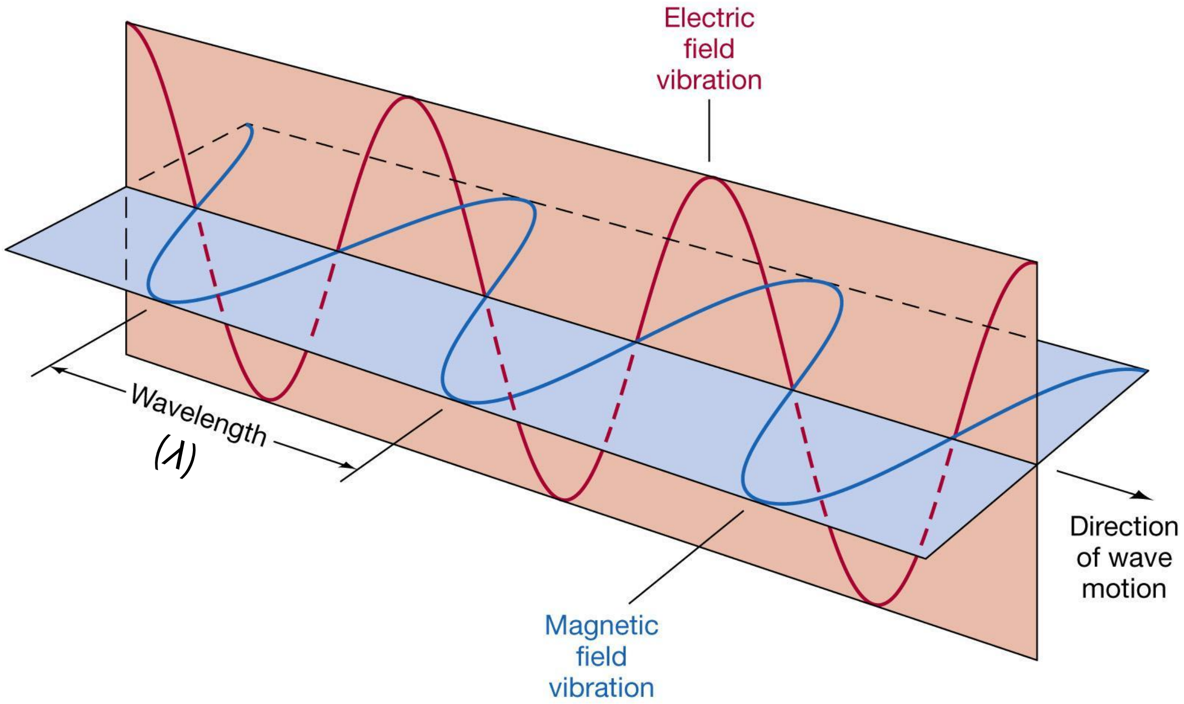
$$\nabla \times \nabla \times \mathbf{E} + \gamma^2 \mathbf{E} = 0$$

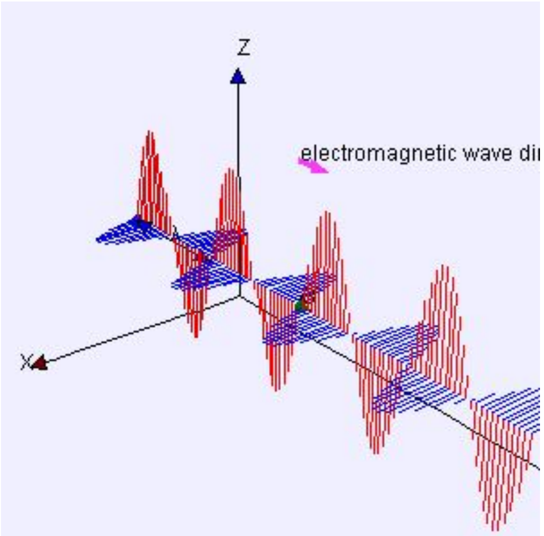
$$\nabla \times \nabla \times \mathbf{H} + \gamma^2 \mathbf{H} = 0$$

where

$$\gamma^2 = j\omega\mu\sigma - \omega^2\mu\varepsilon$$

Electromagnetic wave propagation





Linearly polarised electromagnetic wave

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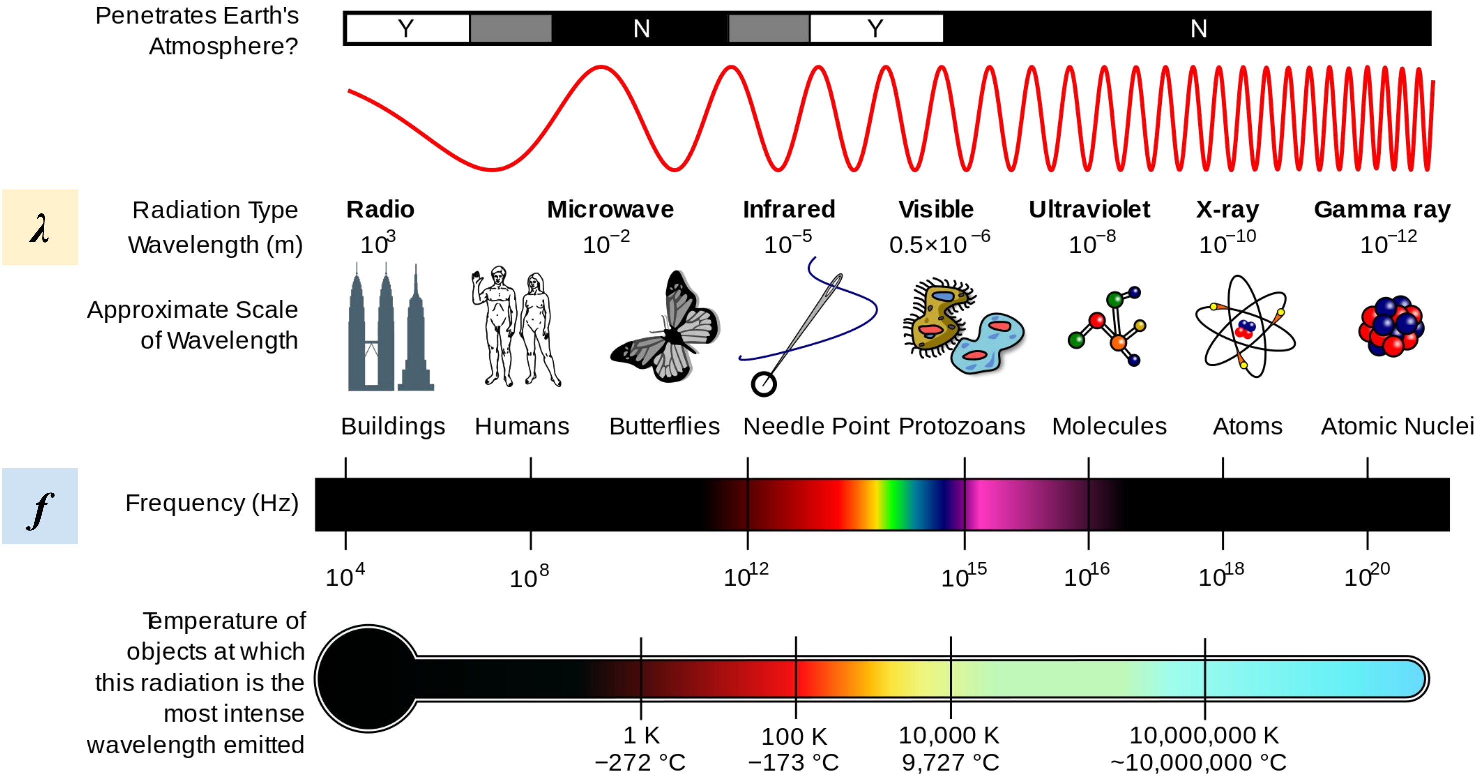
Electromagnetic spectrum



$$f = c/\lambda$$

c : speed of light

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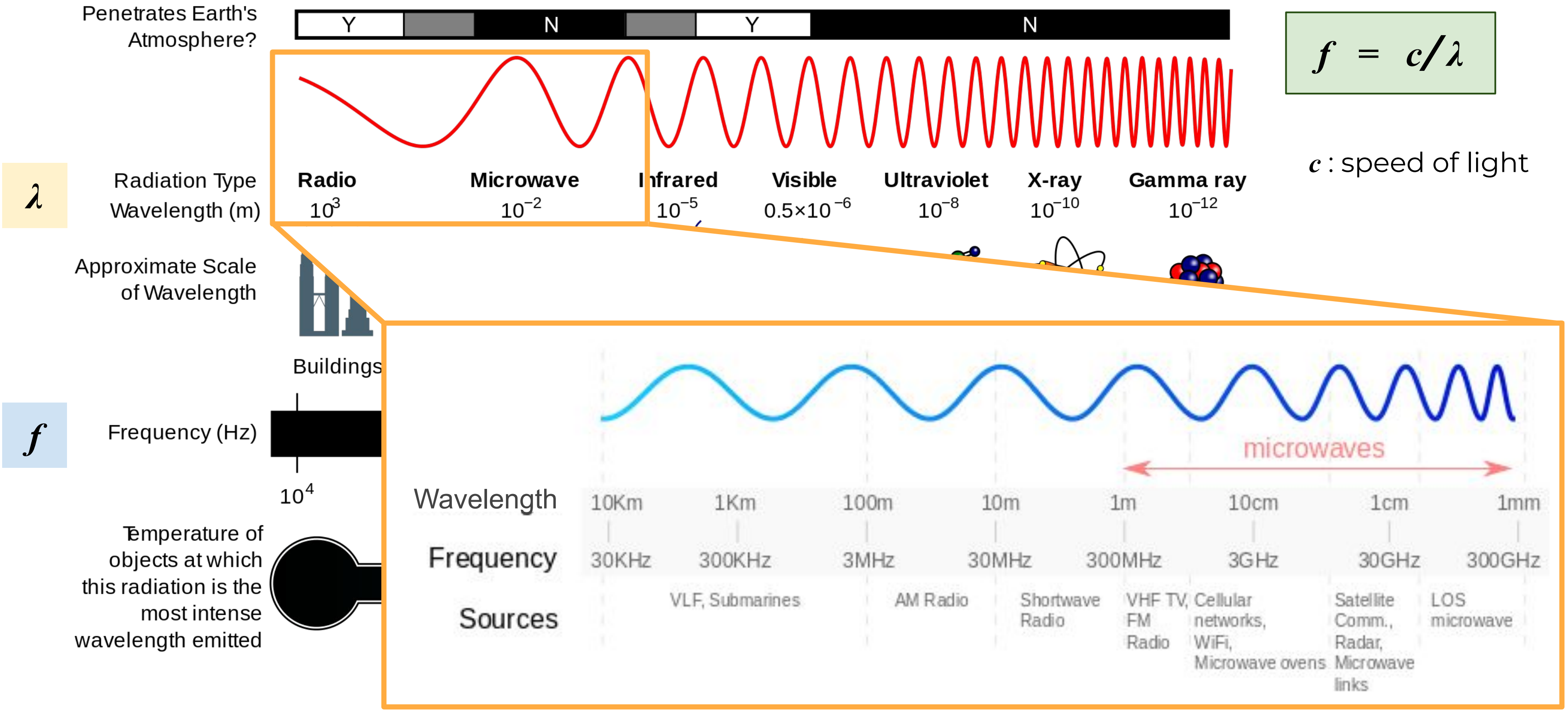
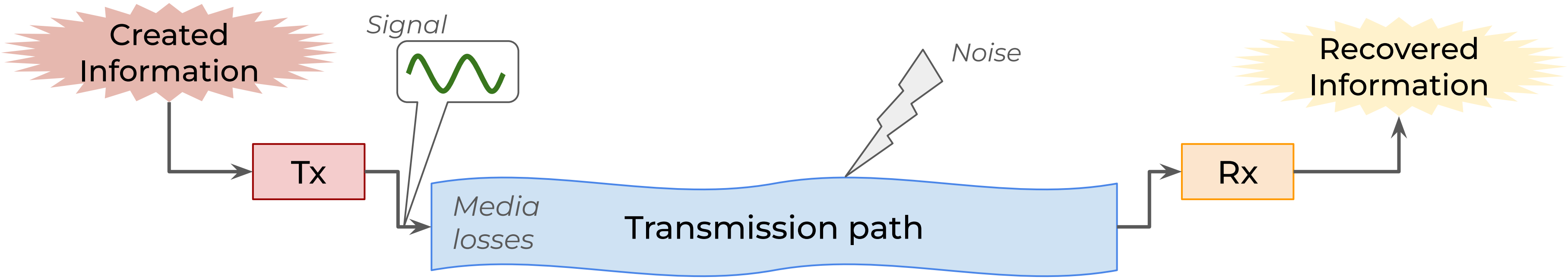
Electromagnetic spectrum



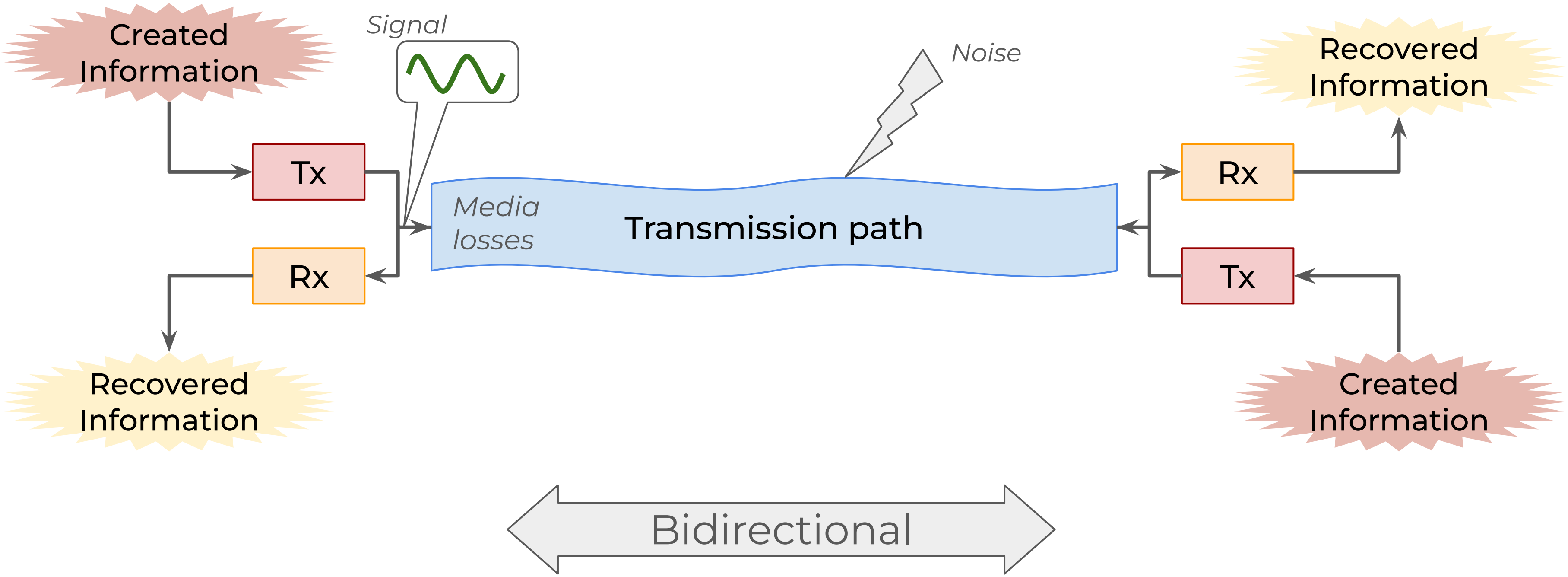
$$f = c/\lambda$$

c : speed of light

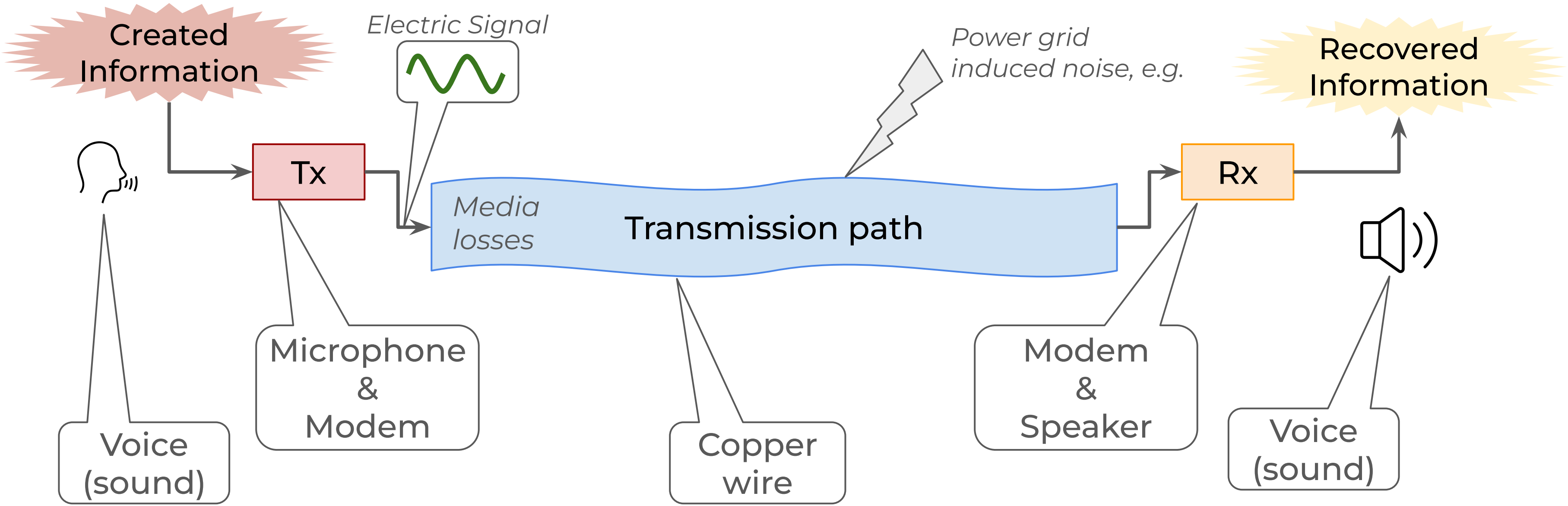
Telecommunication systems



Telecommunication systems

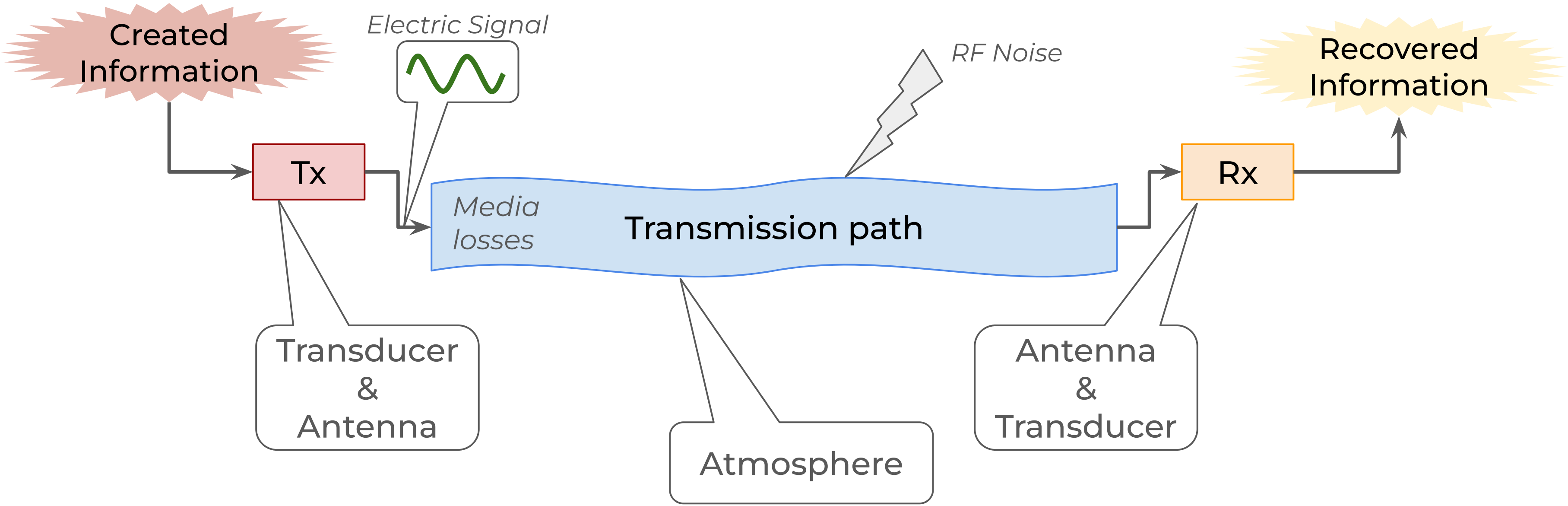


Telecommunication systems



Basic telephone system

Radio telecommunication systems

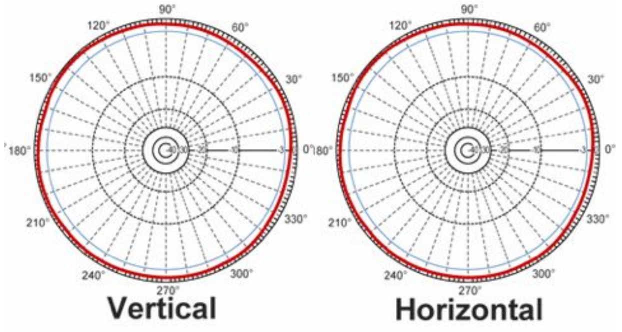


Outer space, water and ground are also possible transmission media!

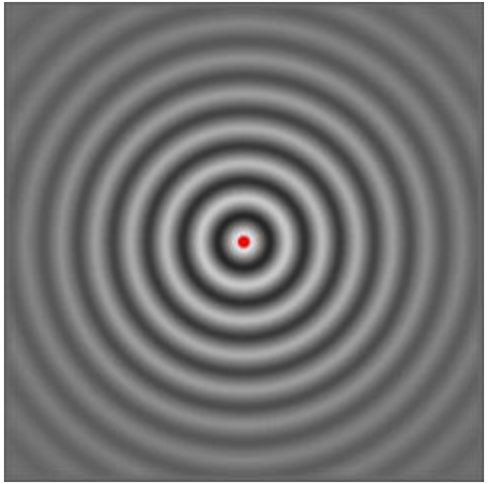
Antennas

Isotropic antenna: theoretical 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

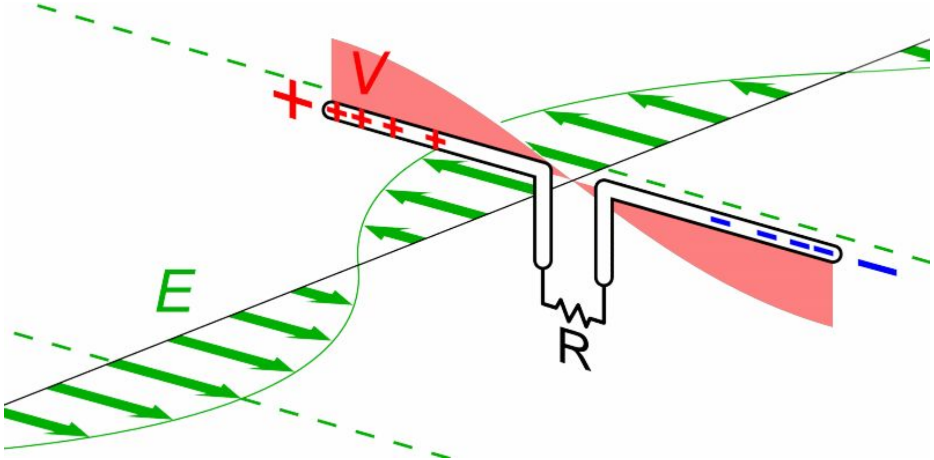
An isotropic antenna is used as a reference to evaluate antenna "gain"

Antennas

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

Reciprocity principle

(Tx ⇌ Rx)

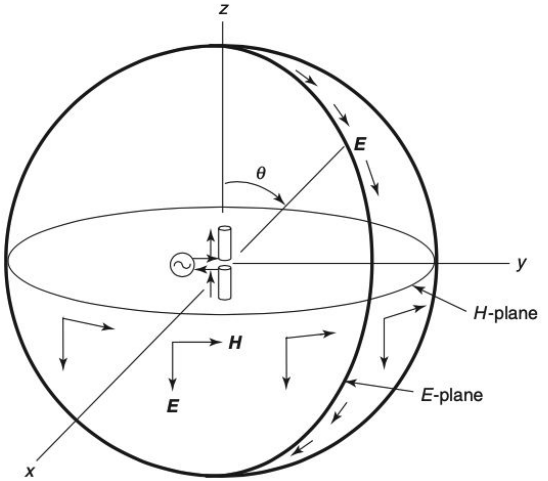


Half-wave dipole antenna receiving a radio wave

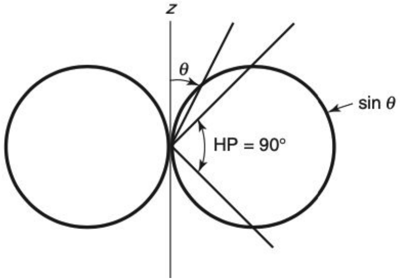
- Geometry (3D) plays an important role
- Dimension is linked to λ

Antennas

Idealized dipole

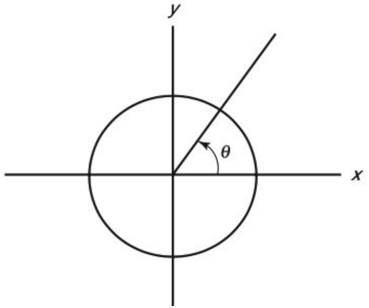


Field components

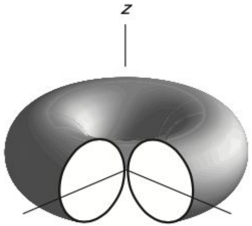


E-plane radiation pattern

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



H-plane radiation pattern

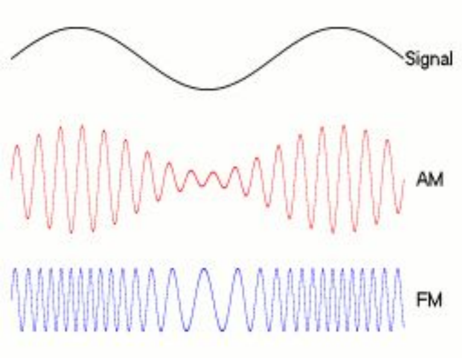


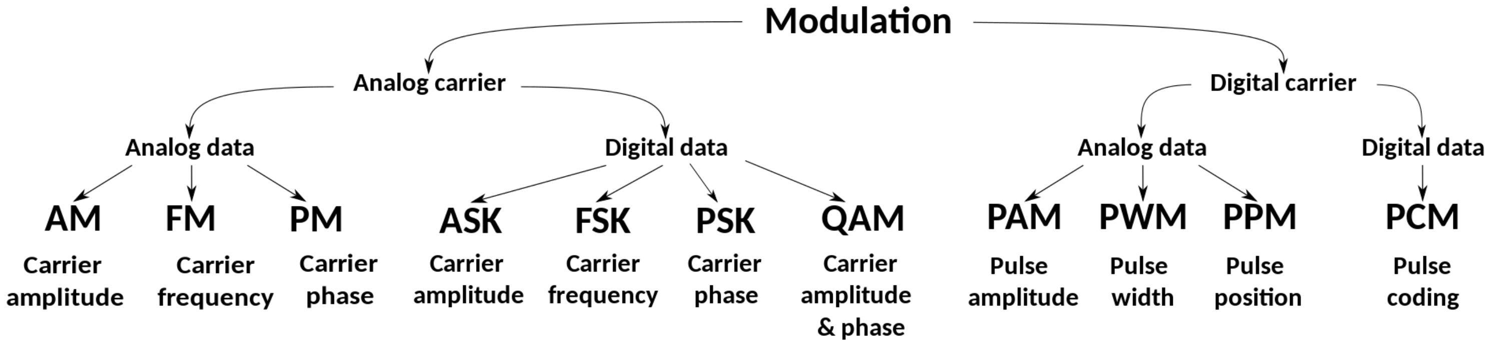
3D pattern plot

Modulation

- Frequency of an RF channel is best understood as the frequency of a *carrier wave*, i.e. a pure wave of constant frequency

- To include information, another wave needs to be imposed, called an input signal, on top of the carrier wave. This process of imposing an input signal onto a carrier wave is called **modulation**.



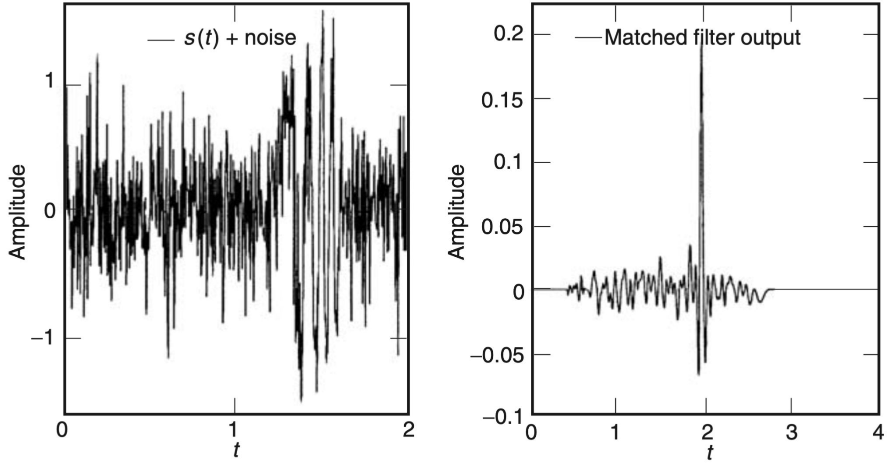


RF Noise

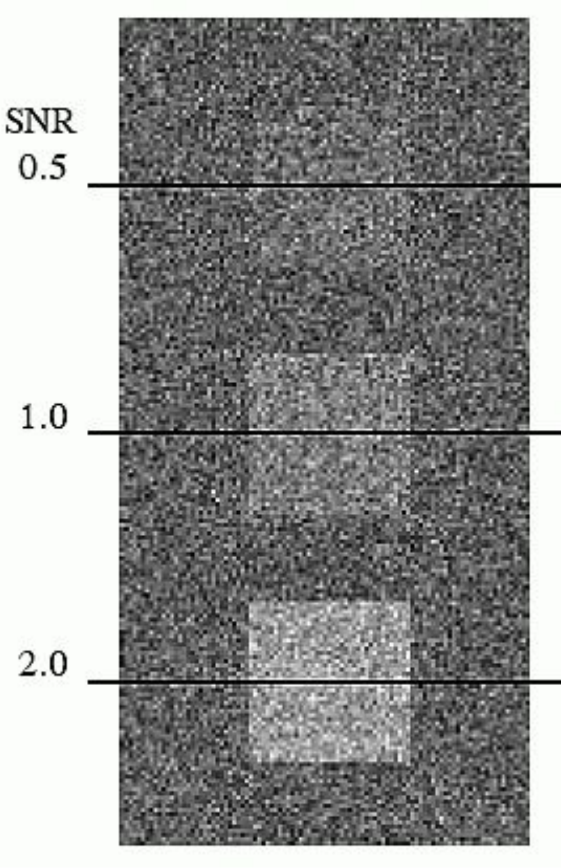
Signal-to-Noise Ratio (SNR):

$$SNR = \frac{P_{signal}}{P_{noise}} \qquad SNR_{[dB]} = 10\log(SNR)$$

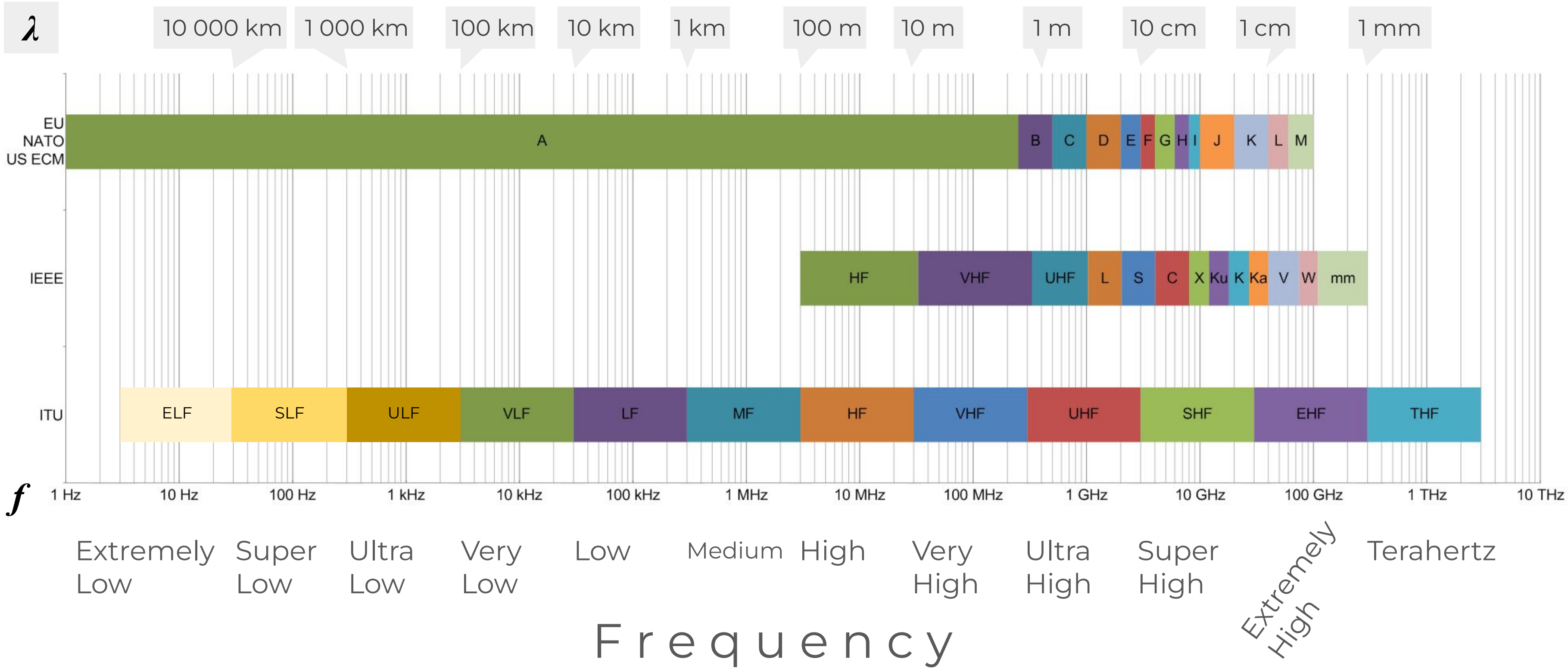
A ratio higher than 1:1 (greater than 0 dB) indicates more signal than noise.



(a) (b)



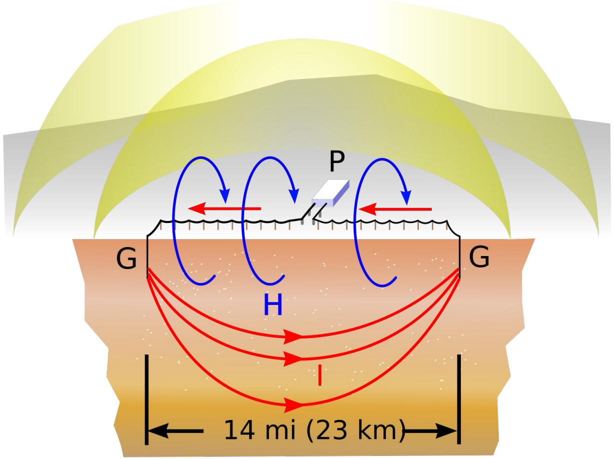
Radio bands



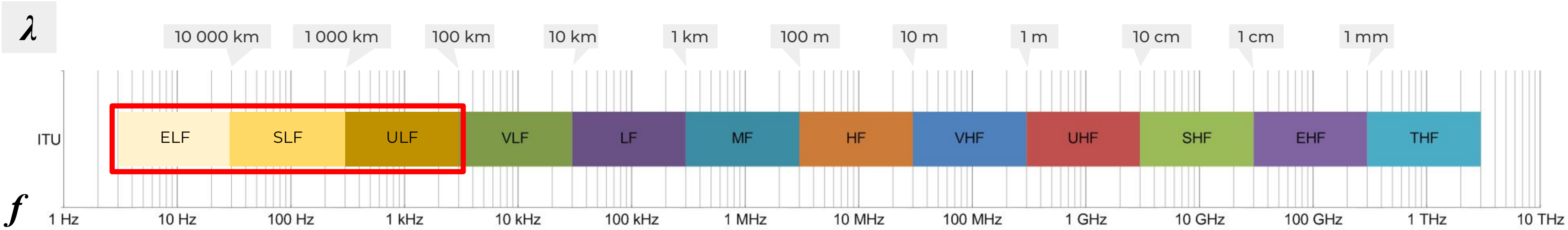
λ
10 000 km
1 000 km
100 km
10 km
1 km
100 m
10 m
1 m
10 cm
1 cm
1 mm
EU NATO US ECM
A
B
C
D
E
F
G
H
I
J
K
L
M
IEEE
HF
VHF
UHF
L
S
C
X
Ku
K
Ka
V
W
mm
ITU
ELF
SLF
ULF
VLF
LF
MF
HF
VHF
UHF
SHF
EHF
THF
f
1 Hz
10 Hz
100 Hz
1 kHz
10 kHz
100 kHz
1 MHz
10 MHz
100 MHz
1 GHz
10 GHz
100 GHz
1 THz
10 THz
Extremely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

ELF – SLF – ULF Systems

- Communication with Submarines
- Communication within mines



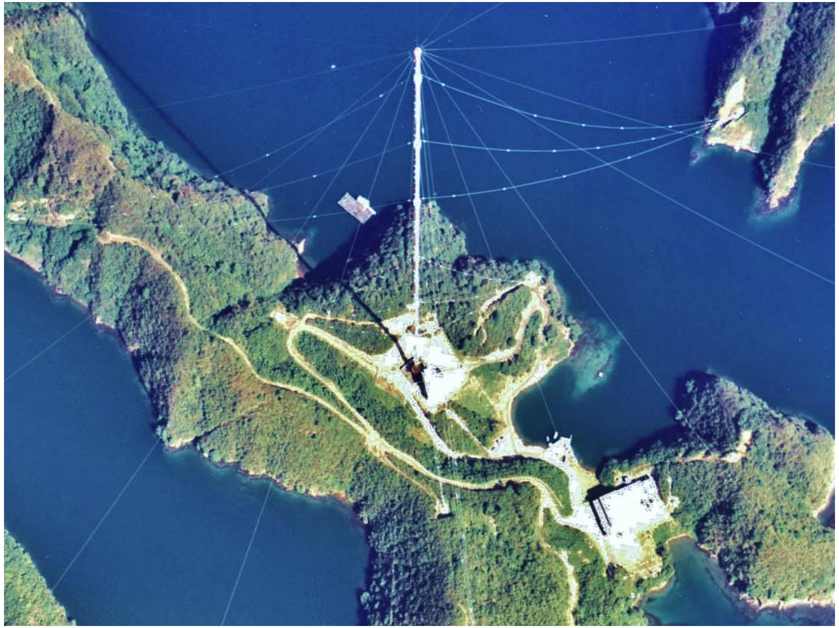
Aerial view of the U.S. Navy Clam Lake (WI) ELF transmitter facility



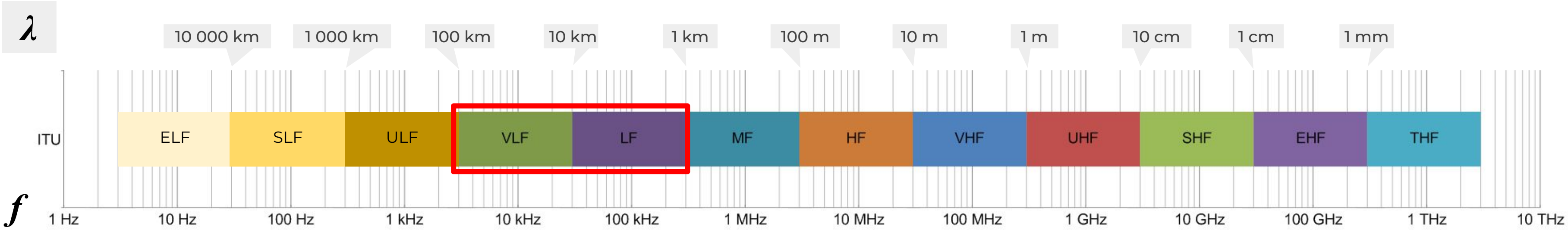
VLF – LF Systems

- Radio navigation systems (e.g. Omega)
  - Submarine (near surface) comm

- Time signal dissemination



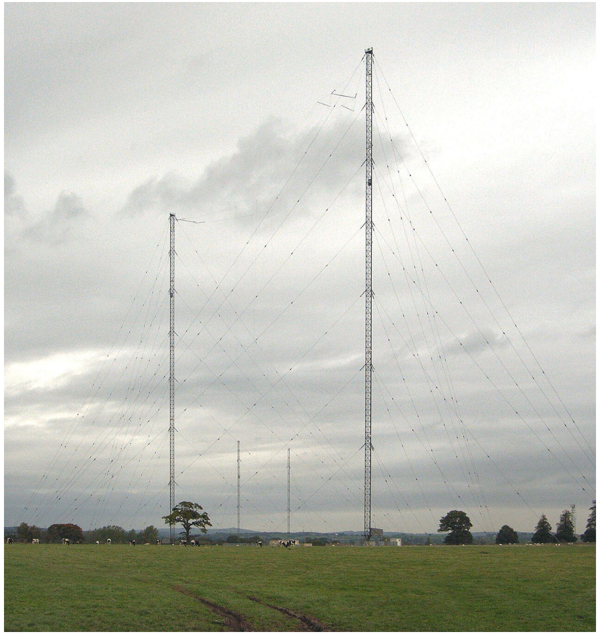
Shushi-Wan Omega Transmitter (station H) of the Omega navigation system (389 m high!)



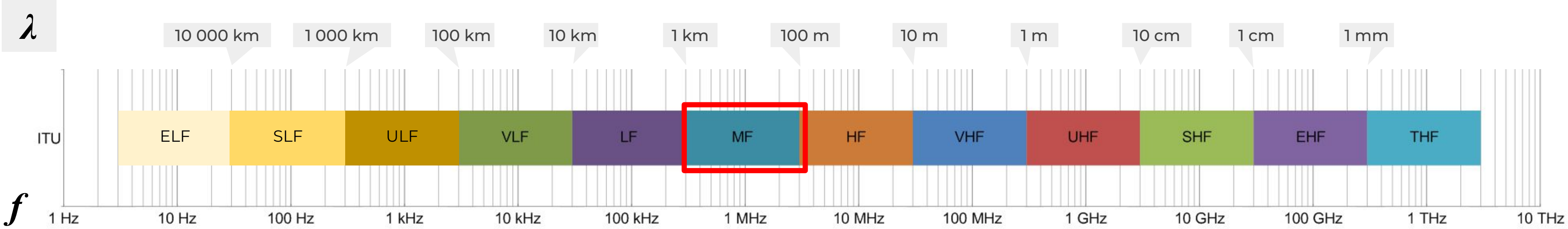
MF Systems

- AM Broadcast
- Avalanche beacons

Commercial avalanche transceiver



Masts at the Droitwich (UK) transmitting station



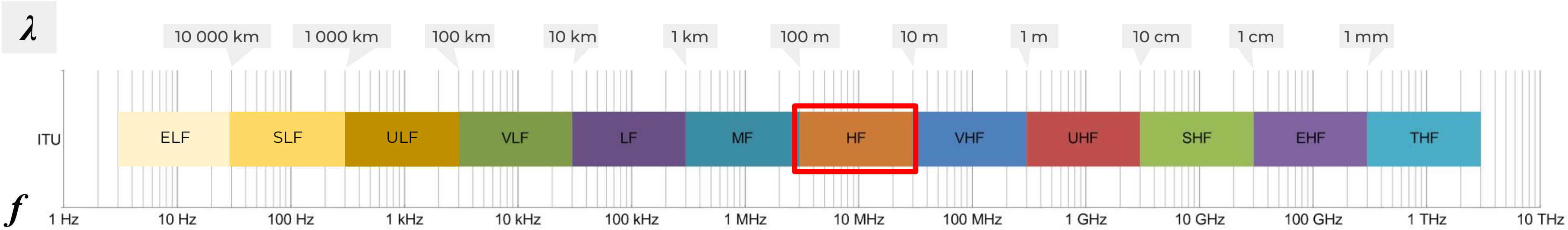
HF Systems

- Over-the-horizon aviation comm

- Automatic link establishment (ALE)

  worldwide de facto standard for digitally initiating and sustaining HF radio communications

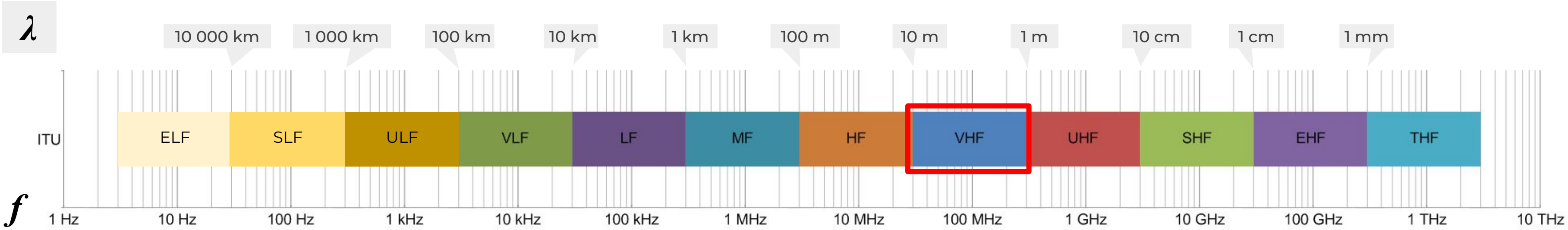
ATF Dingo of German Bundeswehr equipped with ALE capable HF-transceiver



VHF Systems

- FM & TV Broadcasting
- Radars
- LOS ground-to-aircraft
- Police, fire & emergency services

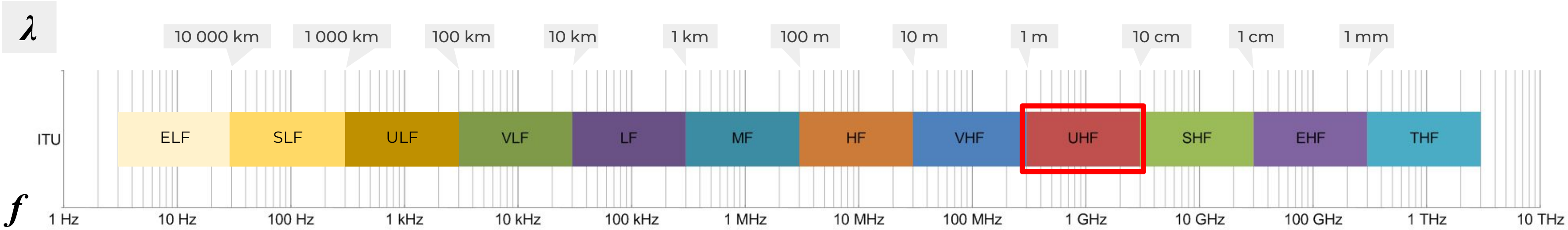
VOR / DME station



UHF Systems

- TV Broadcasting
- Radar & Satellite phones (L-band)
- Mobile phones
- ADS-B (Aviation)
- GPS
- Emergency services (TETRA)

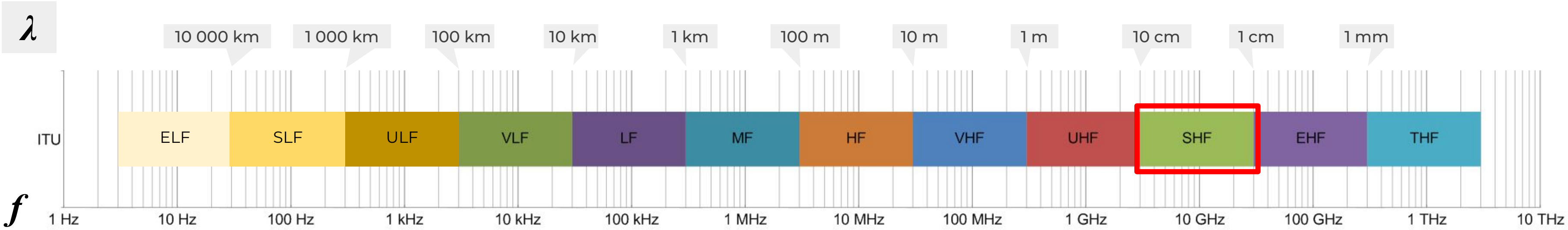
Setting up a satellite communications antenna for a demonstration of the Mobile User Objective System (MUOS)



SHF Systems

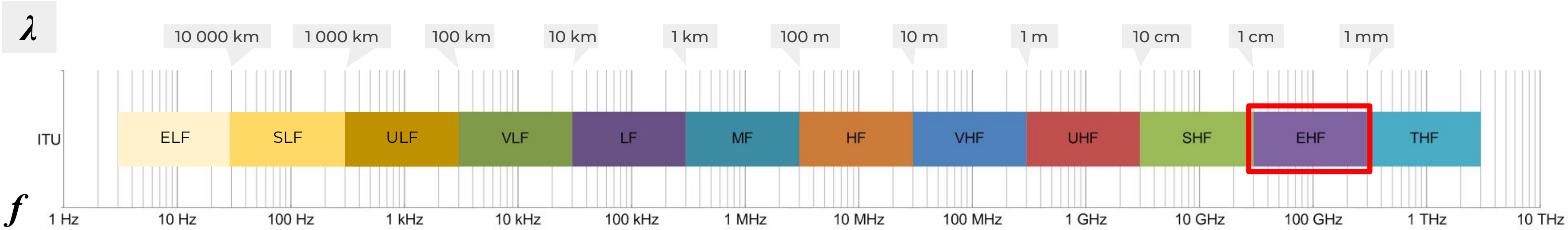
- Microwave comm
- Satellite phones (S-band)
- Radar
- Missile guidance

A variety of parabolic antennas on a communications tower in Australia for point-to-point microwave communication links



EHF Systems

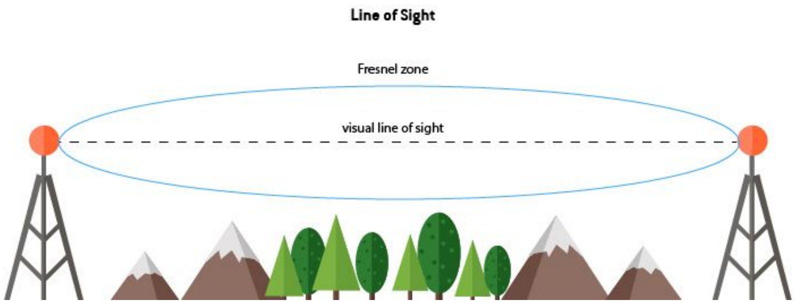
- Satellite on-the-move & comm
- Microwave radio relay

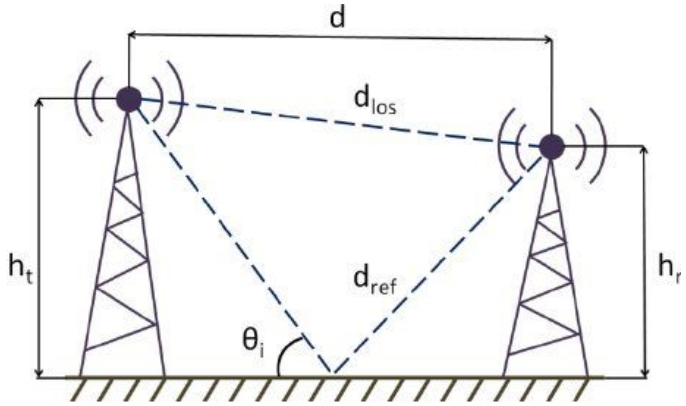


Propagation Mechanisms & Models

Direct Propagation or *Line-of-sight* (LoS)

The signal travels from the emitter to the receiver unaffected by any propagation medium, except possibly for attenuation and mild refraction.





Terrain Reflections

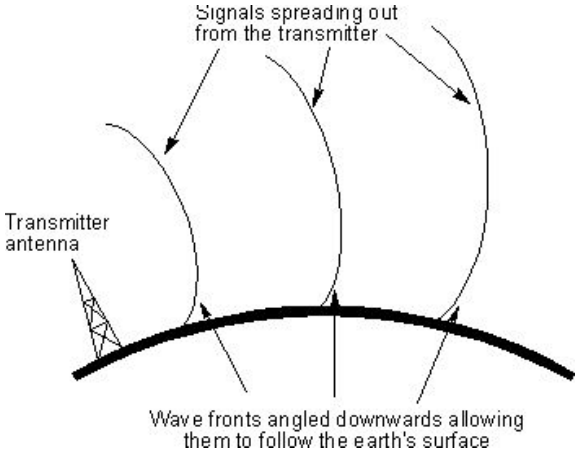
When antennas are not highly directional, signals travel LoS but also by reflection from the ground.

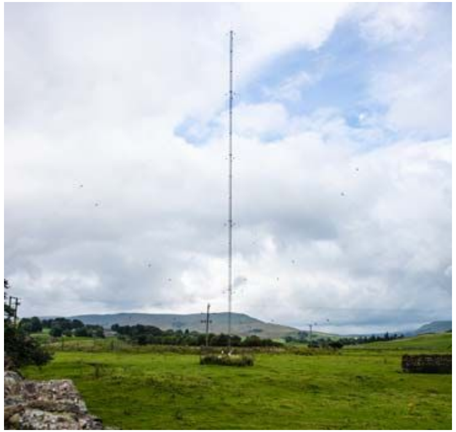
Examples: ground-to-air-to-ground, air-to-air comms at UHF/SHF, and satellite UHF/SHF/EHF comms (GNSS included)

Propagation Mechanisms & Models

Ground Wave

MF and lower frequency antennas near the ground cancel direct and ground-reflected waves, generating a surface-traveling wave that diminishes rapidly with altitude.





Efficient transmitting antennas at these frequencies are large structures on or near the ground, making ground-wave propagation crucial, especially for local AM broadcast and short distances at LF and VLF.

Propagation Mechanisms & Models

Ionospheric Reflection or *Sky Wave Propagation*

In the upper LF, MF, and HF bands, signals give the appearance of traveling in rays that are reflected by the ionosphere above and by the ground below, resulting in a series of "hops."

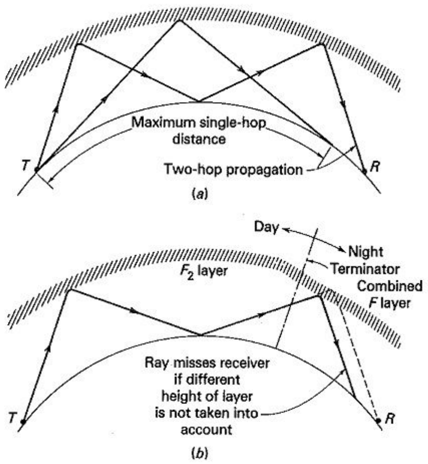


FIGURE 8-17 Long-distance sky-wave transmission paths. (a) North-south; (b) east-west.

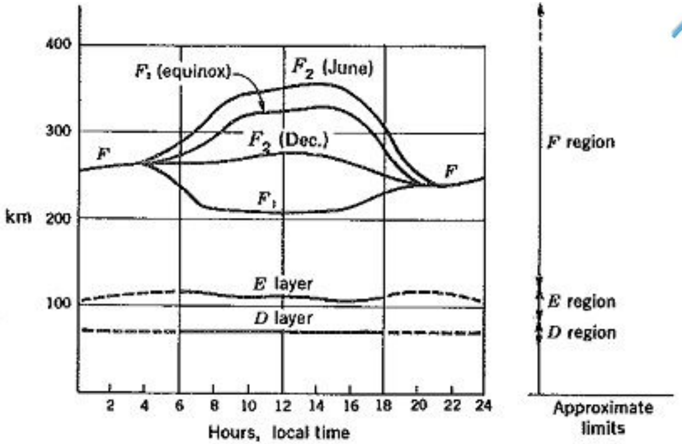
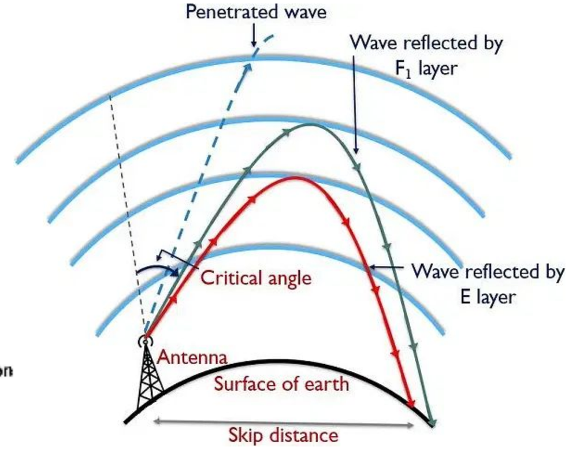


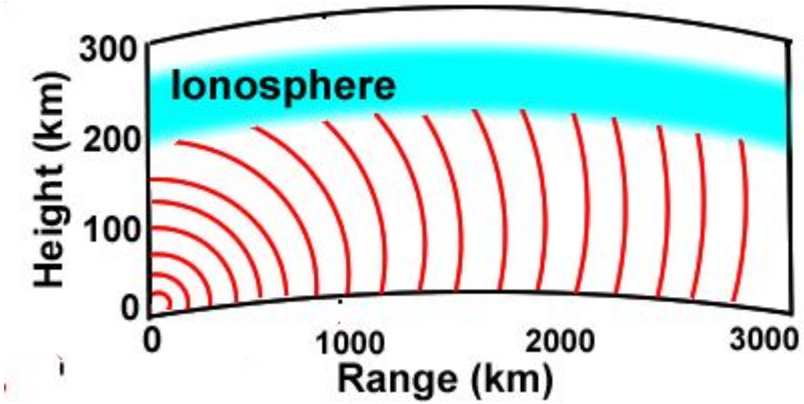
FIGURE 8-13 Ionospheric layers and their regular variations.



Propagation Mechanisms & Models

Waveguide Mode

At VLF and ELF the Earth–ionospheric space is modeled as a concentrically spherical waveguide with the ground as the lower boundary and the ionosphere as the upper.



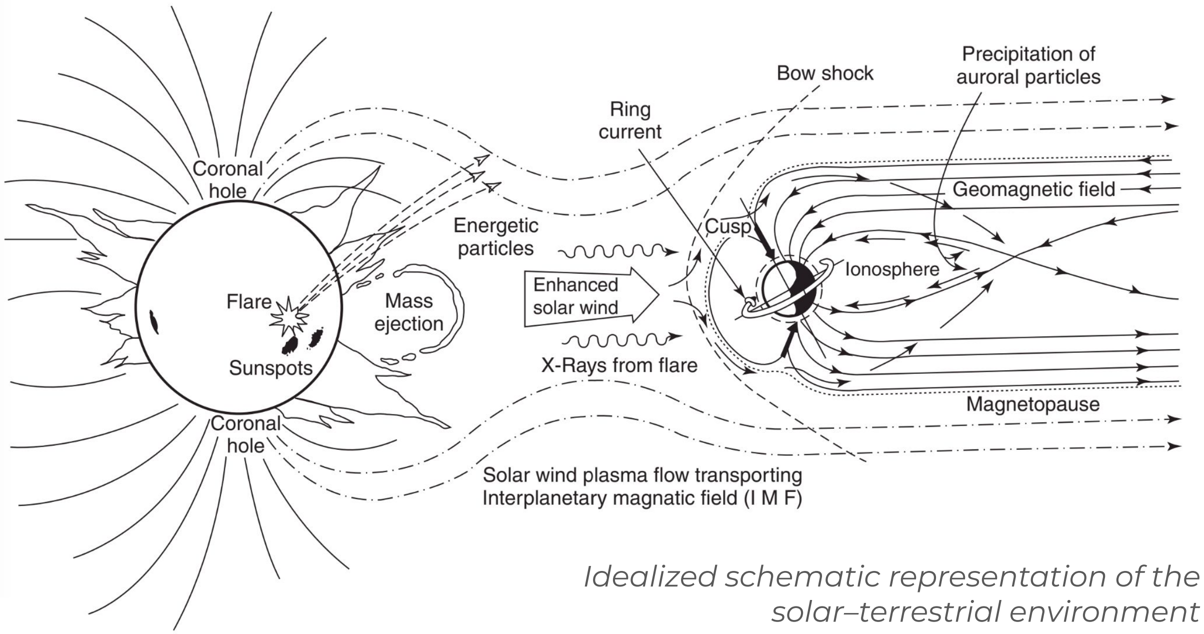
Electromagnetic waves in Ionosphere

EM waves over a very large spectral range interact with the terrestrial ionosphere and with radio receivers on Earth's surface or in space:

Solar Radiation (including the extreme ultraviolet, soft X rays, Lyman Alpha; hard X rays and cosmic rays) produce the ionospheric layers

Solar Radio Noise of frequencies ~20 MHz up to 1 GHz penetrates the terrestrial ionosphere and can degrade the SNR ratio received on various radio services

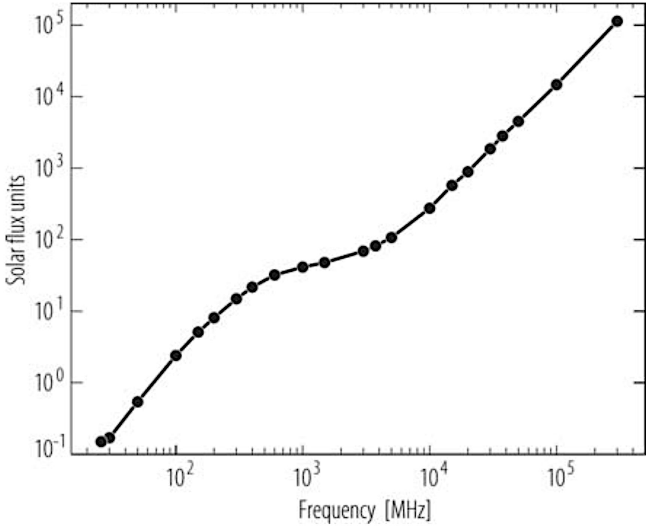
Radio signals from ELF through low VHF (~10 Hz to ~35 MHz) propagate over long terrestrial paths by reflection and refraction by the ionosphere.



Idealized schematic representation of the solar–terrestrial environment

Radio Sun

- The solar atmosphere emits radio emission at all wavelengths and at all times
- Total flux density varies with magnetic activity as manifest in sunspots
- During periods without sunspots, the sun exhibits a minimal radiation level known as **quiet radio emission**
- The presence of sunspots enhances the radio emission, producing a *slowly variable* component



Spectrum of quiet solar radio flux density.
1 Solar Flux Unit (sfu) = 10^{-22} W m^{-2} Hz^{-1}

Radio Sun

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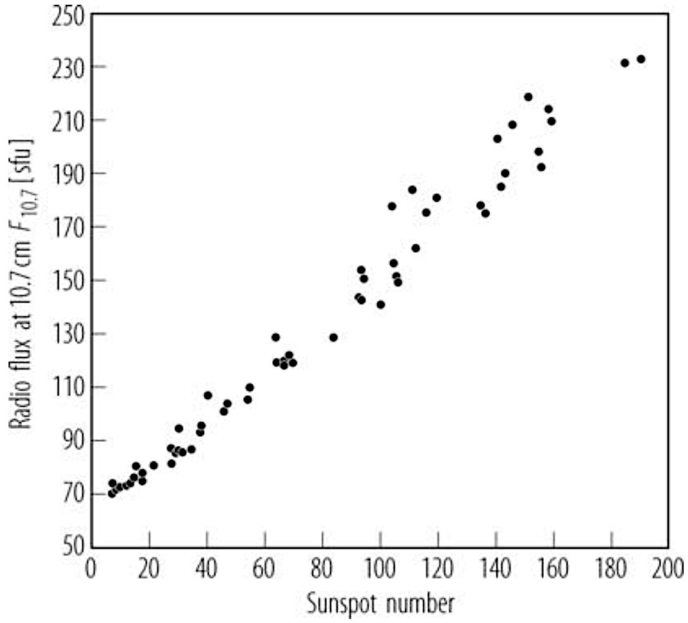


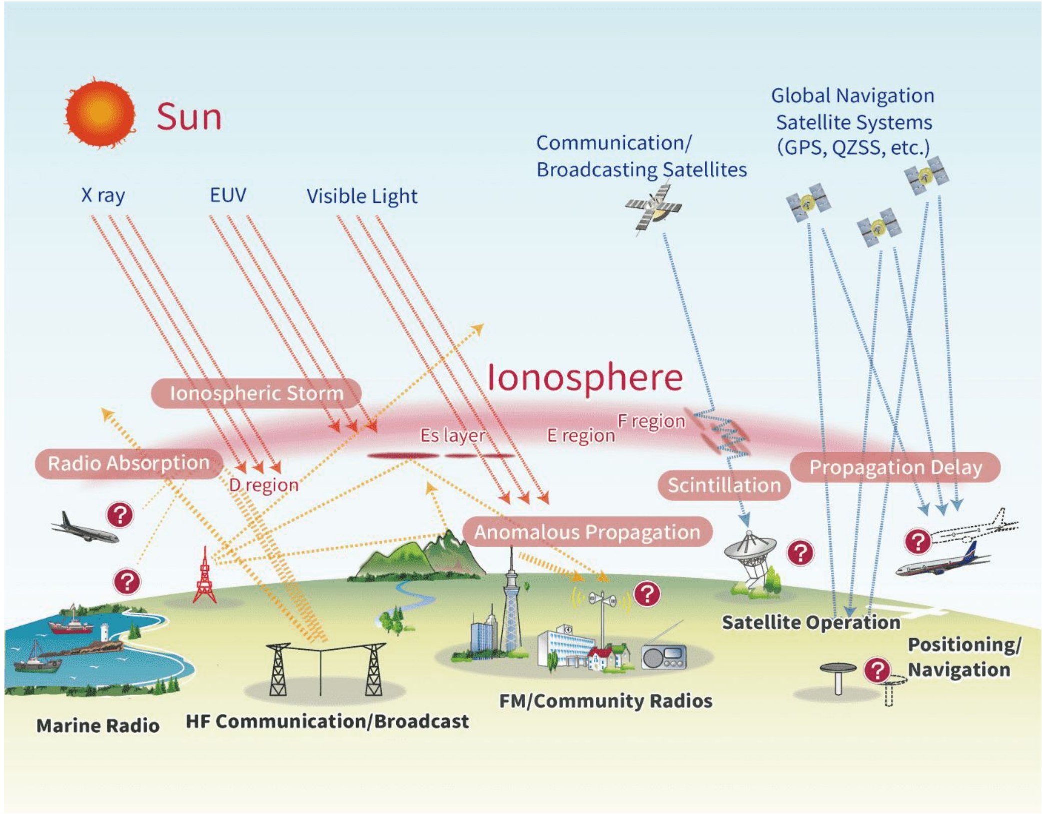
Annually averaged solar radio emission at λ = 10.7 cm from 1947 to 2009 (S-component and quiet sun, excluding temporary bursts) vs. sunspot number.

Radio Sun

Solar Eruptive Activity

- Most solar eruptions originate in areas that have strong magnetic fields, almost always with sunspots: **active regions**
- Active regions are numerous and common during solar maximum and scarce during solar minimum
- **Flares** and **CMEs** are two of the major types of solar eruptions.
- Flares can emit at all frequencies across the electromagnetic emission spectrum, from gamma rays to radio.
- CMEs are effective in perturbing the Earth's magnetic field and are known to cause the strongest magnetic storms, due to the strong magnetic fields encapsulated in CMEs.
- The frequency of solar flares and CMEs tracks with the solar cycle.

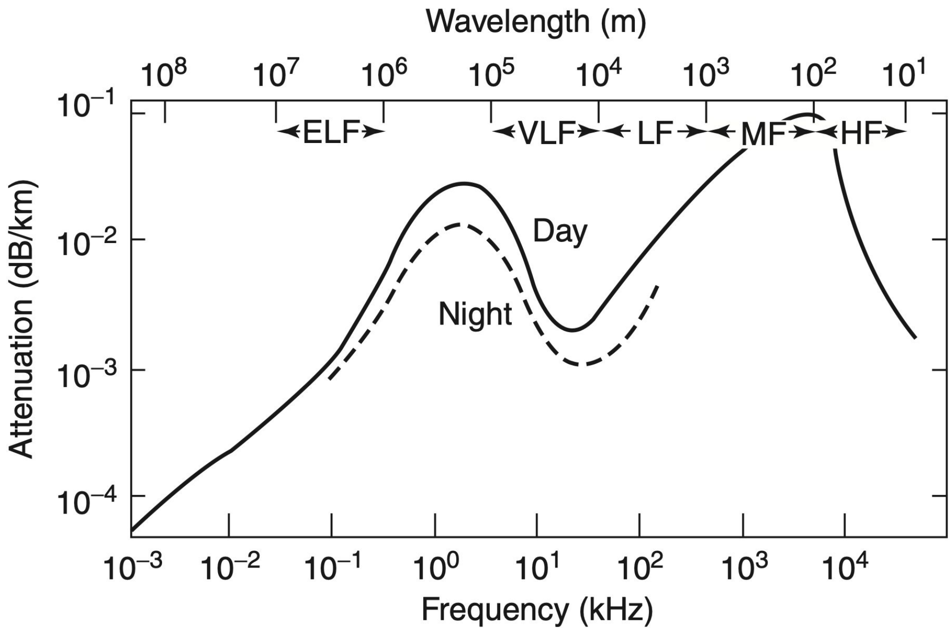
Impact of Space Weather



X-class flares	Major events that can trigger planet-wide radio blackouts and long-lasting radiation storms
M-class flares	Medium-sized. Can cause brief radio blackouts that affect mainly polar regions. Minor radiation storms sometimes follow an M-class flare
C-class flares	Are small with few noticeable consequences on Earth

Impact on ELF & VLF

Basic propagation mode: waveguide (also ground wave)



Night–day variation of attenuation of radiowaves in the ionosphere as a function of frequency from 1 Hz to 30 MHz.

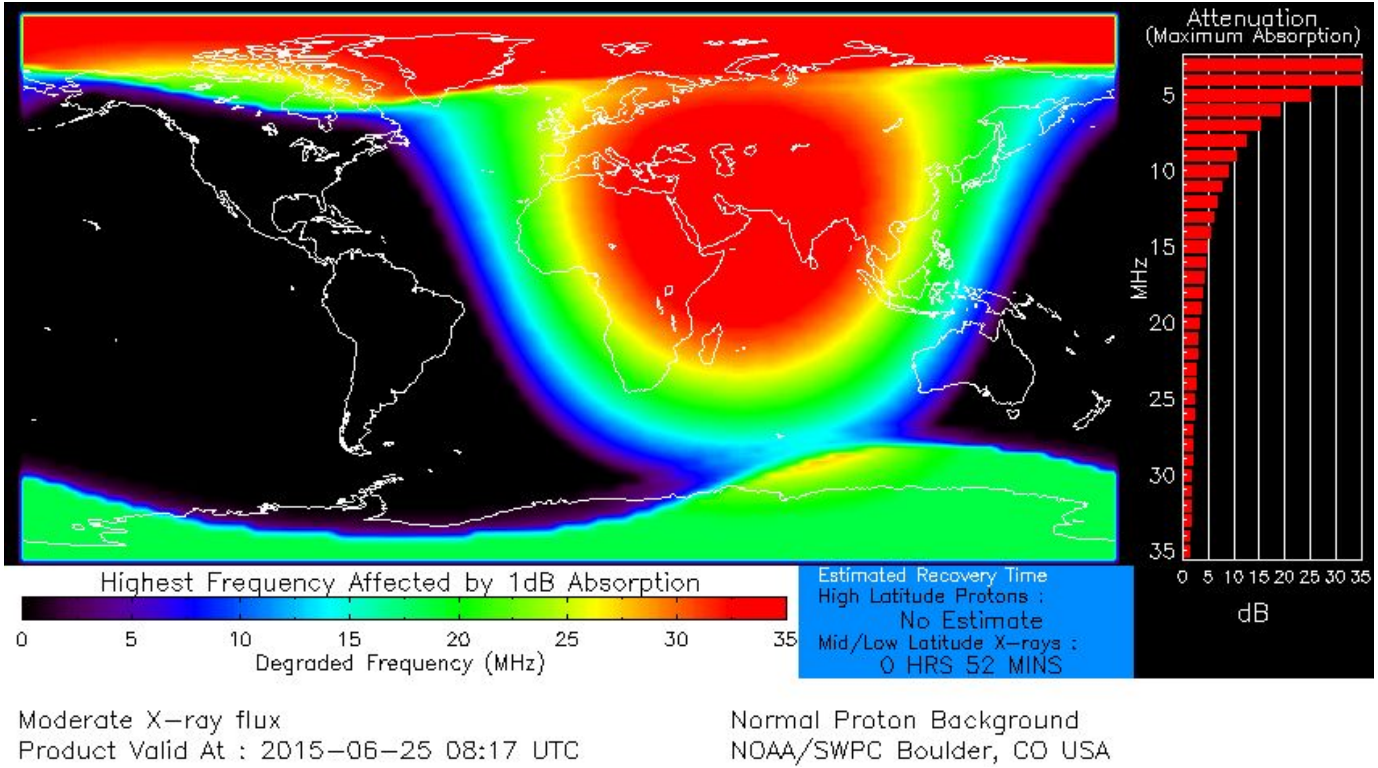
Impact on LF & MF

Basic propagation modes:

- LF, below 100 kHz → ground wave
- LF, above 100 kHz → Ionospheric reflection (sky wave)
- MF, daytime → ground wave
- MF, above 500 kHz→ Ionospheric reflection (sky wave)

Impact on HF

Basic propagation mode: Ionospheric reflection (sky wave)



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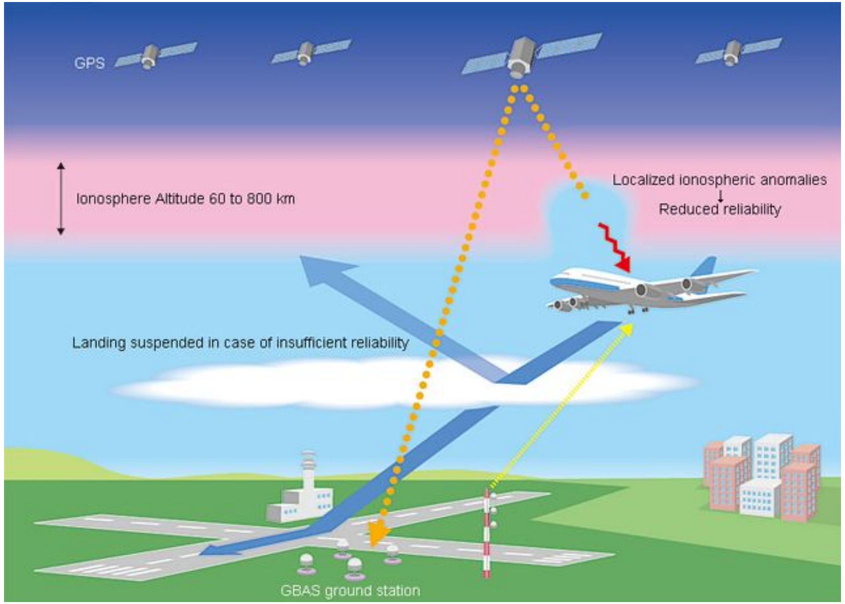
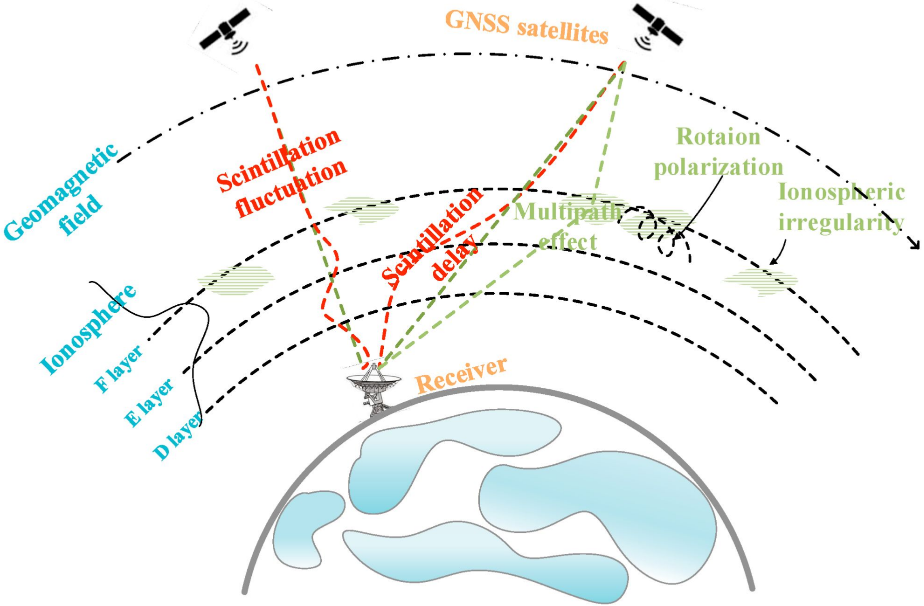
Impact on VHF – UHF – SHF – EHF

Basic propagation mode: LoS



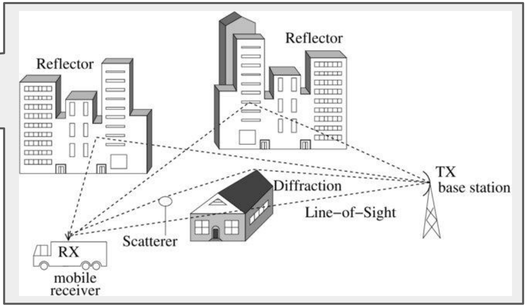


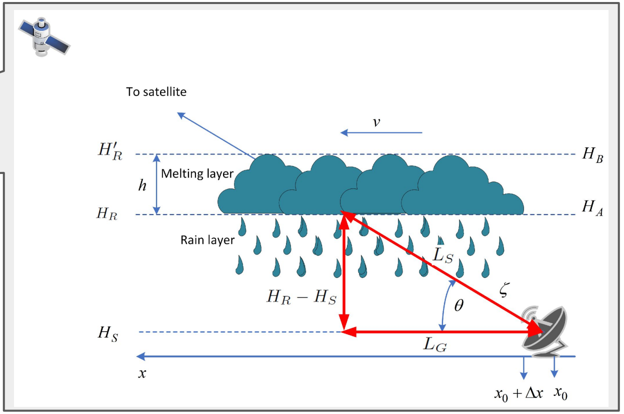
Ionospheric Scintillation

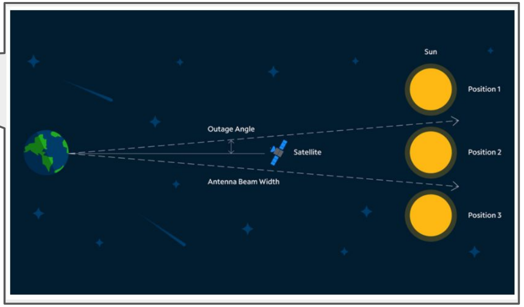
Other RF-comm degradation causes

Many other aspects are involved:

- Multipath
- Shielding
- Radio specs
- Noise (human originated)
- Rain attenuation (SHF/EHF)
- Sun outage







Royal Observatory of Belgium

Questions?

Panorama of the Humain Radio-Astronomy Station

https://sidc.be/humain/home

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