Chapter 3: Propagation

Physical Phenomena and Propagation Modelling

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V 1.0

References

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Further Reading

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  http://www.itu.int/rec/R-REC-P/eN

3. Physical Phenomena

1. Free Space Loss Review
2. Propagation Modes
   - Earth-Ionosphere Waveguide
   - Surface Waves
   - Sky Waves
   - Space Waves
   - Tropospheric Scattering
   - Meteor-Burst Propagation
3. Physical Phenomena
   - Refraction
   - Diffraction
   - Reflection
   - Scattering
   - Molecular Absorption
   - Hydrometeors
4. Summary

1. Free Space Formula: Basic Concept Review

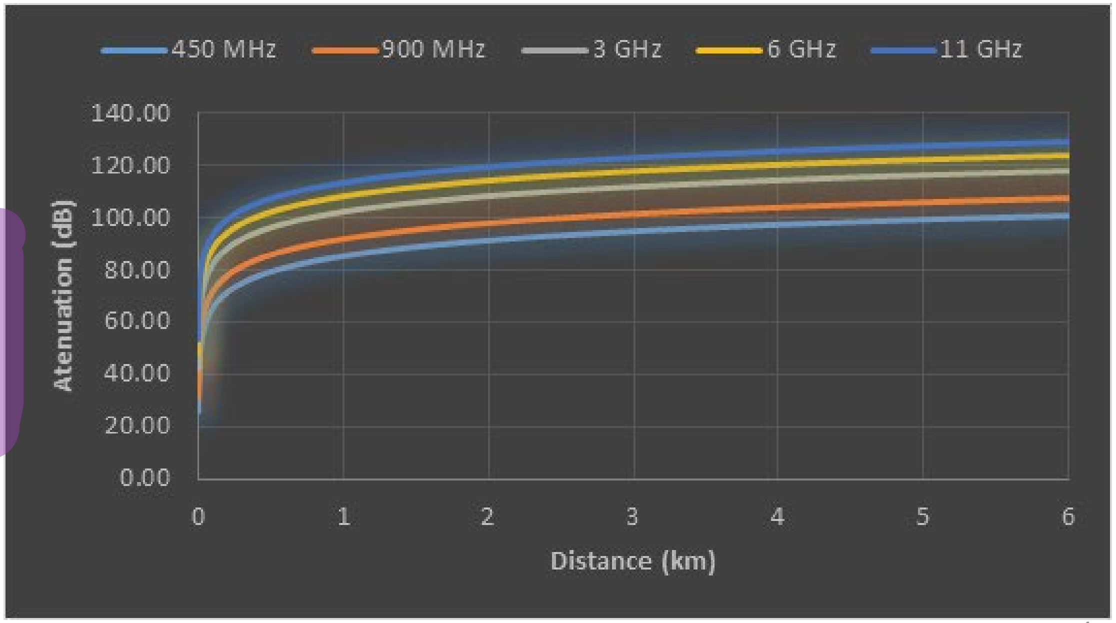
- **Free Space Loss:**
  - Used to predict the received signal strength when transmitter and receiver have clear unobstructed LOS (line-of-sight) path. Perfect line-of-sight (LOS) propagation is complicated by the fact that the typical radio communication system is land-based, close to earth, and affected by the environment through which it passes. Even terrestrial links that are unobstructed, such as links between mountaintop towers, may be affected by atmospheric conditions, rain, or ground reflections, and are therefore technically not "free space."
  - No "real" losses. Free space does not attenuate electromagnetic waves. FS losses are caused by the spreading of EM energy.

- The free space loss (in decibels):

$$L_{FSL}(dB) = 10\log\left(\frac{4\pi d}{\lambda}\right)^2$$

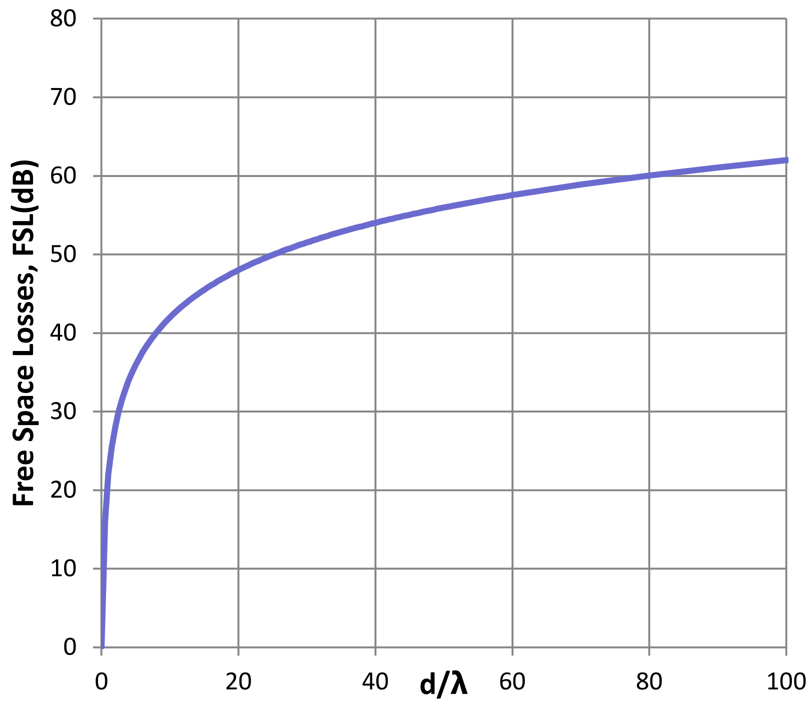
Distantzia bikoiztu: Ezberdintasuna = 6dB

d < lambda/(4*pi) denean:
Top gear top tip: AVOID
(Gauza arraroak)



1. Free Space Formula: Basic Concept Review

- Some Figures:
  - L_{FSL} for a separation between Tx and Rx equal to λ the attenuation is approx 22 dB
  - Geostationary Satellite Link Losses close to 180-200 dB (depending on the frequency)
  - Losses are logarithmic: 20 km or 22 km distance is not a relevant difference in most cases (20 log 22/20=0.82 dB)
  - Variation of 6 dB when the distance is doubled.



2. Physical Phenomena and Propagation Modes

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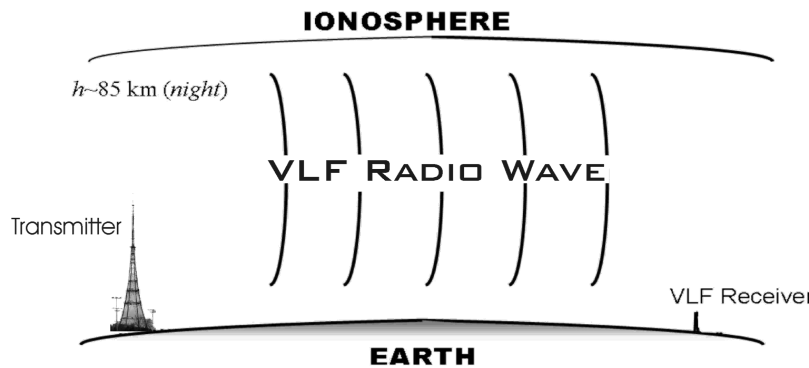
2. Propagation Modes: Earth-Ionosphere Waveguide

VLF (3 kHz-30 kHz)

- In this band the earth's surface and the ionosphere behave as good conductivity media

The distance between the earth's surface and the ionosphere (60-100 km) is in the range of the wavelength and thus the propagation can be described as an **spherical loss waveguide**.



- The **antennas** used in these systems are **electrically small** and **physically big**
- **Radionavigation systems** (old Omega) and Mobile Maritime Telegraphy (submarines)
- The coverage is the **entire earth**

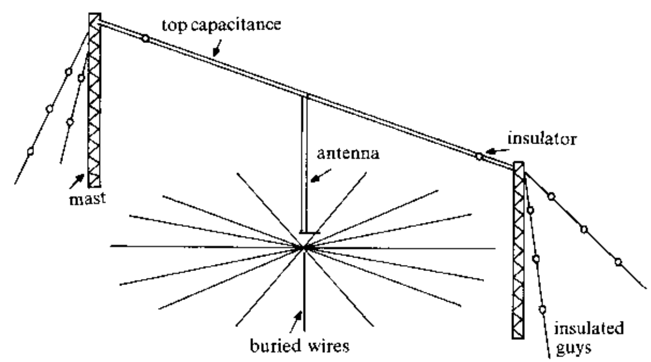


Fig. 2.14 A short vertical monopole transmitting antenna with buried conductors to reduce ground losses and top capacitance to increase the effective height.

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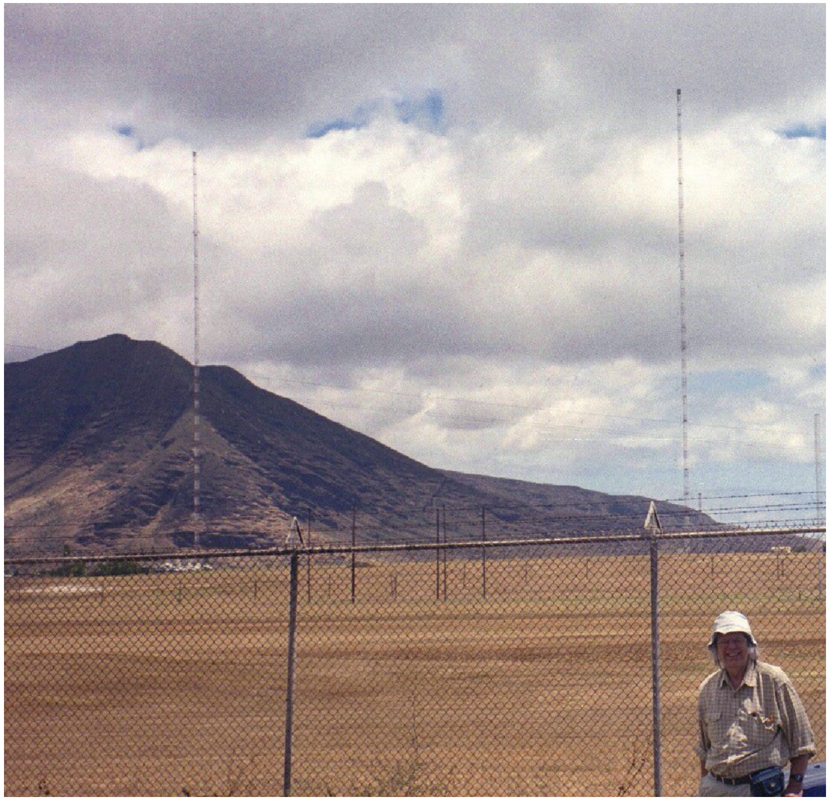
2. Propagation Modes: Earth-Ionosphere Waveguide

The Antarctic-Arctic Radiation-belt (Dynamic) Deposition - VLF Atmospheric Research Konsortium (AARDDVARK) provides continuous long-range observations of the lower-ionosphere



Towers of the US Navy VLF transmitter, at Lualualei, Hawaii. This transmitter has radiated power of ~500 kW operating at frequency of 21.4 kHz. The towers in the background are ~460 meters high each.

http://www.physics.otago.ac.nz/space/AARDDVARK_homepage.htm

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2. Propagation Modes: Surface Wave

- Most relevant for low frequencies (**<30 MHz**) MF, HF
- Can propagate over **long distances (30 – 200 km),** even higher in VLF
- Depends on **ground constants** (conductivity, permittivity)
  - The **best** propagation medium is **sea**
  - The **worst** case are **desserts** and **urban areas** (low conductivity and low permittivity values)
  - **ITU-R World Map of Conductivities**

- **Horizontally** polarized waves are **attenuated** significantly

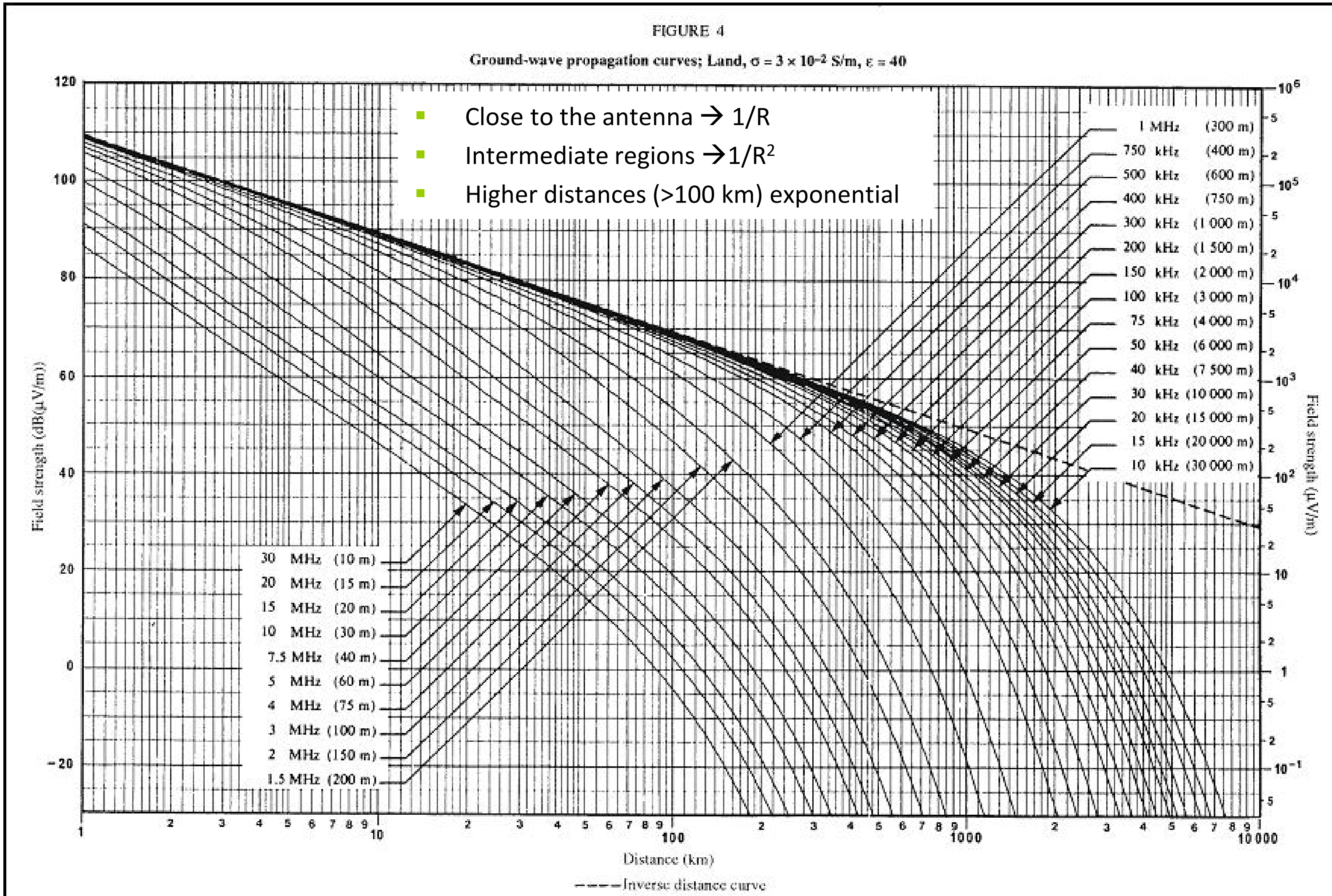
- Practical systems are **vertically polarized**

- Transmitting antennas **vertical dipoles** (λ/4 on earth)

Medium Wave Radio Broadcast Antenna system. Radio Vaticana

2. Propagation Modes: Surface Wave

- ITU-R P.368



- Close to the antenna → 1/R
- Intermediate regions → $1/R^2$
- Higher distances (>100 km) exponential

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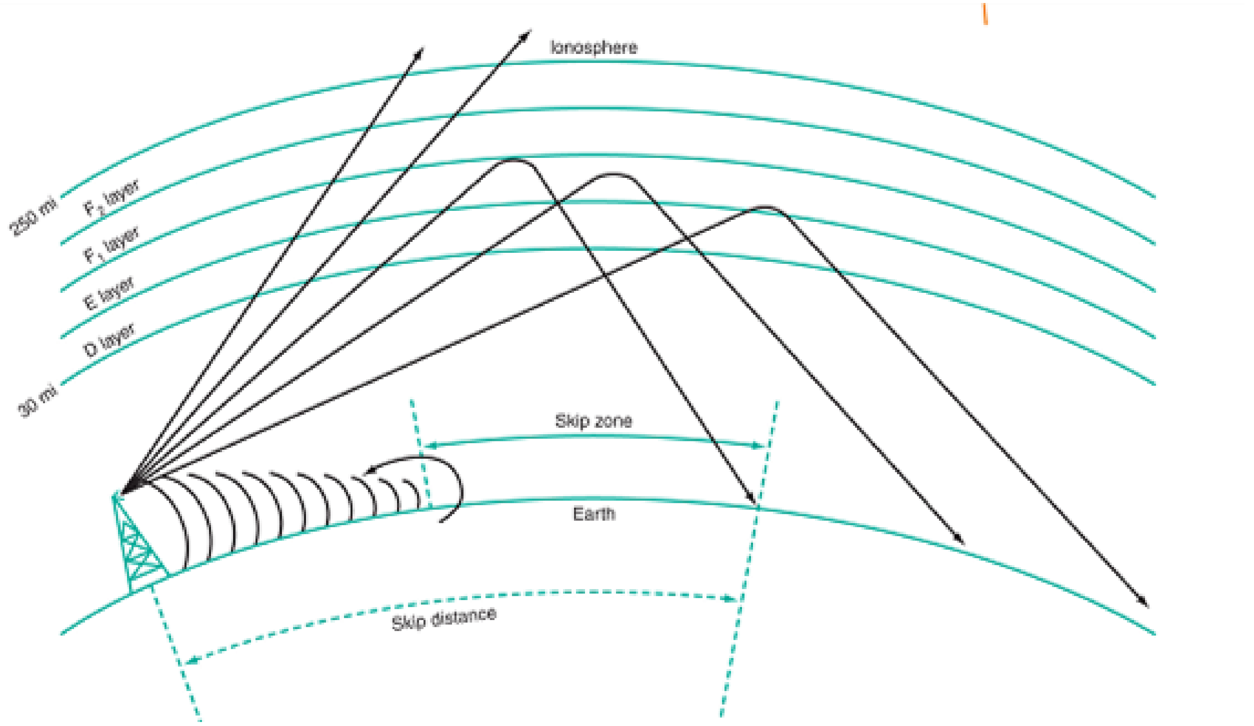
2. Propagation Modes: Sky Wave

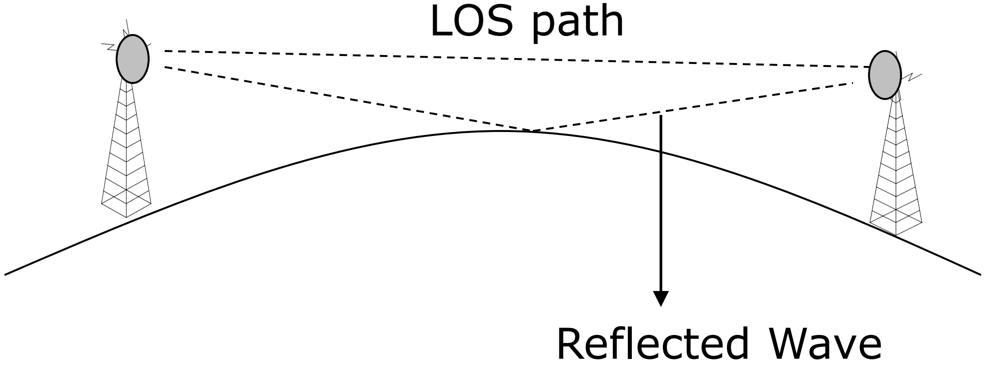
- At **HF** bands (3 -30 MHz), the ground waves tend to be absorbed by the earth
  SHORTWAVE
- The waves that reach ionosphere (100-500 km above earth surface) are **refracted** and sent back to earth
- Propagation is **unstable** and difficult to predict
- Used by **broadcasting** and aeronautical services



More when talking about refraction

2. Propagation Modes: Space Wave

- As f increases (**VHF, UHF…**), the radio wave propagates as “**rays**”
- In reality the rays are not infinitesimal but a zone around the transmitter – receiver LOS line (**Fresnel ellipsoids**)
- At frequencies higher than UHF the ellipsoid is negligible for short links (a few kilometers)
- The energy that reaches the receiver has two components
  - **Direct wave** (follows the line of sight)
  - **Reflected Wave** (reflected on the ground)
- **Refraction, diffraction, scattering, absorption** are relevant phenomena.



2. Propagation Modes: Space Wave

- **Directive antennas** better if located at **elevations** over the average height

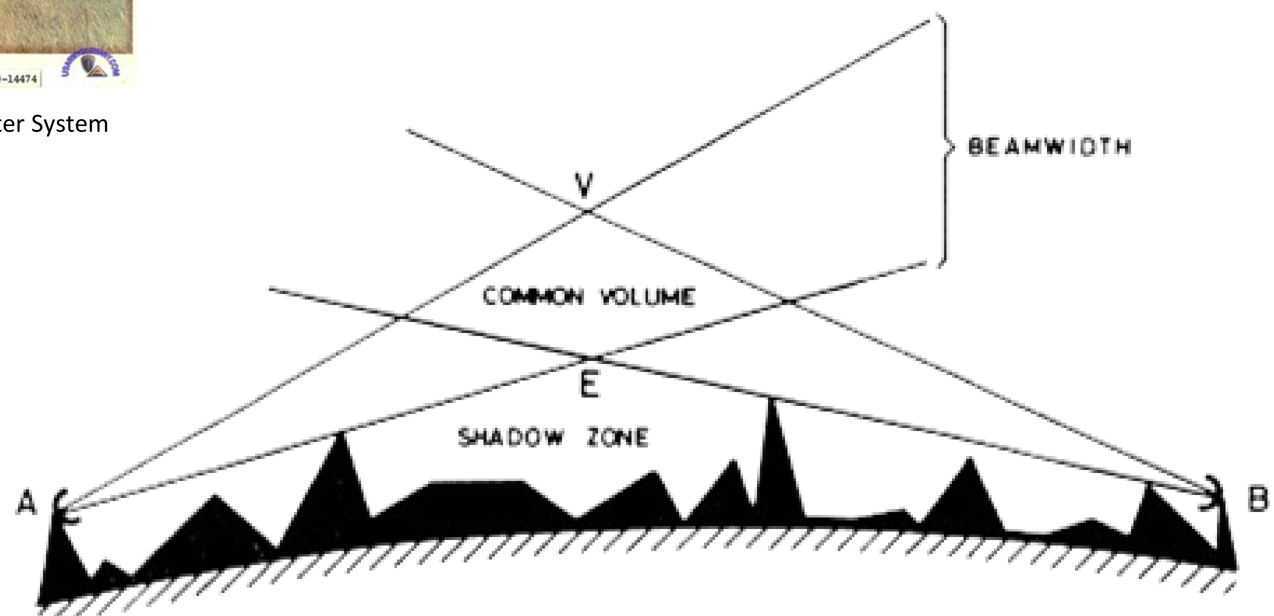
- The **range** is **very variable** and has a wide range of applications
  - Personal communications a few meters
  - Land mobile approx. 1 km
  - LOS links 50 km
  - Satellite-Earth 40000 km

- The **most usual propagation mode** (most systems are above VHF today):
  - Broadcasting
  - Mobile Services
  - Radiodetermination
  - Fixed Services
  - Satellite Communications

2. Propagation Modes: Tropospheric Scattering

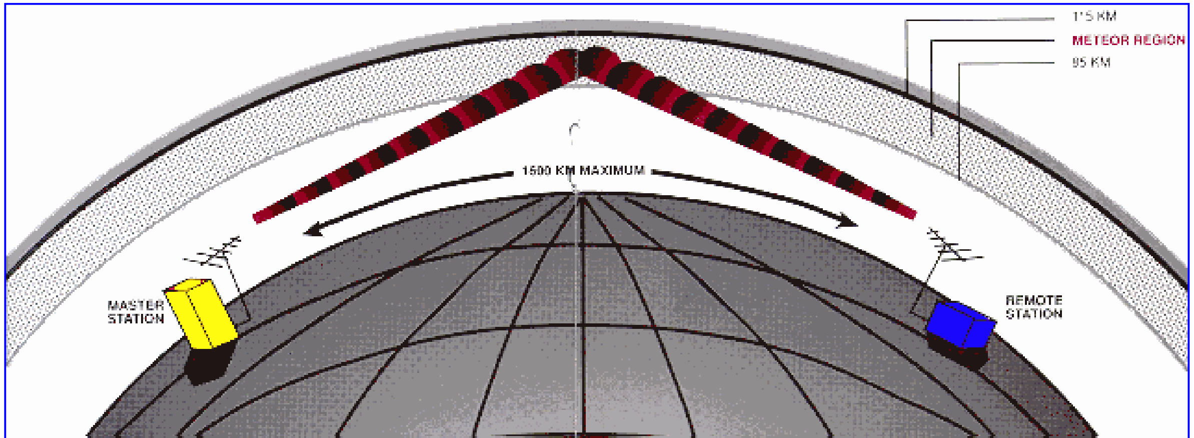
Ringstead, England, UK-Spain Tropospheric Scatter System
120-foot (36.5 m) tall billboard antennas

- Usually **UHF**
- **Aperture antennas**
- **High** transmission **power** and receiver sensitivity
- Power proportional to common volume (antennas not too directive)
- **Low availability** (data communications only)
- Today only **military applications**



2. Propagation Modes: Meteor-burst propagation

- **Scattering** from ionization caused by **meteor trails** can provide a convenient means of communication at **HF** and **VHF.**
- At certain times of the year, meteors occur in the form of showers and may be prolific over durations of a few hours. These small meteor trails are capable of **reflecting radio waves**. Ingeniously, *Meteor Scatter* communication systems make use of this property.
- The operational principle is as follows: the Master Station transmits a continuous, coded signal. When a meteor appears in the proper location, it reflects that signal to a receiving Remote Station. The performance of a meteor burst link is defined, as the "**wait time**" required to transfer a message between two stations at a specified reliability.
- Applications for this system include **environmental monitoring, performance monitoring…**



2. Propagation Modes: Summary

Band	Propagation Mode	Range	Availability	Use
VLF (3-30 kHz)	Earth- Ionosphere waveguide	--	Continuous	Radionavigation Mobile Maritime
LF (30-300 kHz)	Surface Wave	<1000 km (water)	Continuous	Reference Freq.
MF (300-3000 kHz)	Surface Wave	<100 km	Continuous	Broadcasting
	Sky Wave	100< d <500 km	Night	Broadcasting
HF (3-30 MHz)	Sky Wave (3-8MHz) (3-12 MHz) (6-25 MHz)	<300 km >500 km >500km	Day Night Day	Fixed Service Mobile Service Broadcasting
	Surface Wave	<100 km	Continuous	Broadcasting

2. Propagation Modes: Summary

Band	**Propagation Mode**	Range	Availability	Use
VHF (30-300 MHz)	Space Wave	LOS (50 km)	Continuous	Mobile Broadcasting Radio Navigation
UHF (300-3000 MHz)	Space Wave	LOS (40 km)	Continuous	Fixed Service Mobile Broadcasting
	Tropospheric Scattering (f<500 MHz)	600 km	Continuous (low)	Fixed Service
SHF (3-30 GHz) EHF (above 30 GHz)	Space Wave	LOS (40 km)	Continuous	Fixed Service Satellite Services Mobile Services

3. Physical Phenomena

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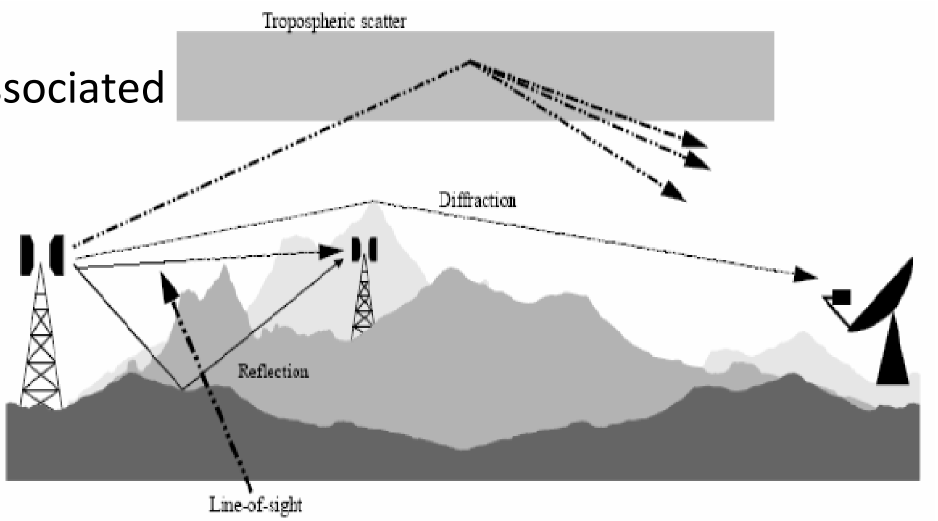
3. Physical Phenomena

- Electromagnetic waves propagate at a speed similar to the speed of light (influenced by the EM characteristics of the media)
- For the sake of simplicity it is assumed in most cases that signals propagate at the speed of light: $3\ 10^8$ m/s
- Propagation is affected by the medium and different objects that interact with the wave front
- The most remarkable phenomena associated to propagation are:
  - Refraction
  - Reflection
  - Diffraction
  - Small Obstacles — Scattering
  - Rain — Absorption



- The impact of these phenomena depends significantly on the frequency
- In most cases, there will be a combined effect of the different effects that will influence on the way that the energy is propagated

3. Physical Phenomena

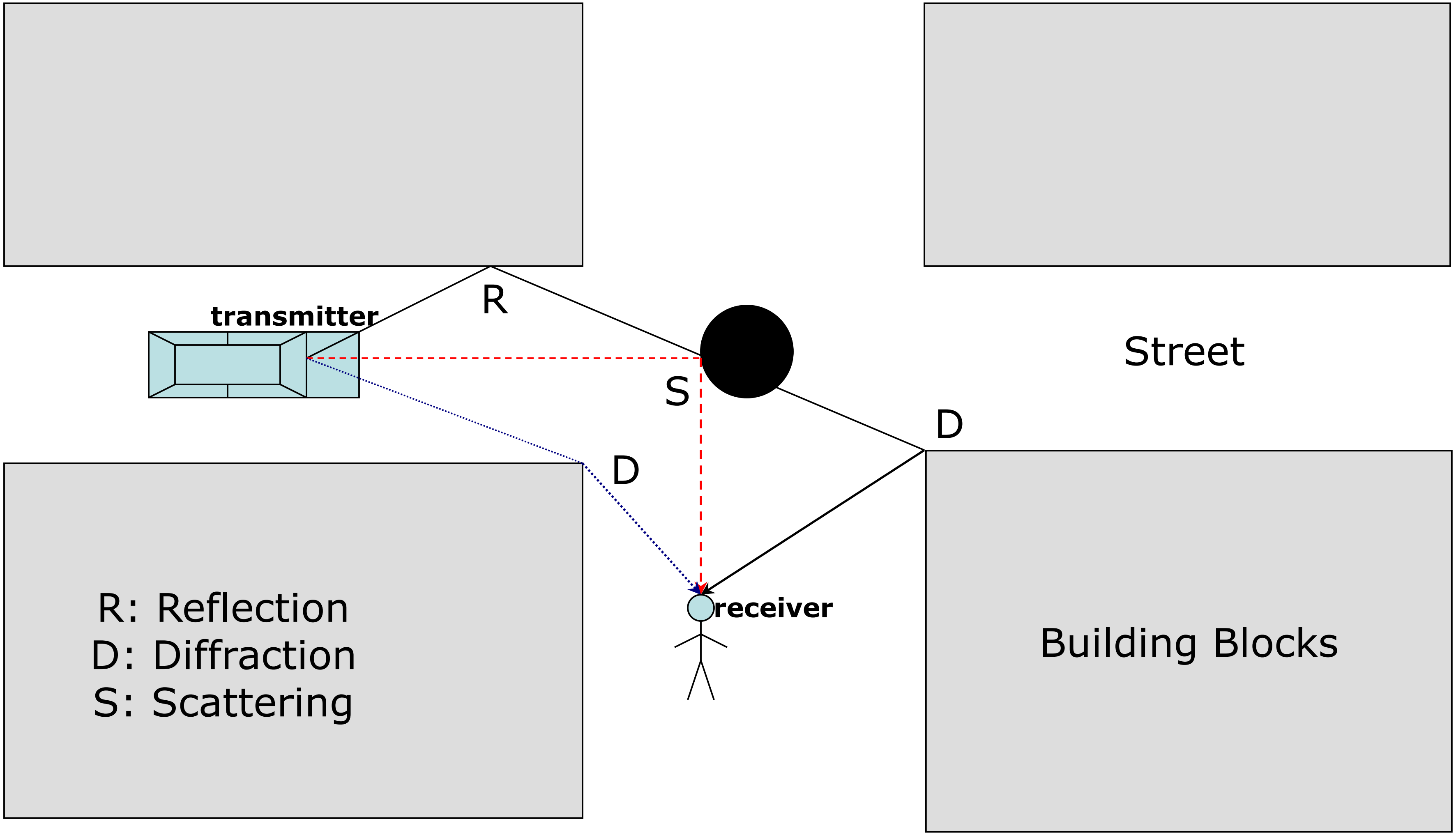
- Radio wave propagation modeling and simulation plays an important role in planning for any wireless communication system.

- Models can be generally categorized as empirical or deterministic:
  - **Empirical models** are based on extensive field measurements and statistical analysis. Usually a simple formula so they are not computationally intensive.
  - **Deterministic**, or physical models attempt to estimate path loss by simulating the link with the math and physics of wave theory.

- Computer simulated propagation results should be tested against real-world measurements in order to refine the models.

- Modeling radio wave propagation is not a simple task.

3. Physical Phenomena



3. Physical Phenomena

- The environment through which the signal propagates includes **macro elements** such as the conductive properties of the earth’s surface or climate types, and **micro elements** like vegetation or man-made objects. In addition, the environment **constantly changes**. Variations in temperature, pressure and humidity change the refractive properties of air causing the signal to bend, scatter or become trapped in a duct.

- Signals can be reflected, refracted, diffracted, scattered and absorbed by any number of environmental elements. Simulating the environment’s effects on radio signals is very complex.

- Some physical phenomena, such as **diffraction** --- **Empirical model**. (Measurements)

- Some physical phenomena, such as **reflection** --- **Deterministic model**. (Theoretical approximations)

- Other physical phenomena --- very complex modeling --- out of the scope of this course

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3. Physical Phenomena

1. Free Space Loss Review
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   - **Refraction**
   - Diffraction
   - Reflection
   - Scattering
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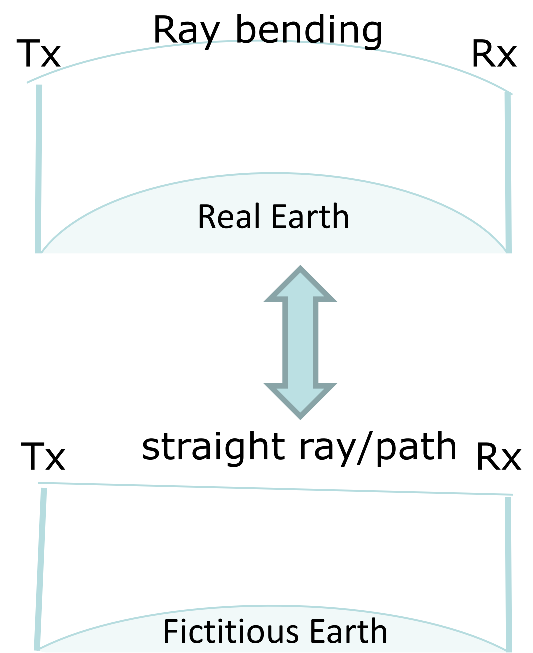
4. Summary

3. Physical Phenomena. Refraction

- **Troposphere Refraction**: physical phenomenon
  - A radio ray passing through the lower layer of the atmosphere undergoes bending caused by the gradient of the refractive index. Since the refractive index varies mainly with altitude, only the vertical gradient of the refractive index is generally considered.
  - Ray curvature (Change in direction)
  - Bending of rays
  - Effective Earth radius
  - It does not suppose additional losses in the link budget.
  - **Effective Earth radius** has to be considered for computing losses due to **difraction**.
  - Ducts
  - Scintillation

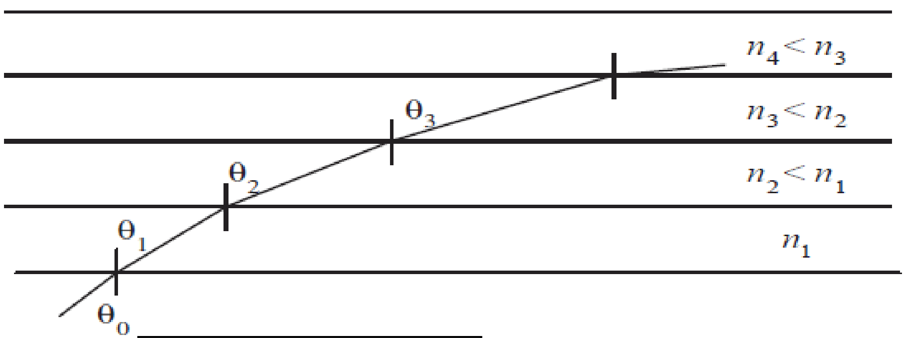


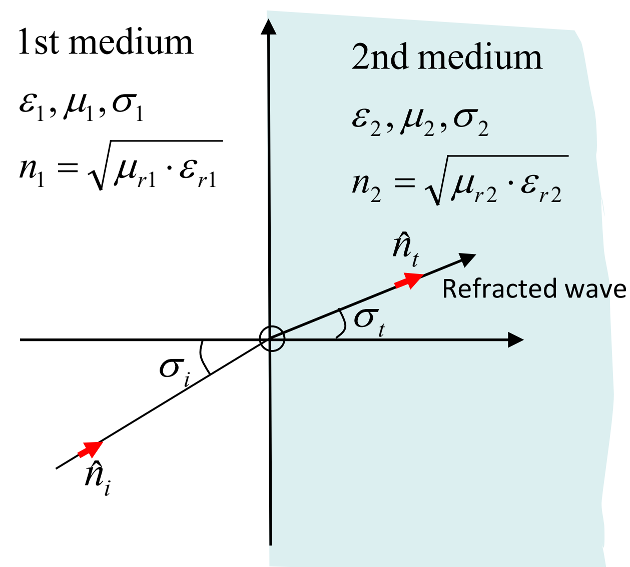
The troposphere is the lowest layer of Earth's atmosphere. Average height is 13 km.

3. Physical Phenomena. Troposphere

- The refractive index of the atmosphere changes with height above the surface
- At greater heights the atmosphere is less dense resulting in a smaller index of refractivity
- This causes the rays to curve downward as they propagate in the atmosphere
- This effect can be understood by considering the atmosphere as divided into layers, with constant values of refractive index over each layer

$$\boxed{n_2 \sin\sigma_t = n_1 \sin\sigma_i}$$





$$\boxed{\begin{aligned} n_1 \sin\theta_1 &= n_0 \sin\theta_0 \\ n_2 \sin\theta_2 &= n_1 \sin\theta_1 \\ n_3 \sin\theta_3 &= n_2 \sin\theta_2 \\ n_4 \sin\theta_4 &= n_3 \sin\theta_3 \end{aligned}}$$

$$\begin{aligned} n_2 < n_1 &\Rightarrow \theta_2 > \theta_1 \\ n_3 < n_2 &\Rightarrow \theta_3 > \theta_2 \\ n_4 < n_3 &\Rightarrow \theta_4 > \theta_3 \end{aligned}$$

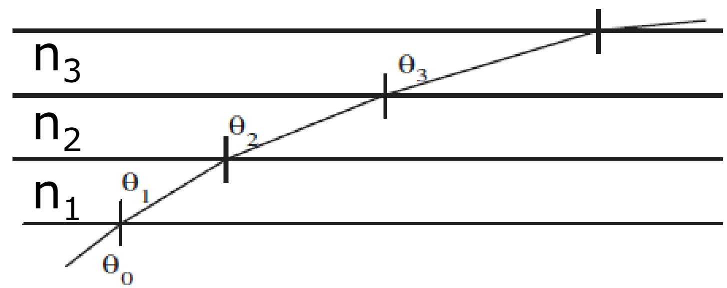
smaller index of refractivity => the ray curves downward

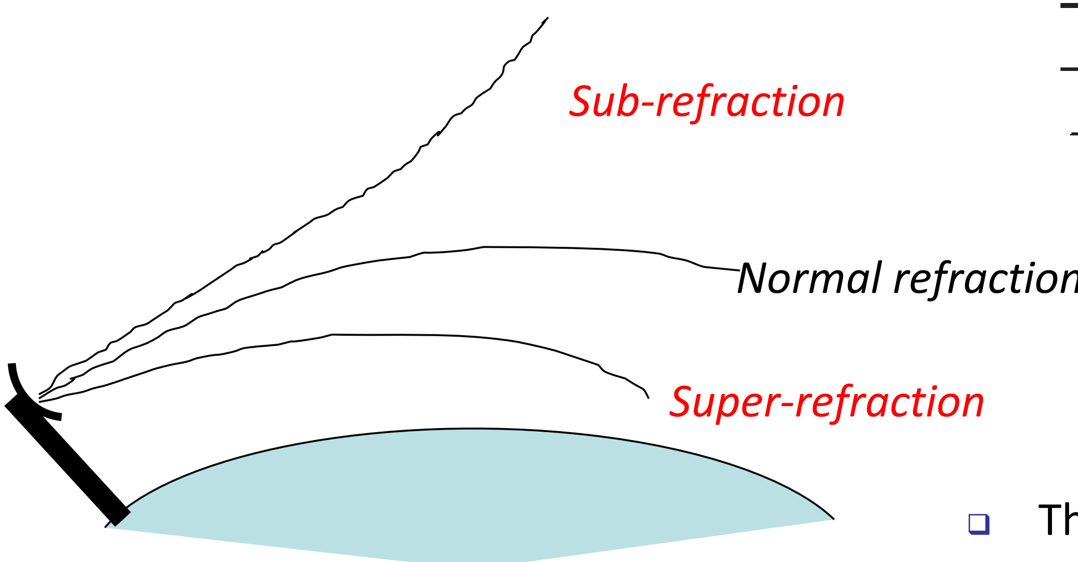
3. Physical Phenomena. Troposphere

$n_2 < n_1 \Rightarrow \theta_2 > \theta_1$ ... the ray curves downward — Normal refraction

$n_2 \ll n_1 \Rightarrow \theta_2 \gg \theta_1$ .... the ray curves downward very fast — Super-refraction

$n_2 > n_1 \Rightarrow \theta_2 < \theta_1$ .... the ray curves upward — Sub-refraction





- The refractive index values are not relevant
- Differences are relevant

refractive index => Radio Refractivity=> Radio Refractivity Gradient

n **N** **ΔN**

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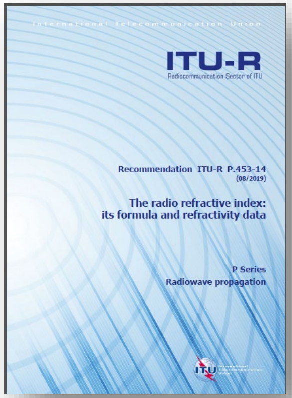
3. Physical Phenomena. Refraction



- **Radio Refractivity** (Sp. "**Coíndice**") **ITU-R P.453**:
- The atmospheric radio refractive index, n, can be computed by the following formula: $n=1 + N\cdot 10^{-6}$

$$N = (n-1)\,10^{6}$$

- The radio refractivity, N, is:

$$N = N_{dry} + N_{wet} = 77.6\frac{P_d}{T} + 72\frac{e}{T} + 3.75\cdot 10^{5}\frac{e}{T^{2}} \qquad N-units$$

n	Refractive index
N_{dry}	is known as the "dry term"
N_{wet}	is known as the "wet term"
P	atmospheric pressure in hPa (1 hPa=1 milibar) $P=P_d+e$
P_d	dry atmospheric pressure in hPa (1 hPa=1 milibar)
T	temperature (K)
e	water vapor pressure in milibars (hPa)

This expression may be used for all radio frequencies; for frequencies up to 100 GHz, the error is less than 0.5%.

3. Physical Phenomena. Refraction

- **Refractivity as a function of height**
- Standard Atmosphere defined as the average value of troposphere properties

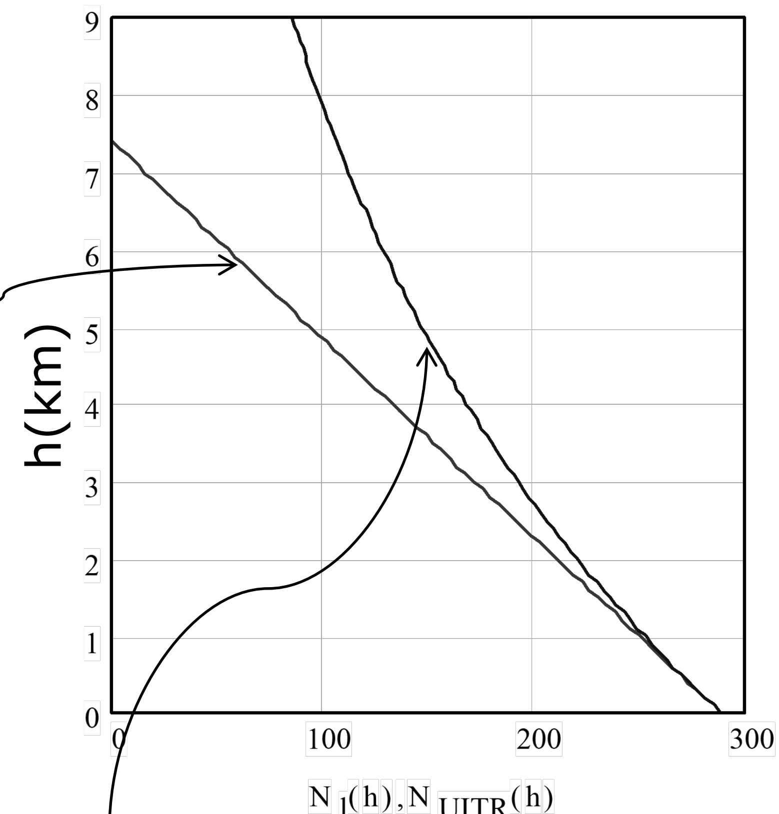
- Several Models:
  - Linear (up to heights lower than 1 km)

$$N(h) = 315 - 43 \cdot h$$

  - Exponential (otherwise:

$$N(h) = N_0 \exp\left(\frac{-h}{h_0}\right)$$

N_0	average value of atmospheric refractivity extrapolated to sea level (different value for different climates)
h_0	scale height for normalization purposes (km)
h	height over the mean sea level (km)



$$N(h) = 315 \cdot \exp(-0.135 \cdot h)$$

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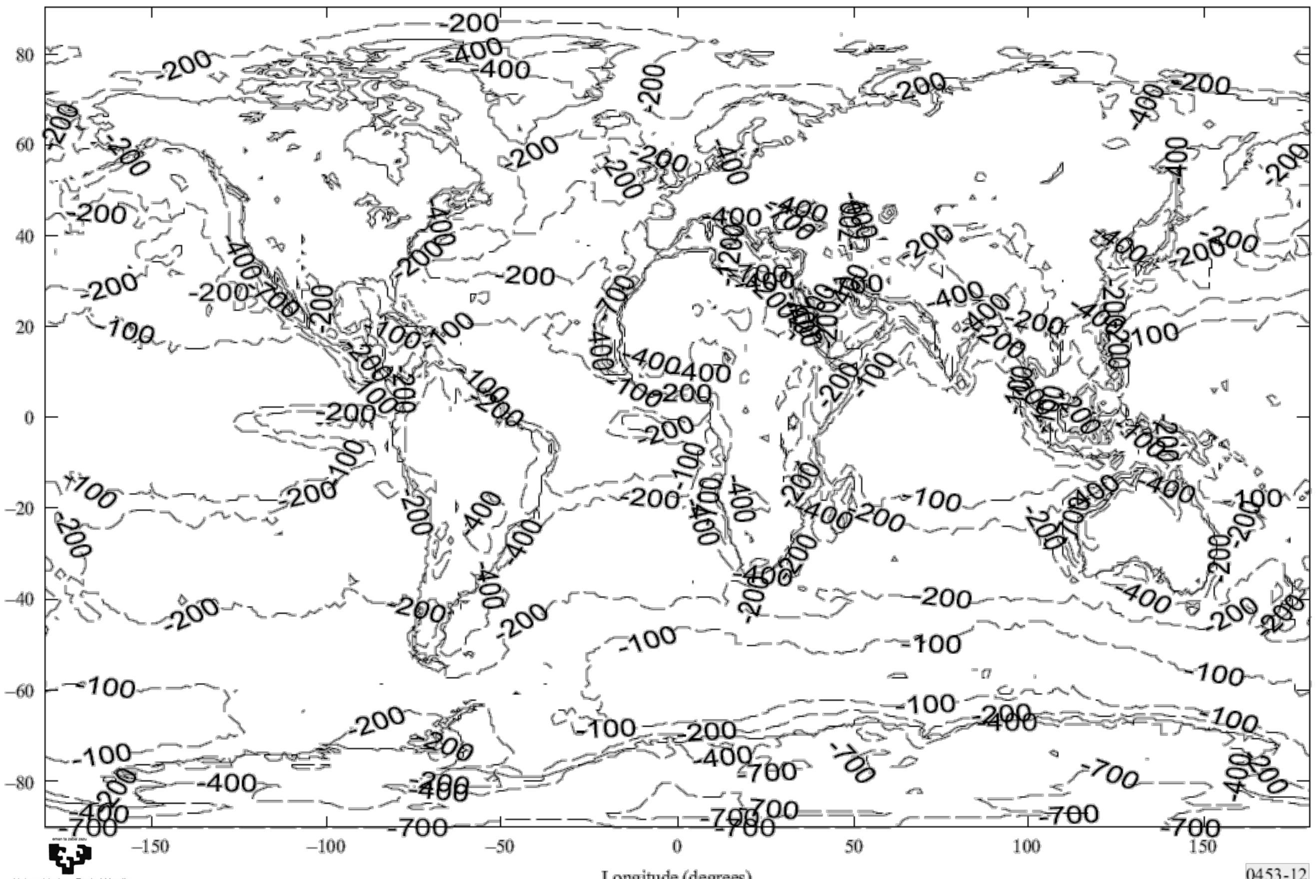
3. Physical Phenomena. Refraction

- The cause of the refraction impact: **refractivity gradient**, ΔN.
- For radiocommunication system design purposes, the statistics of ΔN are given by ITU-R P.453

FIGURE 12

Refractivity gradient not exceeded for 1% of the average year in the lowest 65 m

(This is the parameter referred to as dN_1 in Recommendation ITU-R P.530)

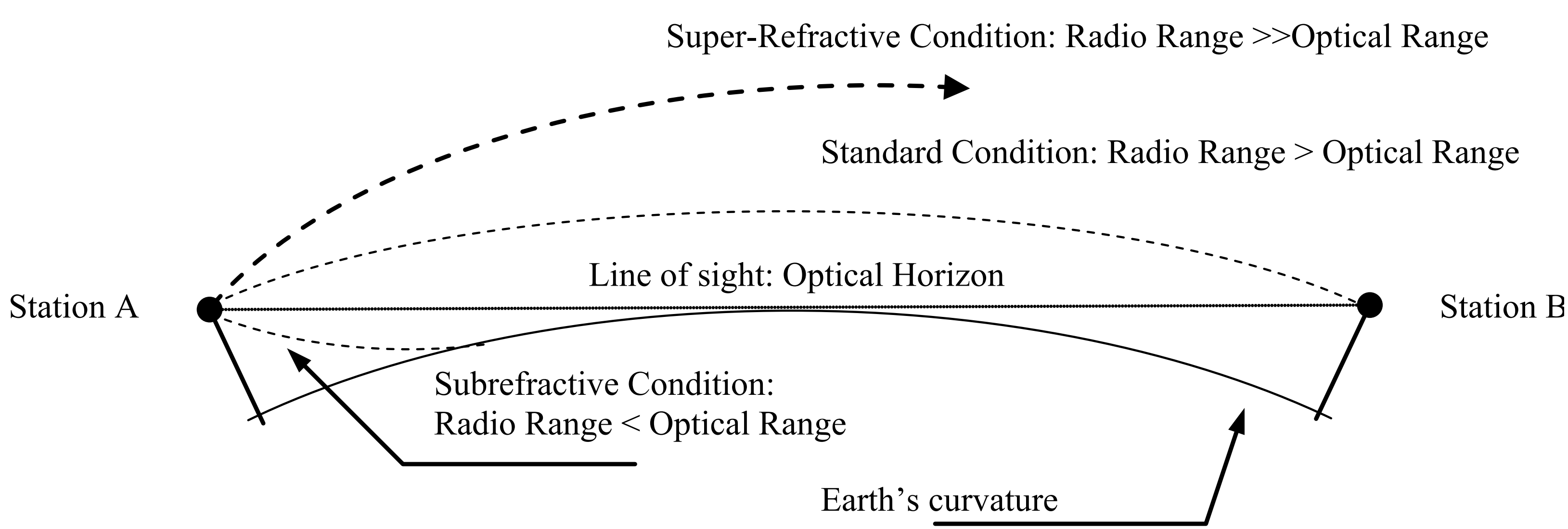


The values are given for:

- specific geographic location
- month of the year
- specific meteorological conditions
- height above median sea level.

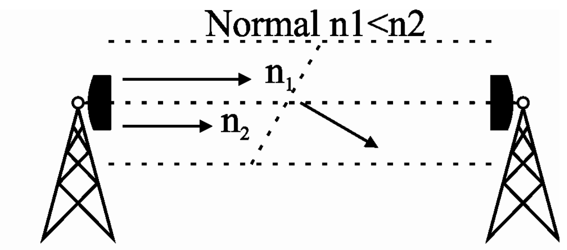
3. Physical Phenomena. Refraction

- Ray bending: effective earth radius
  - Displaying a bended propagation paths is not useful



3. Physical Phenomena. Refraction

- Ray bending: **effective earth radius**



- Under **standard** atmospheric conditions, if the radio refractivity gradient is close to **-39 N units/km**

$$\frac{1}{\rho} = -\frac{\cos\varphi}{n}\frac{\mathrm{d}n}{\mathrm{d}h}$$

ρ	is the bending radius of the wave trajectory
N	is the radio refraction index
$\mathrm{d}n/\mathrm{d}h$	is the vertical gradient of the refraction index
H	is the high above ground level
φ	is the angle measured with respect to the horizontal path

In practice (terrestrial links) It is assumed that:

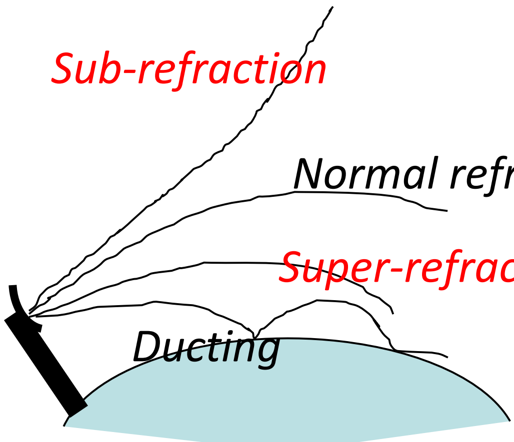
$$\frac{1}{\rho} = -\frac{\mathrm{d}n(h)}{\mathrm{d}h}$$

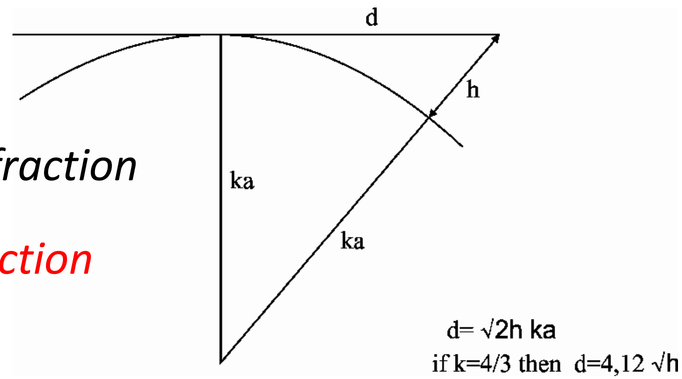
$$\Delta N = \frac{dN(h)}{dh} = -10^6\frac{1}{\rho}$$

3. Physical Phenomena. Refraction

- Ray bending: effective earth radius
  - Displaying bended propagation paths is not useful
  - Solution: effective Earth radius $R = kR_0$

R_0 is the real Earth's Radius
k is the fictitious radius factor





$$\frac{1}{kR_0} = \frac{1}{R_0} + \frac{\mathrm{d}n(h)}{\mathrm{d}h}$$

$$\frac{1}{kR_0} = \frac{1}{R_0} + \Delta N \cdot 10^{-6}$$

$$k = \frac{1}{1 + R_0 \Delta N \cdot 10^{-6}} = \frac{157}{157 + \Delta N}$$

Troposphere Condition	*ΔN (N units/km)*	*k*
Normal	$0 \geq \Delta N > -39$	$1 \leq k < 4/3$
Sub-refractive	$\Delta N > 0$	$0 \leq k < 1$
Super-refractive	$\Delta N < -39$	$k > 4/3$
Ducting Conditions	$\Delta N = -157$	$k\ \infty$
	$\Delta N < -157$	$k < 0$

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3. Physical Phenomena. Refraction

- Ray bending. Effective earth radius: Example

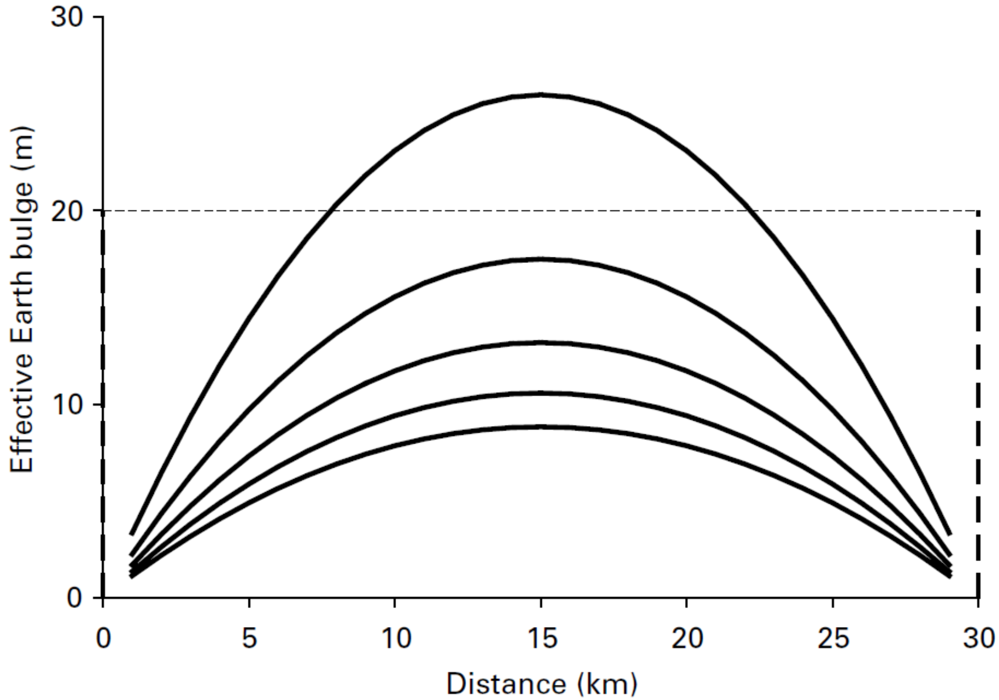


Figure 6.3 The variation in effective Earth bulge for k-factors of 0.67, 1.0, 1.33, 1.67 and 2. The dashed line at a height of 20 metres is shown for guidance.

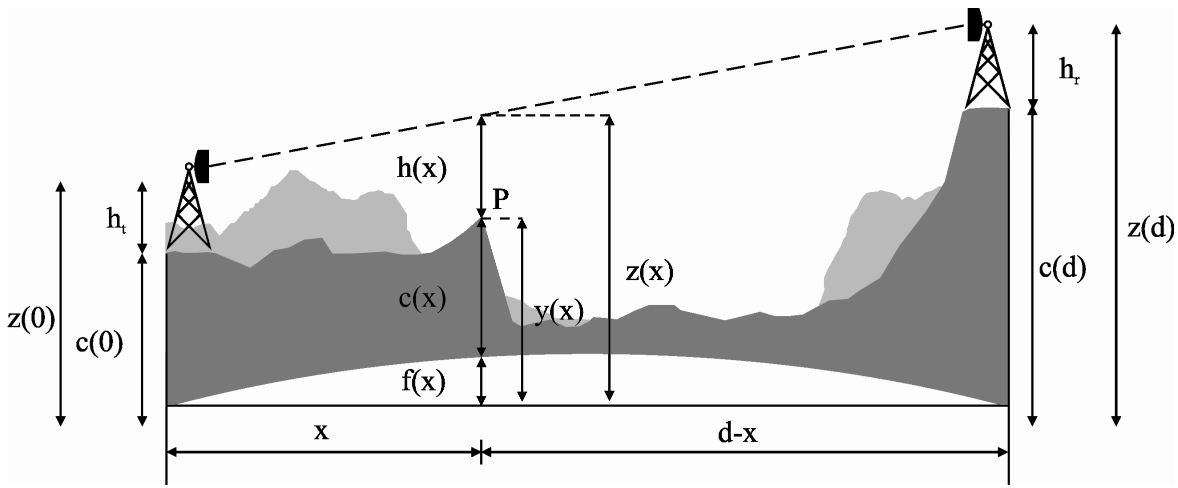
- Bulge:

$$f(x) = \frac{x(d-x)}{2kR_0}$$

3. Physical Phenomena. Refraction

- Calculation of the Earth's bulge

The effective terrain height, Y(x), at P, is the geographical elevation, plus the Earth's bulge at that location P, i.e. f(x):



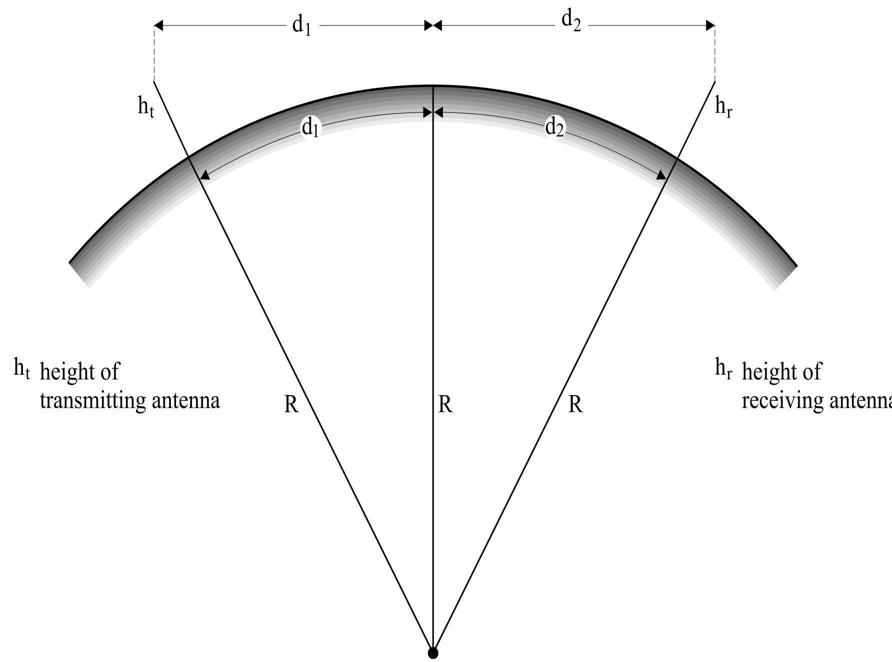
$$Y(x) = C(x) + f(x) \qquad f(x) = \frac{x(d-x)}{2kR_0}$$

R_0 is the real Earth's Radius

k is the fictitious radius factor

3. Physical Phenomena. Refraction: Radio Horizon

- Because of the curvature of the earth there is a limiting distance at which a receiving antenna has an unobstructed view of the transmitting antenna.



- Since h_t, h_r << R

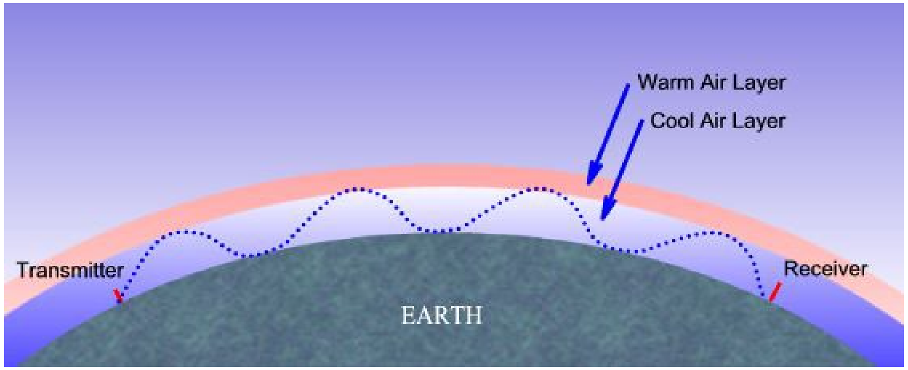
$$d_1^2 = (R+h_t)^2 - R^2 = h_t^2 + 2h_t R \approx 2h_t R$$
$$d_2^2 = (R+h_r)^2 - R^2 = h_r^2 + 2h_r R \approx 2h_r R$$
$$d = d_1 + d_2 \approx \sqrt{2R}\left(\sqrt{h_t} + \sqrt{h_r}\right)$$

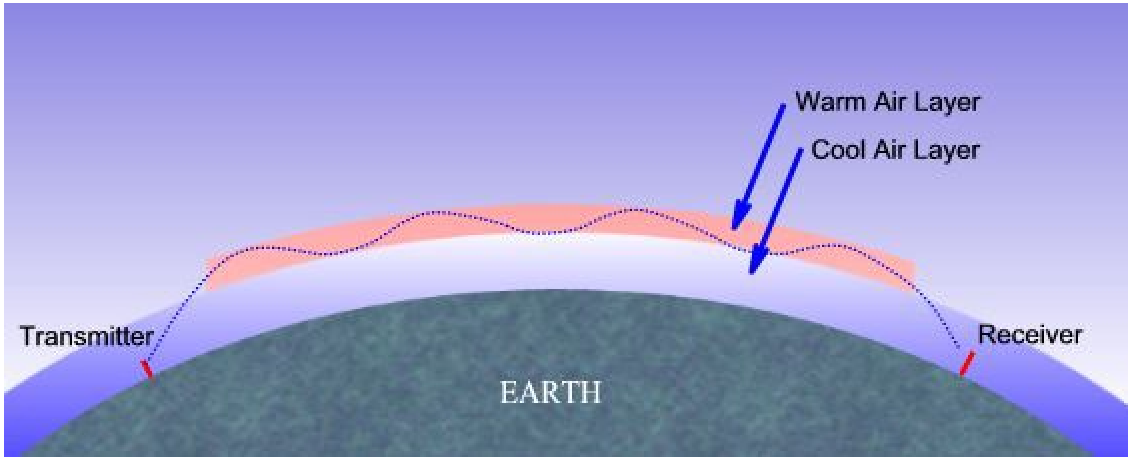
- For a k in normal refraction conditions

$$d(km) = 4.126\left(\sqrt{h_t(m)} + \sqrt{h_r(m)}\right)$$

3. Physical Phenomena. Refraction: Ducts

- **Ducting** is a phenomenon associated to anomalous refraction conditions
- A duct is a region of the troposphere that due to anomalous radio refractivity gradient values, keeps the propagation of a certain signal confined between two layers of the troposphere





- Or between a layer of the troposphere and the Earth's surface.
- Duct propagation is difficult to characterize quantitatively.
- Ducts (ITU-R P.453)

3. Physical Phenomena. Refraction: Ducts

- Ducts

Country/Region	*Area*	*Season*
North America	USA. North East Coast	Summer
North America	USA. Florida	Winter
North America	USA. West Coast	Indifferent
East Europe	British Islands and North Sea	Summer
Europe	Mediterranean Sea	Summer
East Africa	Arabic Peninsula and Indian Ocean	Dry Season (October - May)
Bay of Bengal	India/Sri Lanka/Myanmar-Birmania/Bangladesh	Dry Season (October - May)
Pacific Ocean	Korea	Indifferent
Pacific Ocean	West Coast of Australia	Indifferent
Pacific Ocean	Japan Sea	Summer
Pacific Ocean	South China Sea	Winter

3. Physical Phenomena. Refraction: Scintillation

- **Scintillation**
  - Scintillation is characterized by a **random variation** of the received signal level around the median value
  - These are fast and low intensity variations below 40 GHz
    - **Troposphere Scintillation**: refraction index . Scintillation is associated to small scale irregularities in the troposphere, which are changing their features very fast
    - **Ionosphere Scintillation**: total electron content (TEC), a measure of the ionization level of the ionosphere

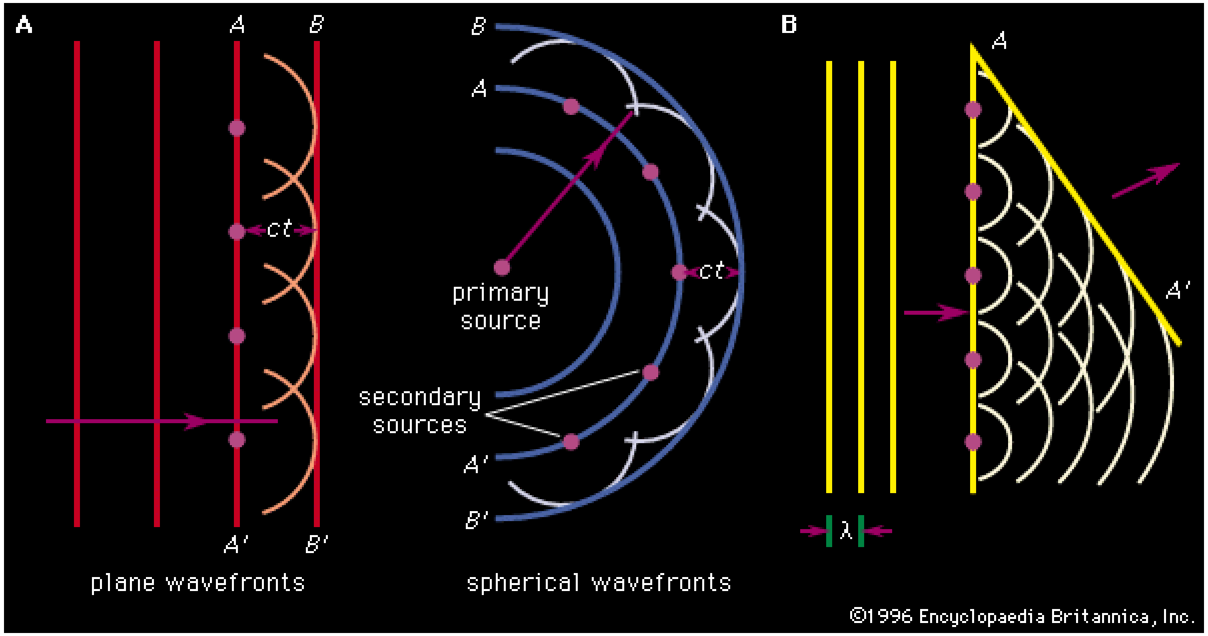
- Depends on the frequency band and on the application purpose: might have a relevant influence in satellite communications (ionosphere scintillation)

3. Physical Phenomena

1. Free Space Loss Review
2. Propagation Modes
3. Physical Phenomena
   - Refraction
   - **Diffraction**
   - Reflection
   - Scattering
   - Molecular Absorption
   - Hydrometeors
4. Summary

3. Physical Phenomena. Diffraction

- The energy at the receiver location is the contribution of the infinite paths that are contained by the plane perpendicular to the Pointing vector
- The theoretical base is the Huygens' Principle



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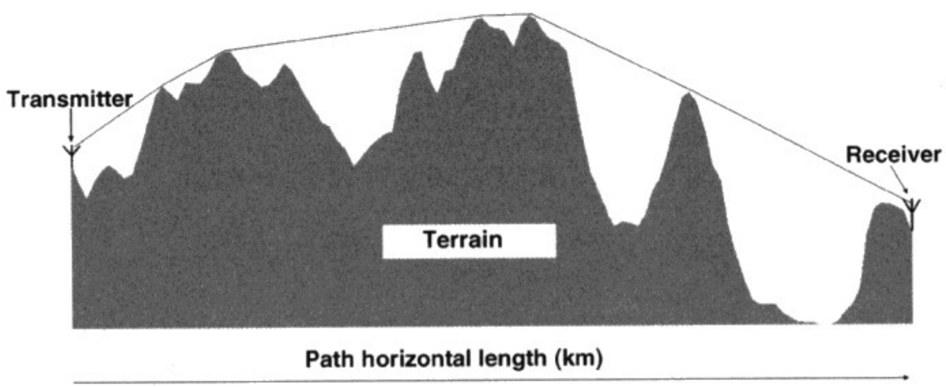
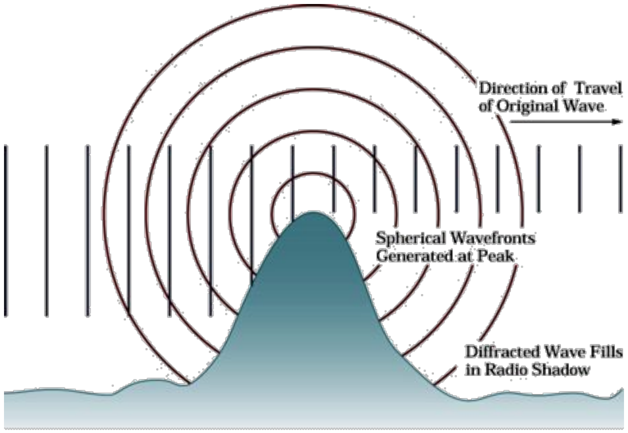
3. Physical Phenomena. Diffraction

- Allows RF signals to propagate to obstructed (shadowed) regions
  - over the horizon (around curved surface of earth)
  - behind obstructions

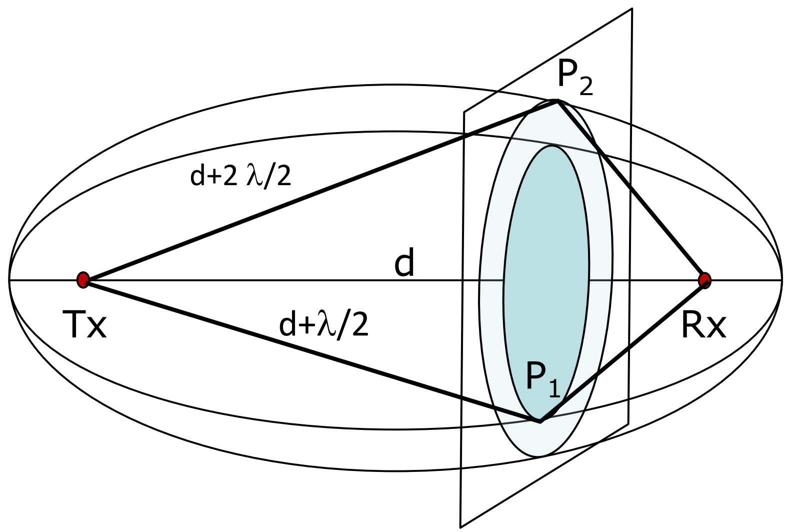


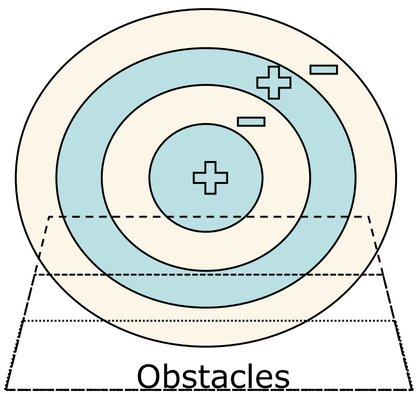


- Smooth earth diffraction – curvature of the Earth itself on a transhorizon path. (Rec P.526; below 10 MHz, use Rec P.368.)
- Single obstacles. Approximated as ideal knife-edge or rounded cylinders. Methods in Rec. P.526

3. Physical Phenomena. Diffraction: Fresnel ellipsoids

- There will be an infinite number of propagation paths followed by the energy from the transmitter to the receiver.
- The contribution of each path to the total received power will depend on the phase of each component associated to the plane wave front





N-th **Ellipsoid** Radius

$$R_n = \left[\frac{n\,\lambda\,d_1\,d_2}{d_1 + d_2}\right]^{1/2}$$

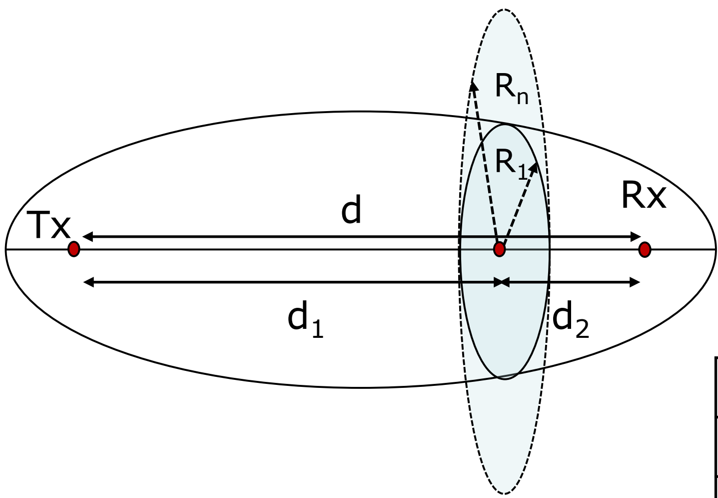
Constructive and destructive Paths:

$$T_xP_n + P_nR_x = T_xR_x + n\cdot\frac{\lambda}{2}$$

3. Physical Phenomena. Diffraction: Fresnel ellipsoids

- **Fresnel Zones**
  - Odd ellipses contribute to the overall energy positively
  - Even ellipses represent negative contributions
  - The lower the order the more relevant to the overall energy

- For practical system design and dimensioning **only the first zone** is considered



$$R_n = 548\sqrt{\frac{n \cdot d_1 \cdot d_2}{f \cdot d}} \quad (m)$$

$$R_n = \left[\frac{n\,\lambda\,d_1\,d_2}{d_1 + d_2}\right]^{1/2}$$

N	order of the ellipsoid
Rn	radius of the n-th order ellipsoid
d1	distance to the transmitter (km)
d2	distance to the receiver (km)
d	Transmitter- receiver distance (d1+d2) (km)
f	frequency (MHz)

3. Physical Phenomena. Diffraction: Clearance

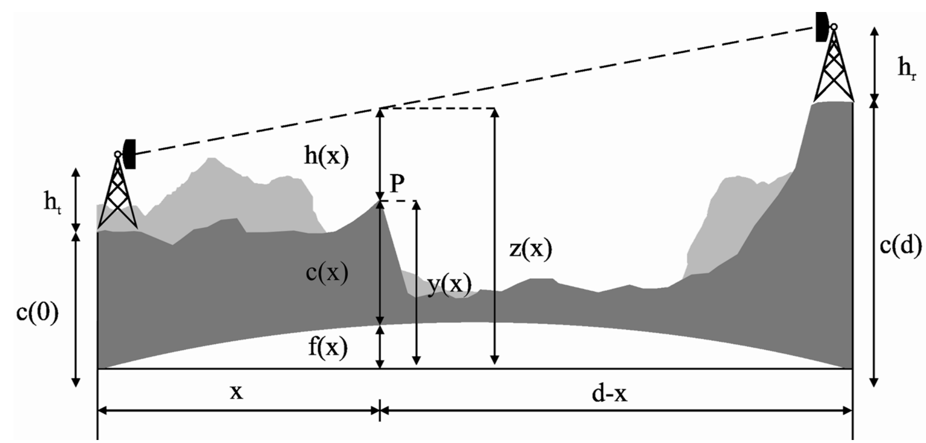
- The clearance, h(x), of an arbitrary location P on the profile with an abscise x, as defined by UIT-R, is the difference between the effective terrain height at location P and the ordinate value of the TR line at this location

$$h(x) = y(x) - z(x)$$

- The free margin on obstacles (FMO) represents the distance between the signal path (TR line) and the terrain obstacles at that location P.

$$FMO(x) = z(x) - y(x)$$

- The clearance, h(x), is negative if the signal path is above the effective terrain height, and otherwise positive.



- Note: Some authors used clearance h(x) and others used FMO(x). Signs of these two parameters are opposite.

Difraction: Bulge $f(x) = \dfrac{x(d-x)}{2kR_0}$

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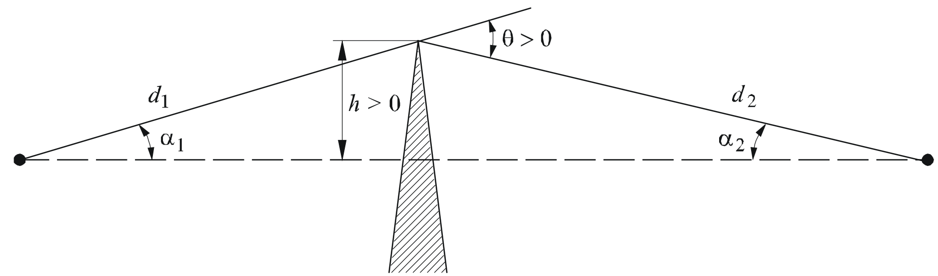
3. Physical Phenomena. Diffraction: Knife edge model

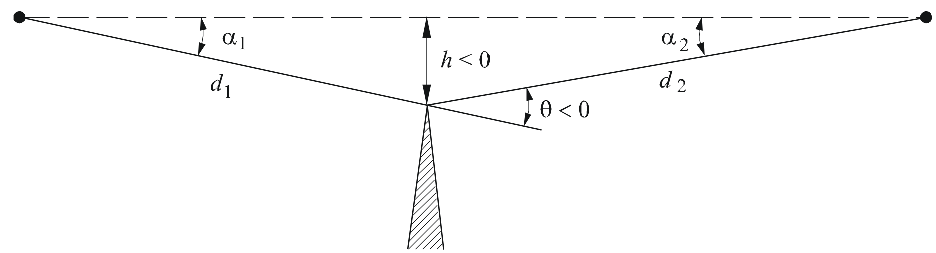
- Diffraction on a 'knife-edge' isolated obstacle is based on the geometric model shown in the figure



a)

- The isolated obstacle width is assumed infinitesimal

- Losses depend on clearance h and are calculated using a dimensionless parameter ν:



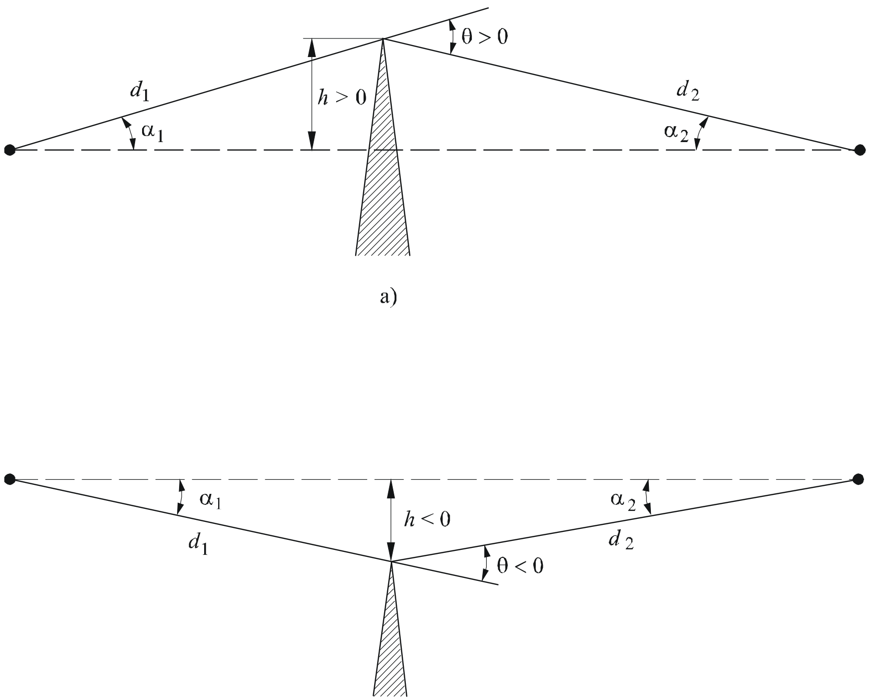
$$v = h\sqrt{\frac{2}{\lambda}\left(\frac{1}{d_1}+\frac{1}{d_2}\right)}$$

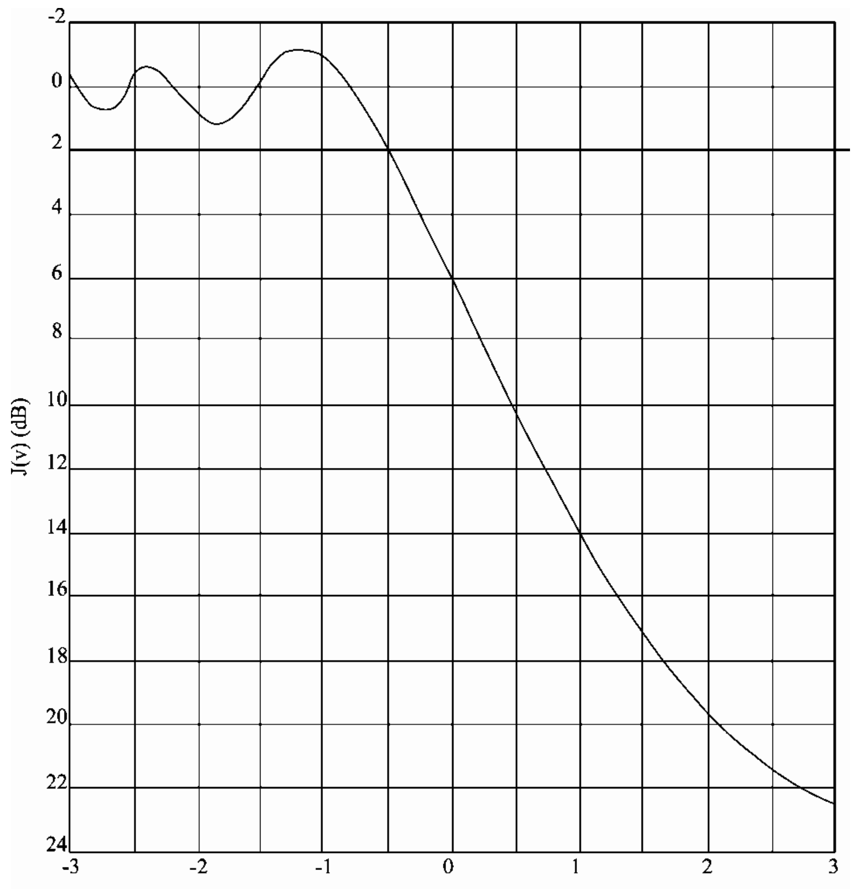
$$v = \sqrt{2}\,\frac{h}{R_1} \qquad R_1 \text{ is the radius of the } 1^{st} \text{ Fresnel ellipsoid}$$

Note: ν and h are negative if the signal path is above the effective terrain height, and otherwise positive.

3. Physical Phenomena. Diffraction: Knife edge model

$$L_D(\upsilon) = 6.9 + 20\log\left[\sqrt{(\upsilon - 0.1)^2 + 1} + \upsilon - 0.1\right] \text{ dB} \qquad \text{if } -0.7 \le \upsilon \le \infty$$





3. Physical Phenomena. Diffraction: Knife Edge Model

- Some consequences
  - It is possible to obtain higher reception values in the presence of perfect/ideal obstacles (unreal in practice)
  - The excess losses increase rapidly after the 60% (57.7%) of the ellipsoid radius is blocked
  - The received power for a clearance of 0.6 R and the value in absence of obstacles is the same (practical criteria for system design)

- Despite the simplicity of the model it is the base for real diffraction calculations in:
  - Isolated terrain irregularities
  - Round terrain irregularities
  - Multiple terrain obstacles

3. Physical Phenomena.

1. Free Space Loss Review
2. Propagation Modes
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   - Refraction
   - Diffraction
   - **Reflection**
   - Scattering
   - Molecular Absorption
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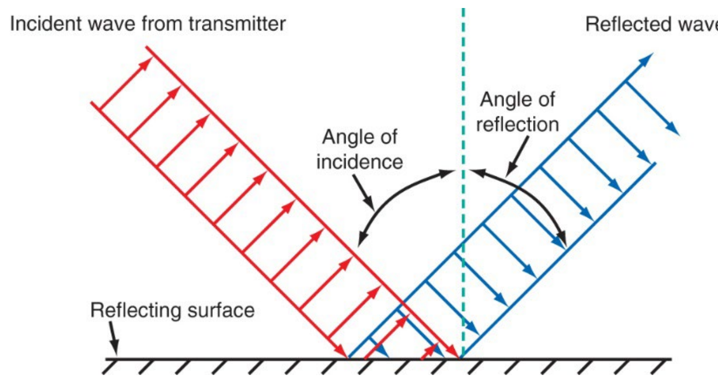
4. Summary

3. Physical Phenomena. Reflection

- When a radio wave propagating in one medium impinges upon another medium having different electrical properties, the wave is
  - partially reflected
  - partially transmitted



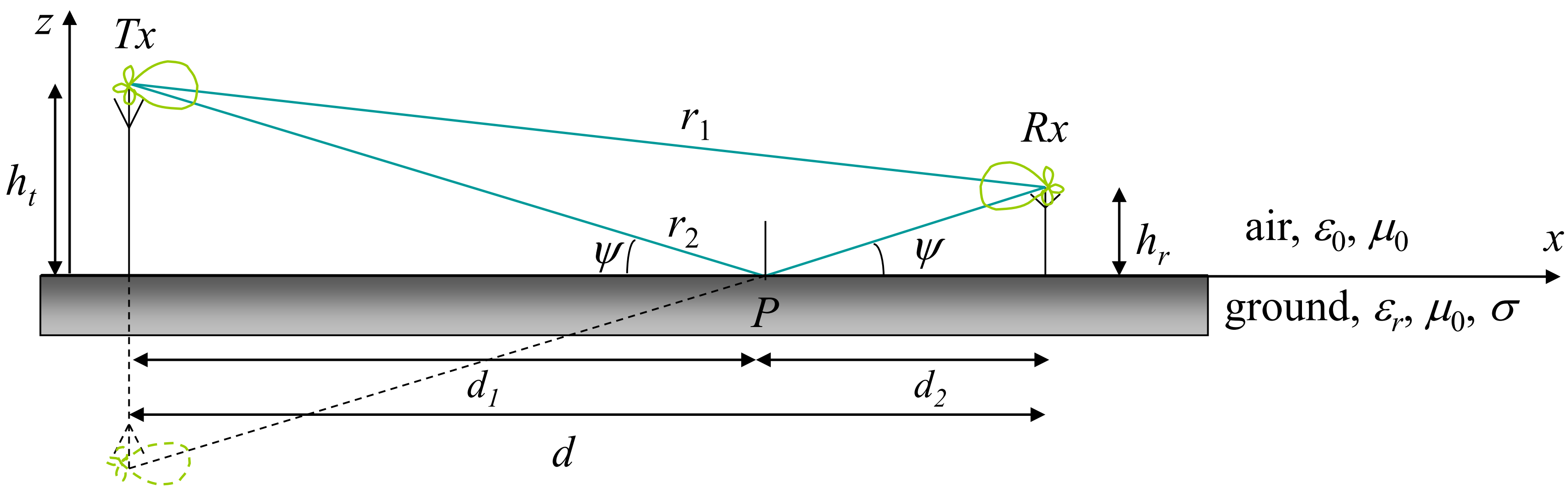
- Reflection Coefficient (Γ) gives the relationship between
  - Reflected and Transmitted waves
  - Incident wave in the medium of origin

- The Reflection Coefficient is a function of the material properties, depending on
  - Wave Polarization (direction of vibration-propagation: orientation)
  - Angle of Incidence
  - Frequency of the propagating wave

3. Physical Phenomena. Reflection

- Basic modelling of reflection:

- Reflection coefficients are calculated assuming oblique incidence on a lossy flat dielectric (ε_r dielectric permittivity, σ conductivity)

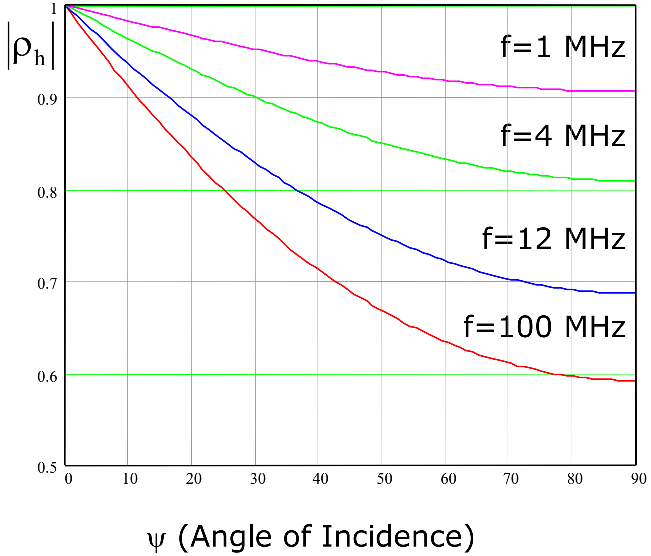


3. Physical Phenomena. Reflection

- **Horizontal Polarization**

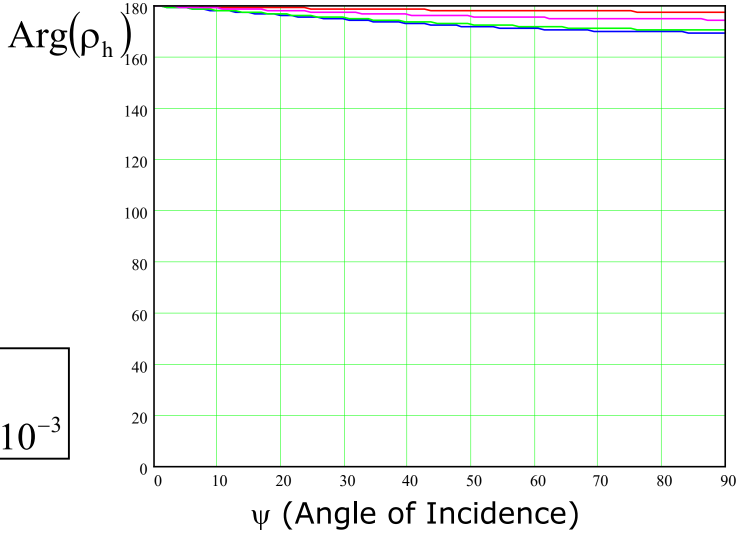
$$\rho_h = \frac{\operatorname{sen}\psi - \sqrt{(\varepsilon_r - jx) - \cos^2\psi}}{\operatorname{sen}\psi + \sqrt{(\varepsilon_r - jx) - \cos^2\psi}} \qquad x = \frac{\sigma}{\omega\varepsilon_0}$$

- For angles of incidence close to zero (ψ=0): ρ_h=-1
- Otherwise
  - The phase change remains close to 180º
  - The module varies significantly for high frequencies and low conductivity values
- If f>100 MHz use the 100 MHz curve



$\varepsilon_r = 15$

$\sigma = 12\cdot10^{-3}$

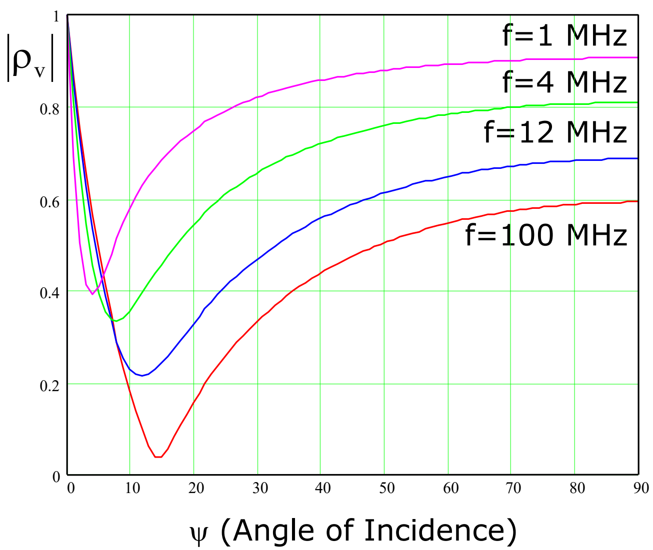


3. Physical Phenomena. Reflection

- **Vertical Polarization**

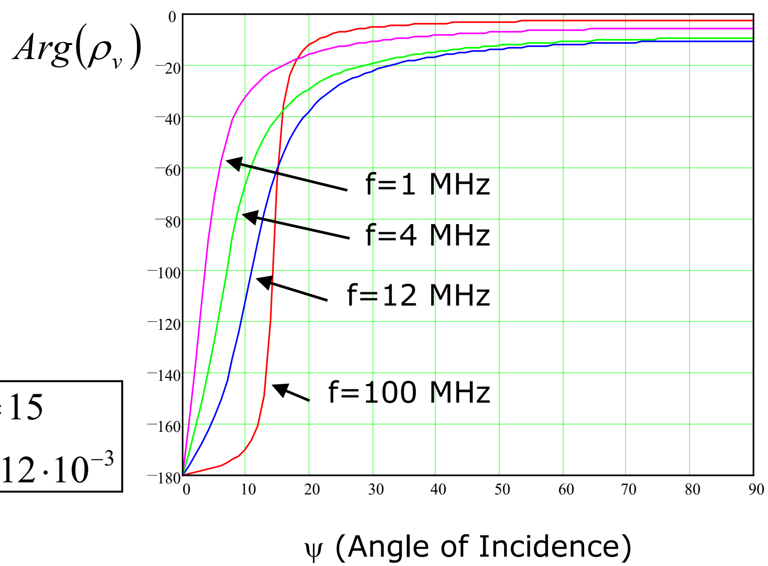
$$\rho_v = \frac{(\varepsilon_r - jx)\,\text{sen}\,\psi - \sqrt{(\varepsilon_r - jx) - \cos^2\psi}}{(\varepsilon_r - jx)\,\text{sen}\,\psi + \sqrt{(\varepsilon_r - jx) - \cos^2\psi}} \qquad x = \frac{\sigma}{\omega\varepsilon_0}$$

- For angles of indicence close to zero (ψ=0): ρ_v=-1
- Higher angles produce phase and module fast variations
- Each frequency has its own pseudo-brewster angle
- If f>100 MHz use the 100 MHz curve



$\varepsilon_r = 15$

$\sigma = 12 \cdot 10^{-3}$



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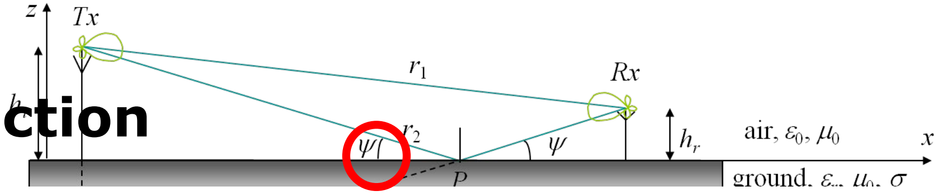
3. Physical Phenomena. Reflection



- Reflection is a more complex phenomena.

- Procedure:
  - The optical reflection theory has a limit: $\psi_{threshold}(mrad) = \left(\frac{5400}{f}\right)^{\frac{1}{3}}$ f: freq (MHz)
  - ψ, grazing angle
    - If $\psi < \psi_{threshold}$ **diffraction** caused by earth's curvature.
    - If $\psi > \psi_{threshold}$ **reflection**
  - Short paths. If f(x) < 5 meters, **flat earth model**
  - Longer paths. If f(x) > 5 meters, **spherical earth model** $\rho = \rho_{effective} \cdot D$

    (formula for D in next slides)

- **Flat earth model**, other criteria:
  - Valid in the VHF band and above
  - Valid for flat ground
  - Valid for short ranges

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3. Physical Phenomena. Reflection

- Divergence associated to Fresnel zones

  - Solution: Effective Coefficient

$$\rho_{effective} = \rho \cdot e^{-\frac{\gamma^2}{2}} \qquad \gamma = \left(\frac{4\pi\sigma_c sen\psi}{\lambda} \right)$$

    - If γ > 0.3 the surface will be considered not specular. $\rho_{effective} = \rho \cdot e^{-\frac{\gamma^2}{2}}$

    - If γ <0.3, $\rho_{effective} = \rho$ because $e^{-\frac{\gamma^2}{2}} \approx 1\ if\ \gamma < 0.3$

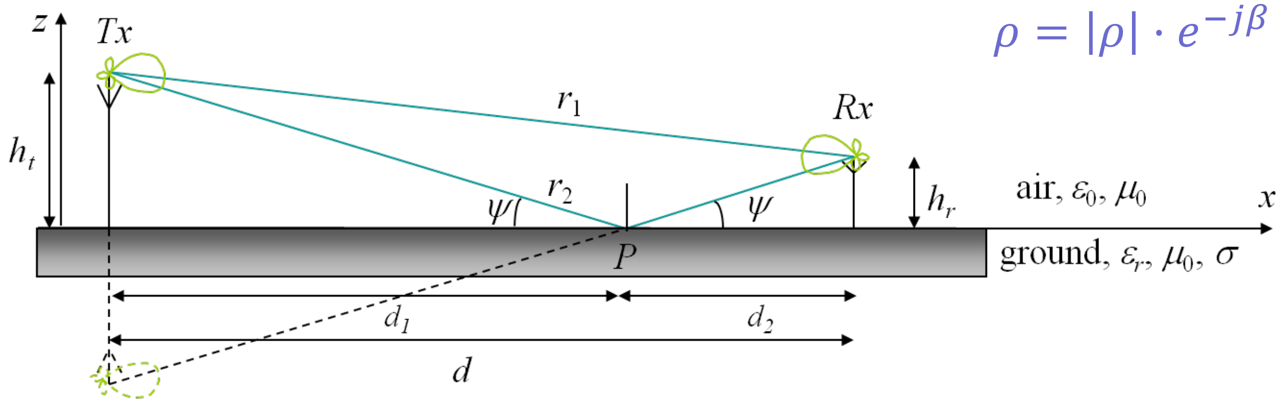
  σ_c is the terrain roughness (standard deviation of terrain samples within the relevant area

- So, more complete model: $\rho = \rho_{effective} \cdot D = \rho \cdot e^{-\frac{\gamma^2}{2}} \cdot D$

3. Physical Phenomena. Reflection

- Reflection is sometimes consider as a correction to FSL in order to estimate the received field strength
- This is known as **two ray model**
  - E direct
  - E reflection path
  - Each field with amplitude and phase
  - The overall field strength might have different amplitudes depending upon each geometry

$$\rho = |\rho| \cdot e^{-j\beta}$$



$$|E| = \left|E_0\left[1 + |\rho| \exp(-j(\Delta + \beta))\right]\right| = |E_0| \left[1 + |\rho|^2 + 2|\rho| \cos(\Delta + \beta)\right]^{1/2}$$

Δ : phase difference between paths

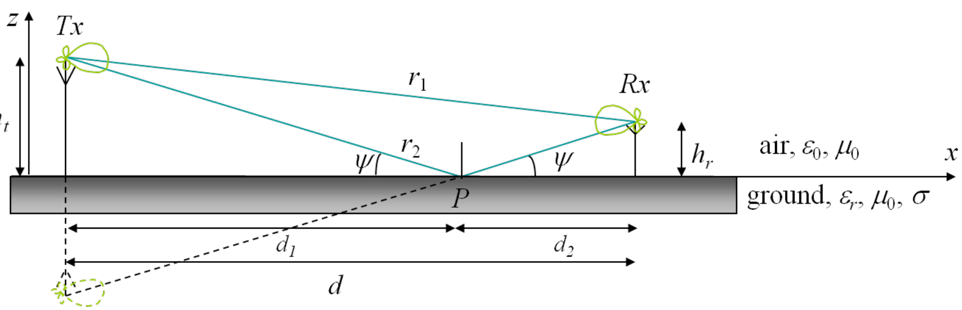
3. Physical Phenomena. Reflection: Flat Earth Model

Reflection Point

$$\Psi = \tan^{-1}\left(\frac{h_t + h_r}{d}\right) = \tan^{-1}\left(\frac{h_t}{d_1}\right) = \tan^{-1}\left(\frac{h_r}{d_2}\right)$$

$$d_1 = \left(\frac{d \cdot h_t}{h_t + h_r}\right)$$

Reflection Coefficient $\rho = |\rho| \cdot e^{-j\beta}$



Direct/Reflected Path Difference

Amplitude $$\Delta l = (r_2 - r_1) = \left(\sqrt{d^2 + (h_t + h_r)^2} - \sqrt{d^2 + (h_t - h_r)^2}\right) \approx \frac{2h_t h_r}{d}$$

Phase $$\Delta = \frac{2\pi\,\Delta l}{\lambda} = \frac{4\pi\, h_t h_r}{\lambda\, d}$$

Field Strength

$$|E| = \left|E_0\left[1 + |\rho|\exp(-j(\Delta + \beta))\right]\right| = |E_0|\left[1 + |\rho|^2 + 2|\rho|\cos(\Delta + \beta)\right]^{1/2}$$

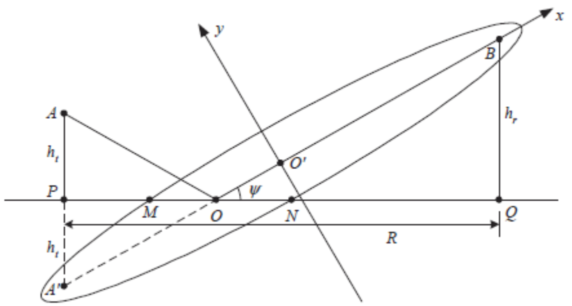
Assuming grazing angle, $\psi \approx 0$, $d \gg h_r$, h_t, and $\rho = -1$

$$|E| = \left|E_0 \frac{4\pi\, h_t h_r}{\lambda\, d}\right|$$

3. Physical Phenomena. Reflection: Flat Earth Model

- Reflection: Divergence associated to Fresnel zones
  - The energy is not concentrated over a infinitely thin “ray”
  - The reflection point is then a surface rather than a spot that might not be specular
  - Solution: Effective Coefficient

$$\rho_{effective} = \rho \exp\left(-\gamma^2 / 2 \right) \qquad \gamma = \left(\frac{4\pi\sigma_c sen\psi}{\lambda} \right)$$

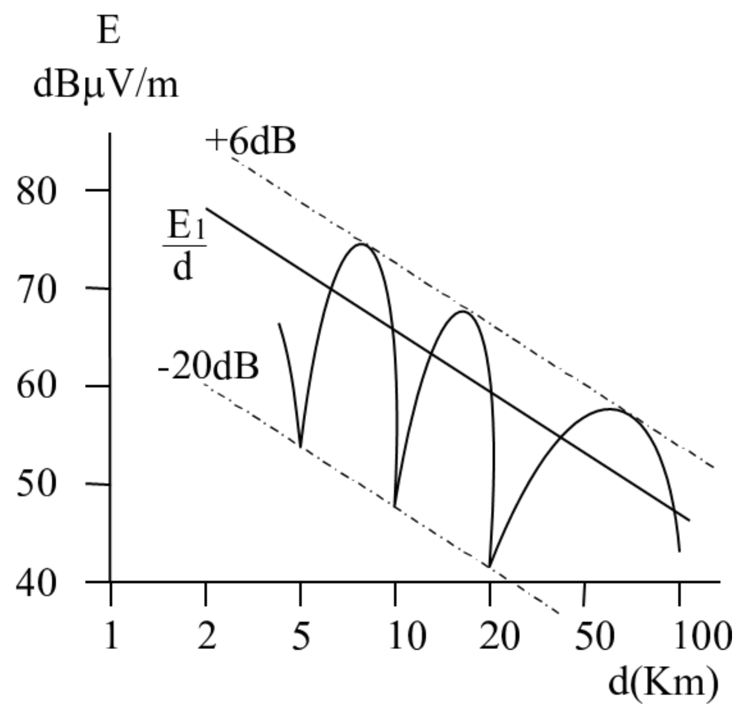


  - Where
    - ψ is the grazing angle
    - σ_c terrain roughness (standard deviation of terrain samples within the relevant area (relevant area calculation method: *H. Rábanos. Transmisión por Radio, Chapter 3, pp. 151*)
    - λ wavelength
    - The surface will be considered not specular if $\gamma > 0.3$

The optical reflection theory has a limit: $\psi_{threshold}(mrad) = \left(\frac{5400}{f} \right)^{\frac{1}{3}}$

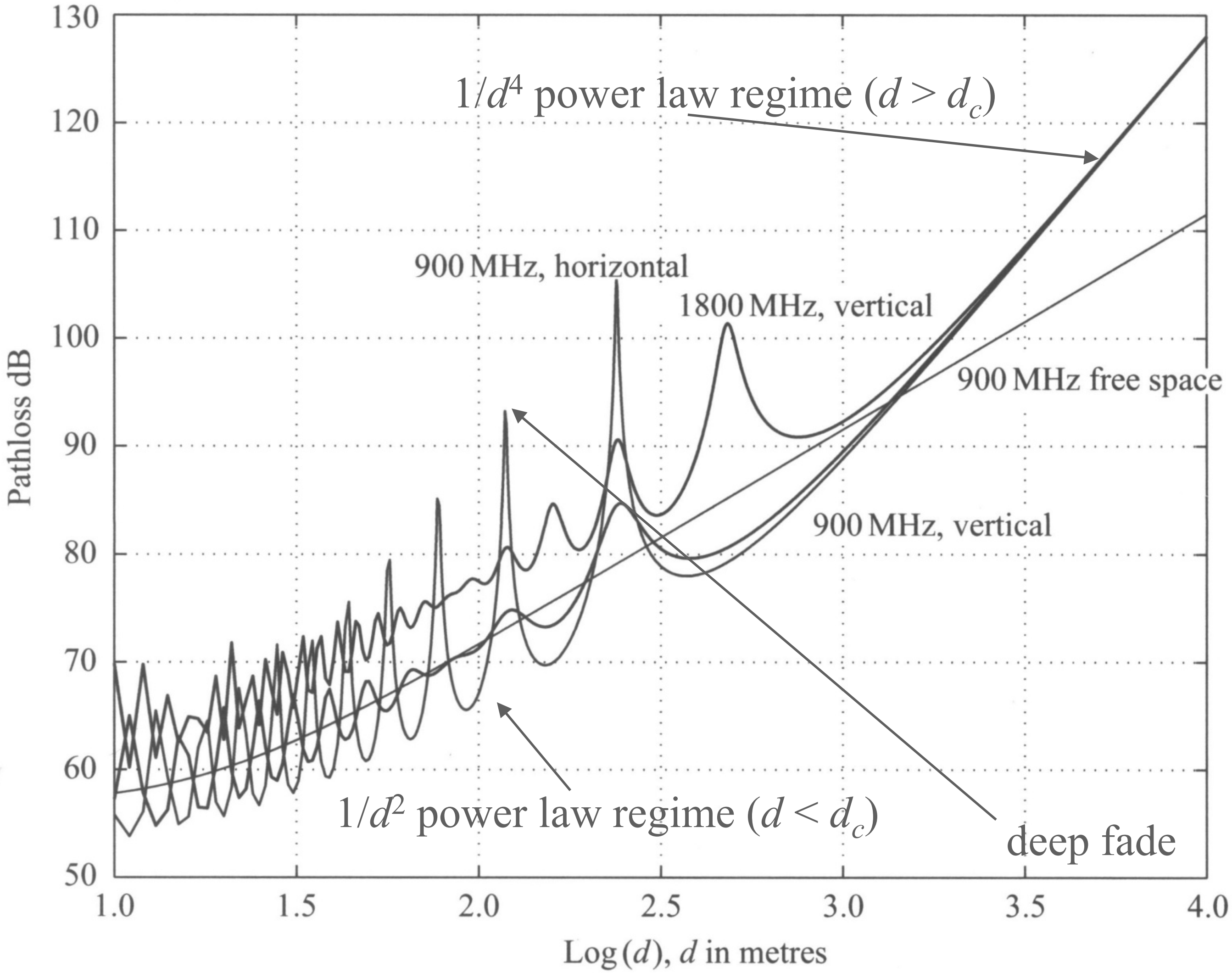
Lower angles imply diffraction caused by earth’s curvature

3. Physical Phenomena. Reflection: Received field Strength



- Variation of field strength with distance in the presence of reflection

3. Physical Phenomena. Reflection: Received Power



Typical ground (earth), with
$\varepsilon_r = 15$
$\sigma = 0.005 \mathrm{Sm}^{-1}$
$h_t = 20\mathrm{m}$ and
$h_r = 2\mathrm{m}$

3. Physical Phenomena.

1. Free Space Loss Review
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   - Refraction
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   - Reflection
   - **Scattering**
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4. Summary

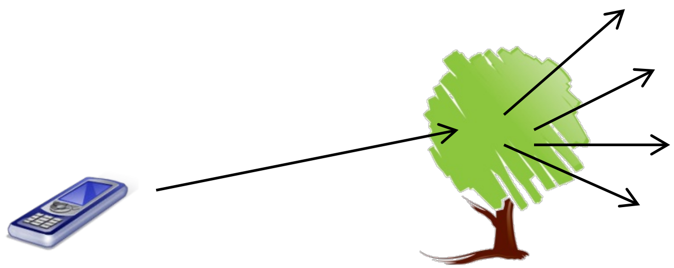
3. Physical Phenomena. Scattering

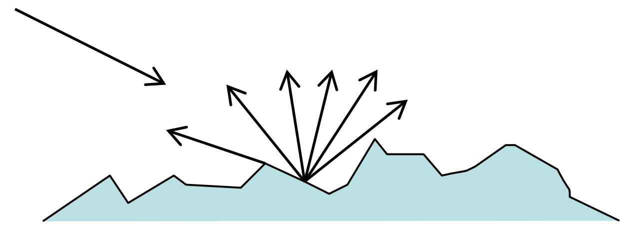
- Scattering is a physical process where light, sound, or moving particles, are forced to deviate from a straight trajectory, by one or more localized non-uniformities, in the medium through which they pass. Energy diffuses in all directions

- The obstacles/irregularities with size in the order of the wavelength of the signal or less:
  - Foliage, lamp posts, street signs, walking pedestrians, irregular terrain

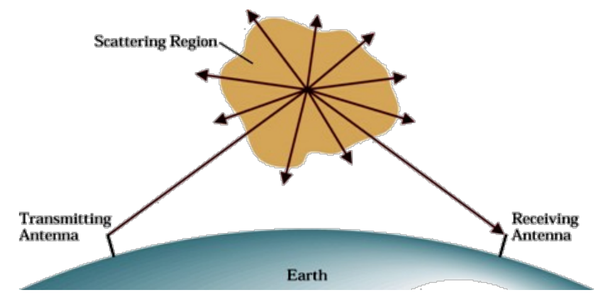
- Scattering is generally difficult to model because the environmental conditions that cause it are complex (e.g. modelling position of every street sign is not feasible):
  - Rough surfaces
    - critical height for bumps is a function of λ and the incident angle
    - scattering loss factor modeled with Gaussian distribution.
  - Nearby metal objects (street signs, etc.): modeled statistically

3. Physical Phenomena. Scattering: Examples of Scattering in Propagation

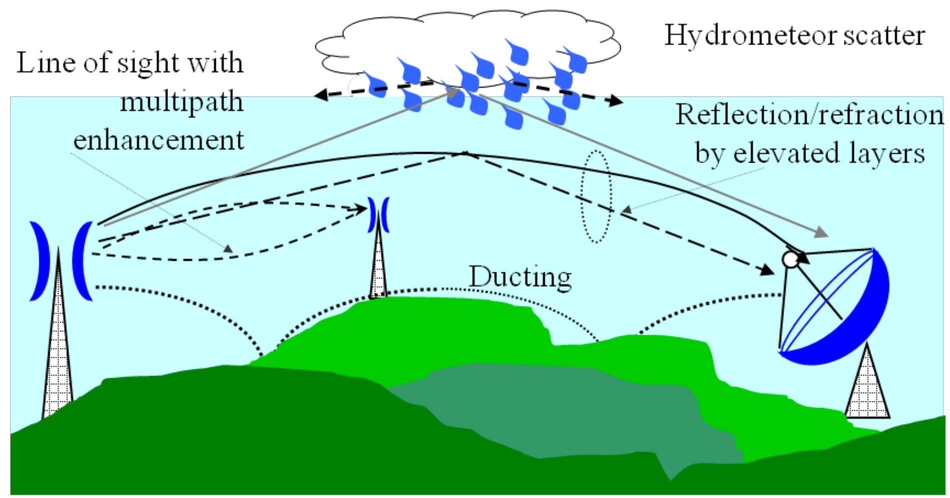




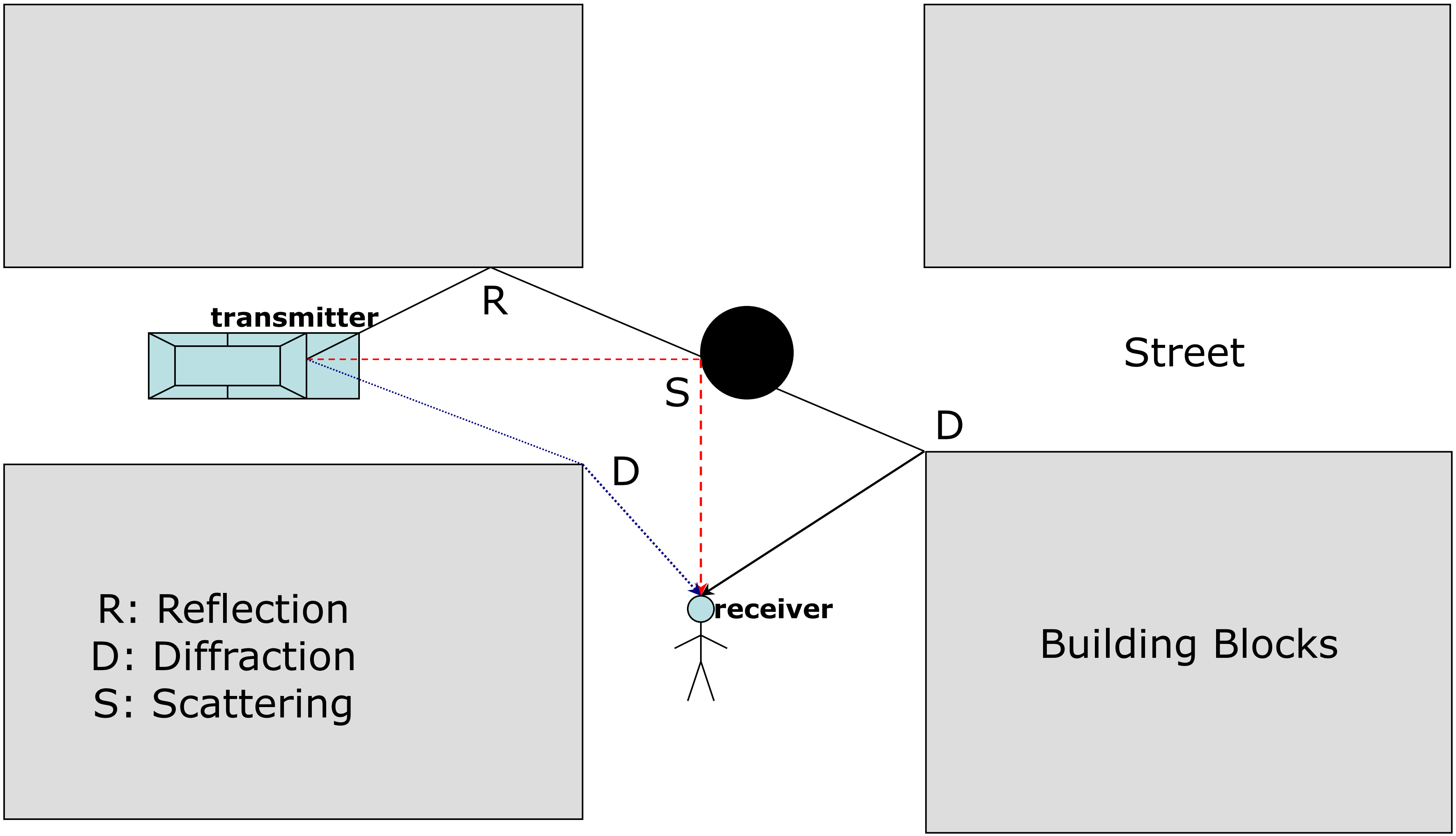
- **Tropospheric Scatter** - makes use of the scattering of radio waves in the troposphere to propagate signals in the 250 MHz –5 GHz range (Data communications specially on the military sector). ITU-R Rec. P.452 and H. Rábanos. Chapter 3, p.188



- Scattering by Rain: Rather a problem than an application. Rec. P.452. (May be significant above ~ 5 GHz)



3. Physical Phenomena. Scattering: Examples of Scattering in Propagation



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3. Physical Phenomena.

1. Free Space Loss Review
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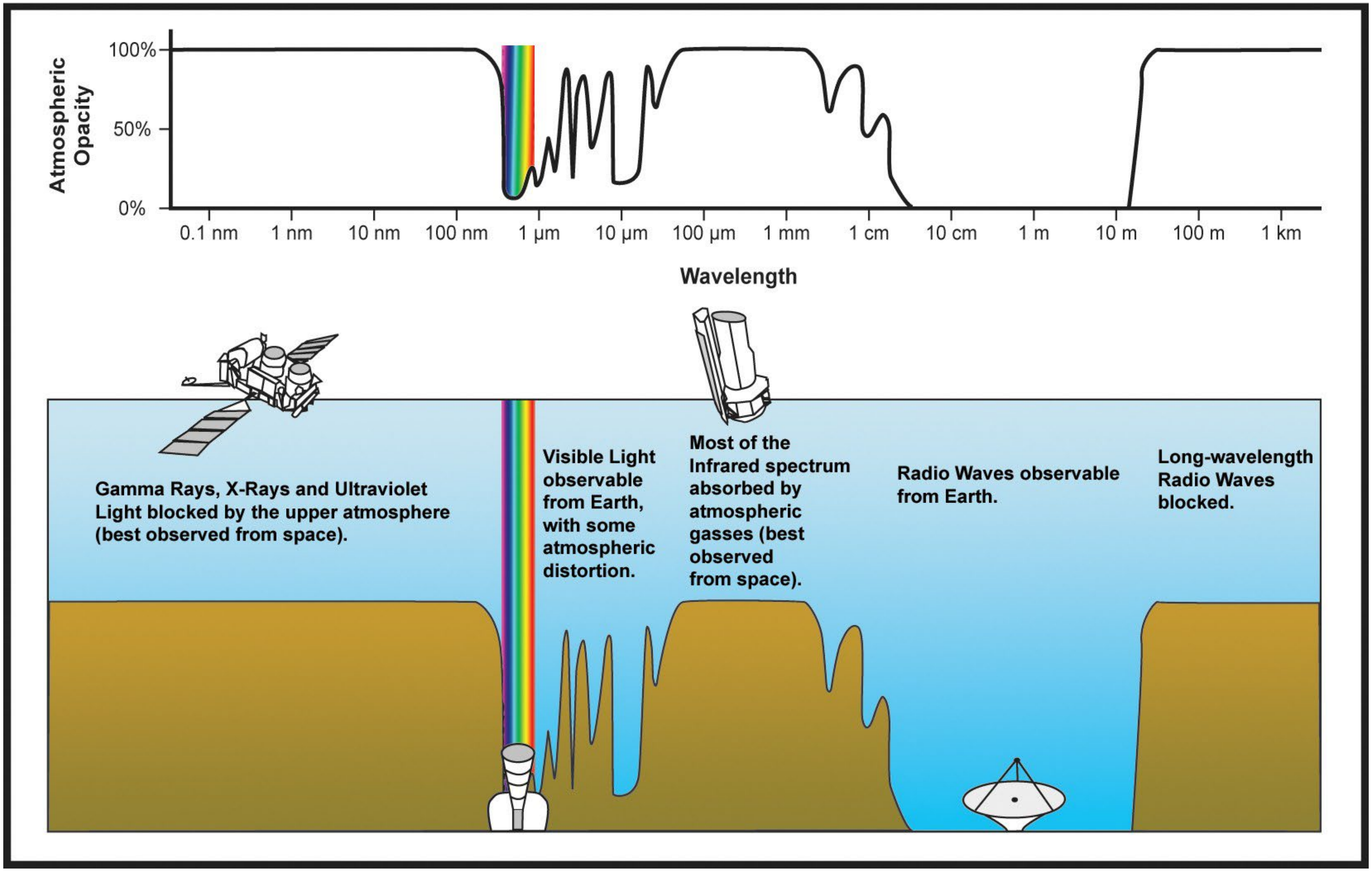
   - **Molecular Absorption**
   - Hydrometeors
4. Summary

3. Physical Phenomena. Molecular Absorption



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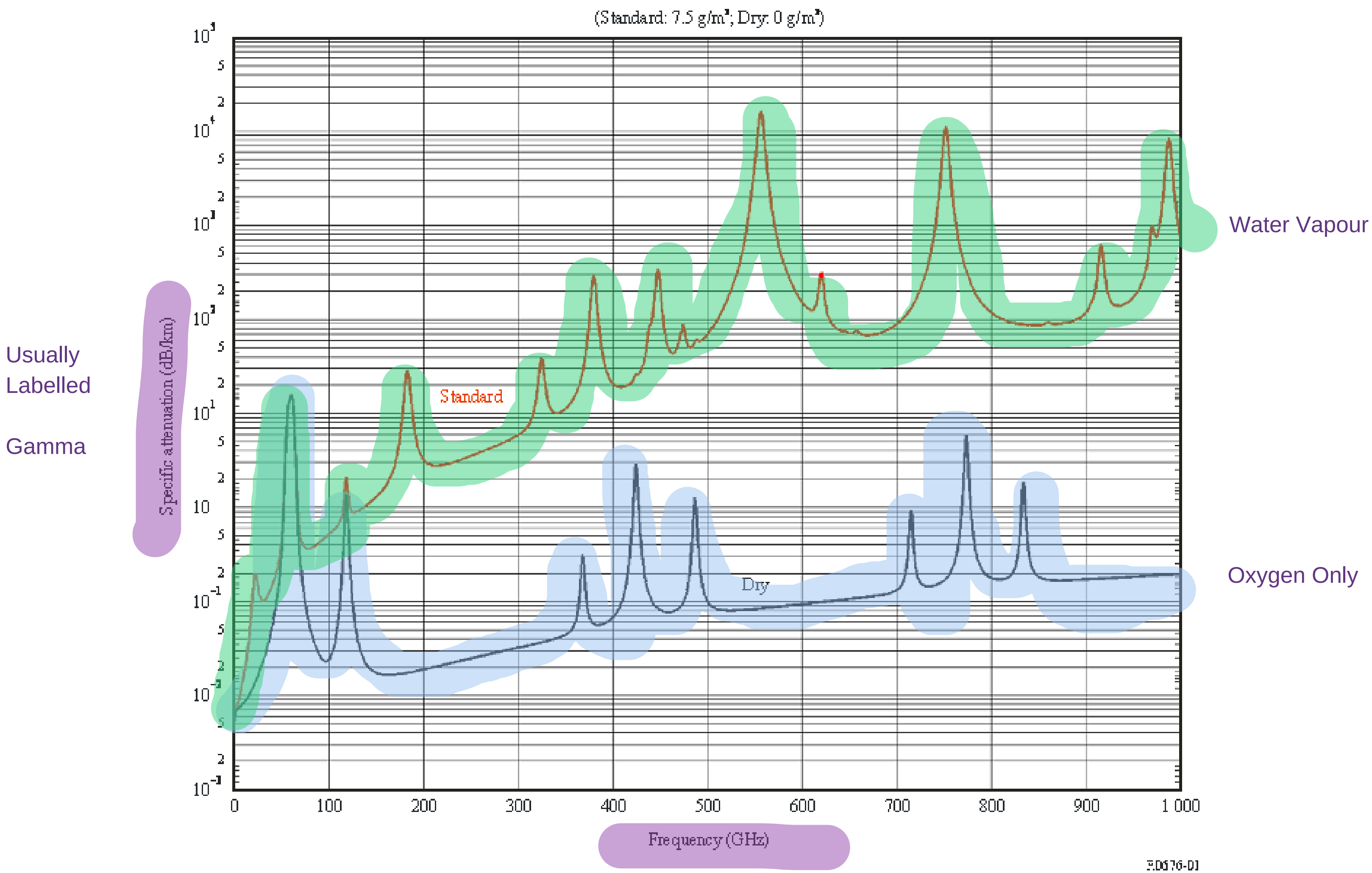
3. Physical Phenomena. Molecular Absorption

- The atmosphere in the first kilometers: Oxygen (O_2), Nitrogen (N_2), Carbon Dioxide (CO_2), Water Vapor (H_2O)
- The molecules of each gas interact in diverse ways with a radio signal → specific for each gas
- The effect is only relevant at frequencies over 10 GHz
- In most cases it is not considered below 20 GHz
- For practical purposes: Oxygen and Water Vapor
  - Water Vapor: Attenuation lines: 22.5 and 183 GHz
  - Oxygen, Attenuation lines: 60 and 119 GHz
- In between these resonant frequencies: transmission windows (see next slide)

3. Physical Phenomena. Molecular Absorption

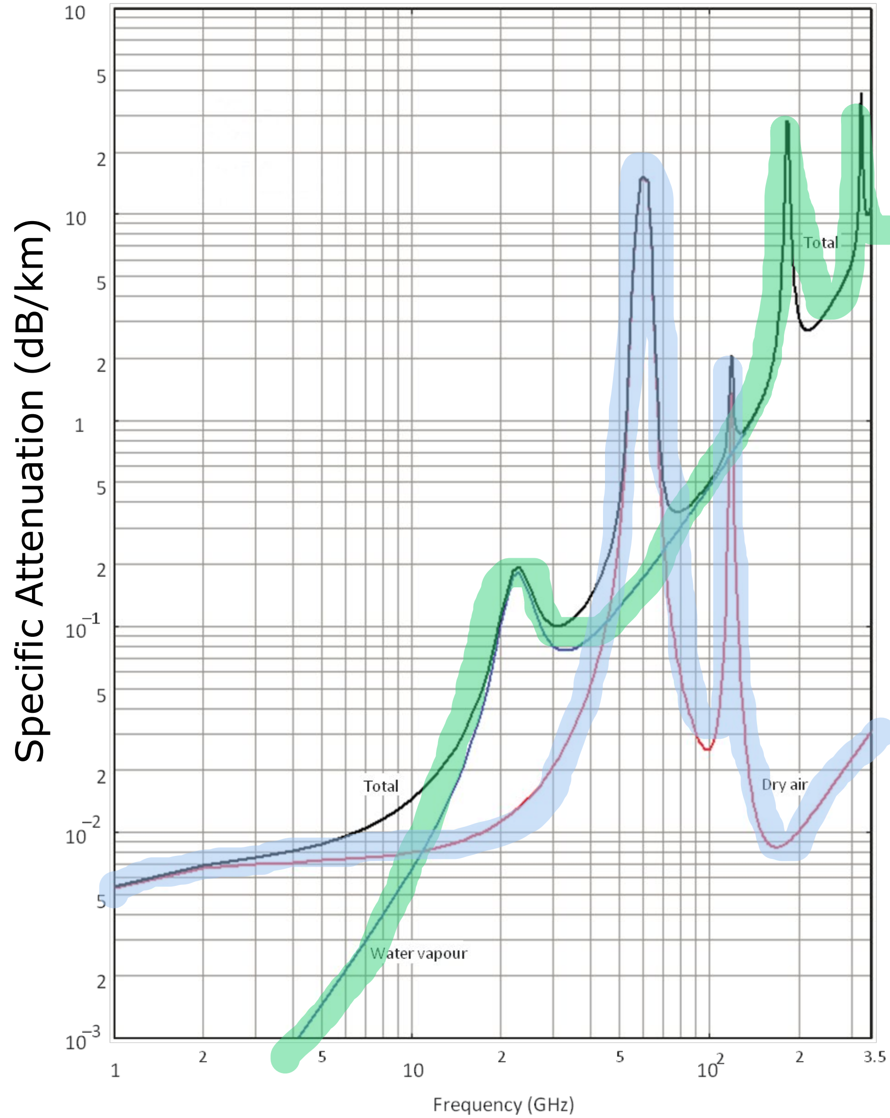


3. Physical Phenomena. Molecular Absorption

- At frequencies above 100 GHz, loss becomes significant.
- Helpful in protecting passive services as very high bands
- The calculation models are based on obtaining the specific attenuation and the absorption distance
- Different if the path is terrestrial or terrestrial-satellite

$$A = \gamma_a d = (\gamma_o + \gamma_w)\, d$$

- Chart shows specific attenuation at 1013 hPa, 15°C, water vapour density 7.5 g/m^3



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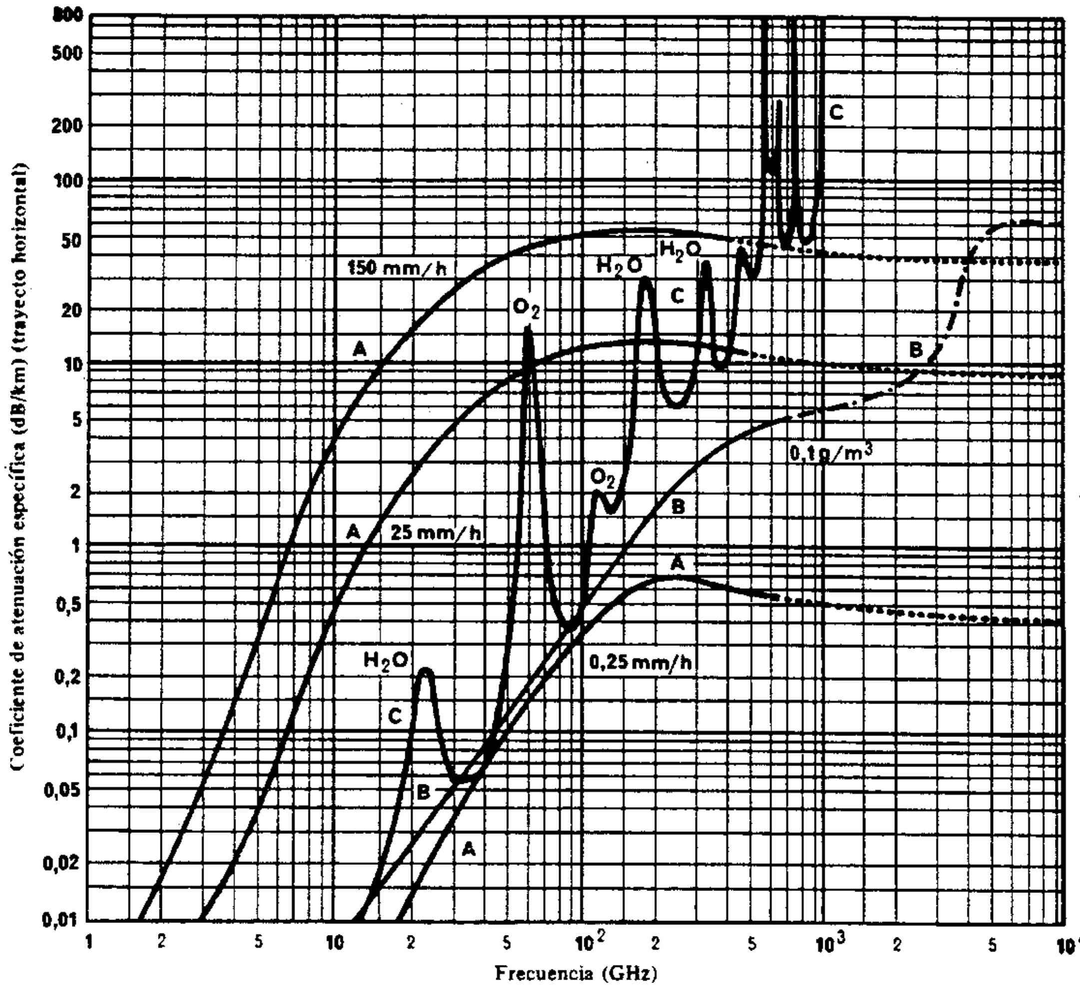
3. Physical Phenomena. Molecular Absorption

- Comparison with other absorption sources (dB/km)

A- Rain
B- Fog
C- Gases

Name	R
Drizzle	0.25 mm/hour
Light rain	1 mm/hour
Moderate rain	4 mm/hour
Heavy rain	16 mm/hour
Thunderstorm	35 mm/hour
Intense thunderstorm	100 mm/hour



3. Physical Phenomena.

3. Physical Phenomena. Hydrometeors

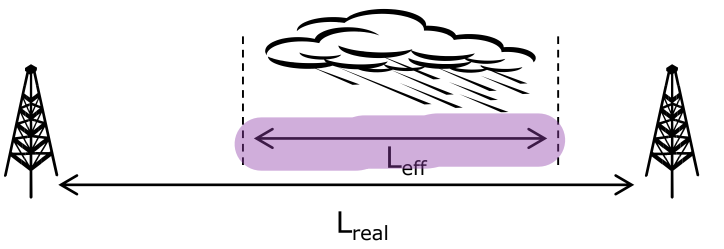
- Hydrometeors are one of the most influencing factors on radiocommunication above 10 GHz
- Rain, clouds, fog, snow or hail fall into the hydrometeor category
- Rain is the most relevant, due to its occurrence statistics and also for its impact
- Perturbations from hydrometeors are two fold:
  - Energy of the radio signal is absorbed and scattered by rain drops or ice particles which rain, snow and hail are composed of.
  - Ice particles and rain drops, due to their non-spherical shape, create a polarization rotation effect that will be associated to the shape, size and distribution of rain drops (or ice crystals).
- The models that describe the rain include
  - Size and distribution of rain volumes
  - Shape, size and distribution of rain drops
- In all cases: empirical

3. Physical Phenomena. Hydrometeors: Rain Absorption

- The absorption is empirically calculated in most cases using a formula similar to:

$$A(dB) = \gamma \cdot L_{eff}$$

$$\gamma\left(dB/km\right) = k \cdot R^{\alpha}$$

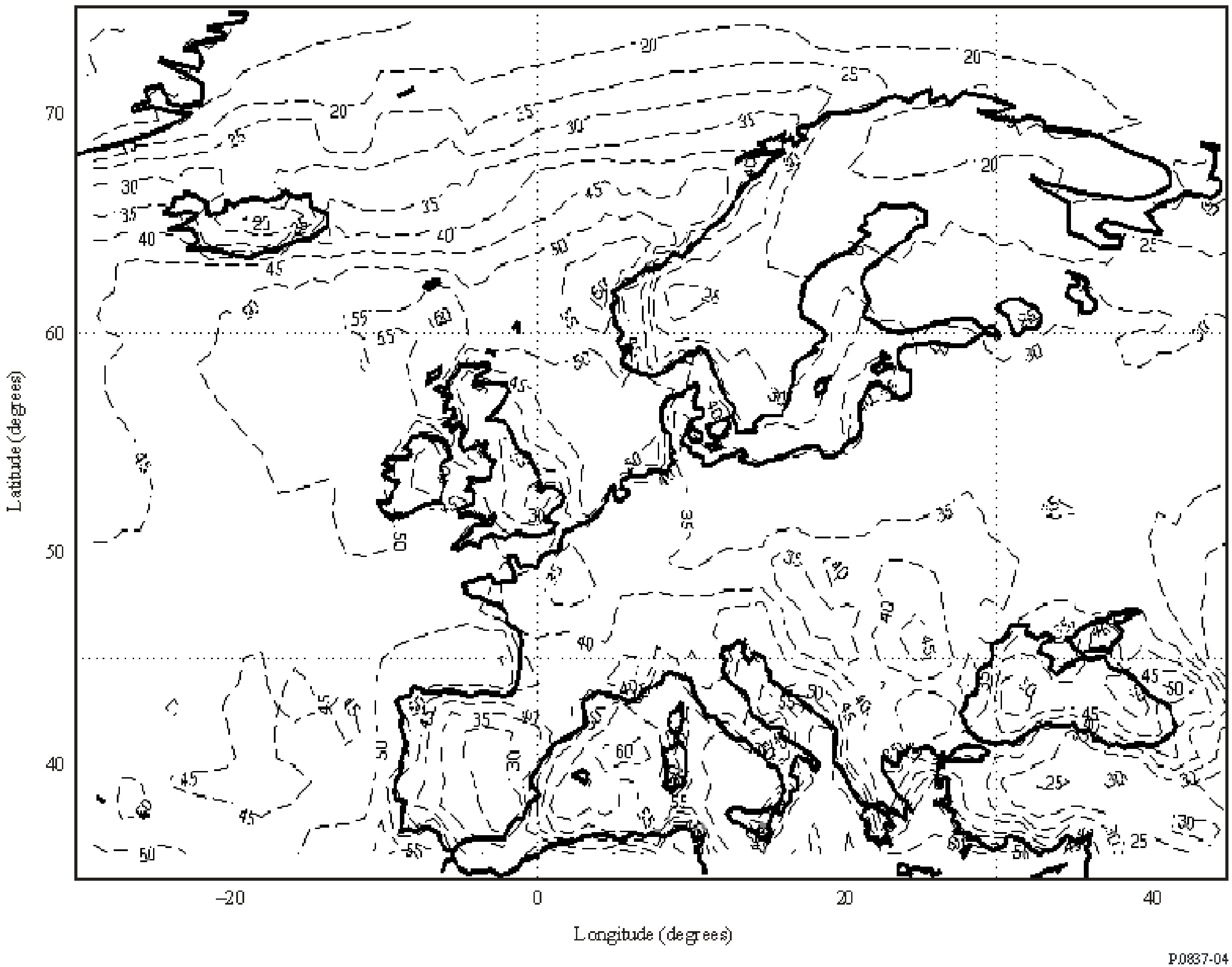


Where

- A: Absorption in dB
- γ: specific attenuation (dB/km)
- L_{eff}: effective path length (km)
- k and α are empirical constants function of the polarization and the frequency
- R is the rain rate (mm/h) associated to a certain probability value, usually 0.01% of the time

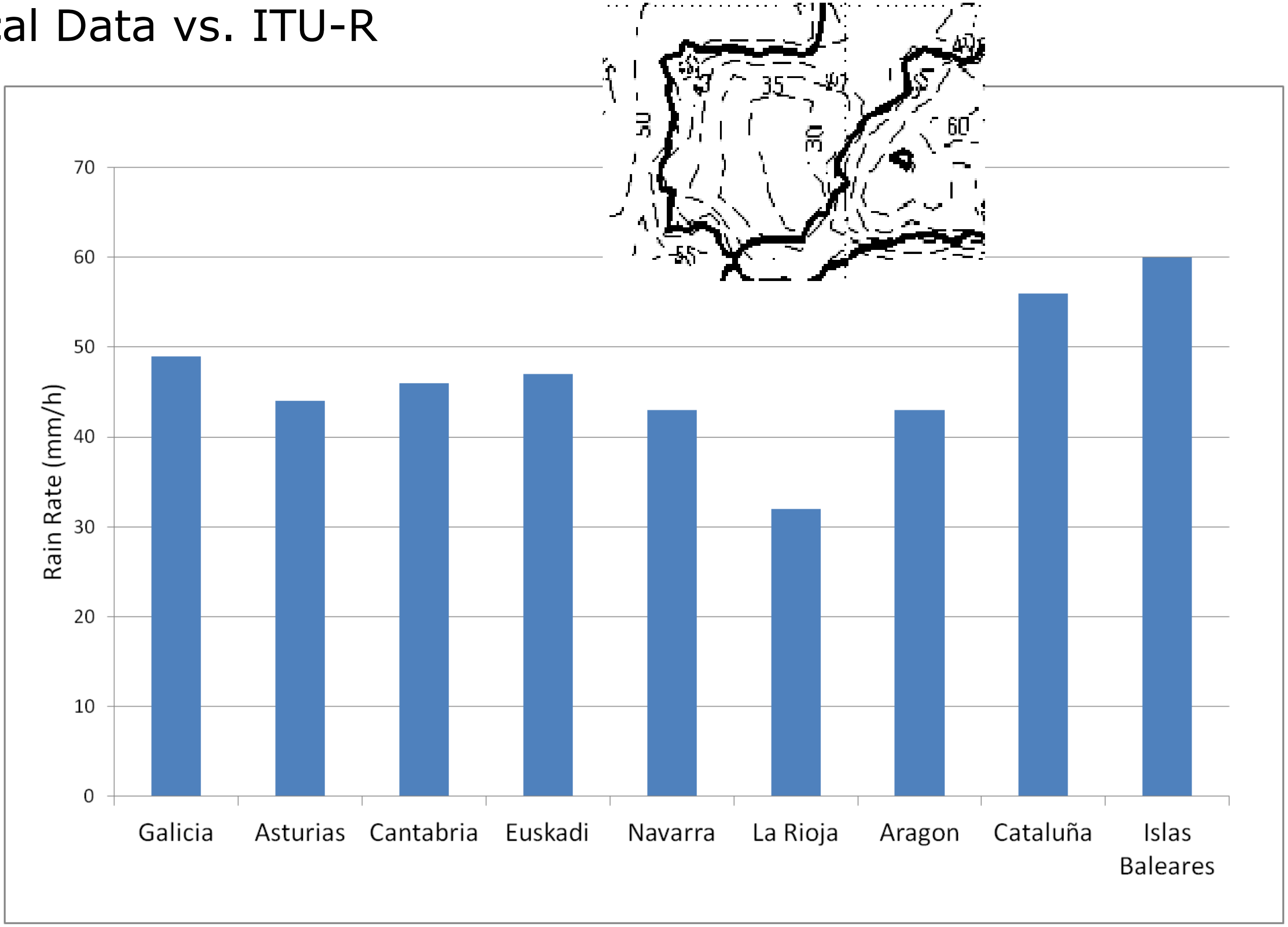
- The method is based on statistical rain data
- The best source is always local data
- Otherwise use rain statistics in ITU-R P-837

3. Physical Phenomena. Hydrometeors: Rain Absorption – ITU-R P.837



3. Physical Phenomena. Hydrometeors: Rain Absorption – ITU-R P.837

Local Data vs. ITU-R



3. Physical Phenomena. Hydrometeors: Rain Absorption

- R is the rain rate associated to a certain probability, in other words

  $R_{0.01}$=35mm/h →the value for 0.01% of the (observation) time is higher than 35 mm/h
- This fact brings probability to the calculation of the attenuation caused by rain

$$A_{0.01}(dB) = k \cdot R_{0.01}^{\alpha} \cdot L_{eff}$$

- 0.01 is a usual value → associated to availability percentages of 99.99%
- Other probability values depend on the system (e.g. Fixed Links: Rec. ITU-R P.530)

$$\frac{A_p}{A_{0.01}} = C_1 \, p^{-(C_2 + C_3 \log_{10} p)}$$

$$C_1 = \left(0.07^{C_0}\right)\left[0.12^{(1-C_0)}\right]$$

$$C_2 = 0.855C_0 + 0.546(1 - C_0)$$

$$C_3 = 0.139C_0 + 0.043(1 - C_0)$$

$$C_0 = \begin{cases} 0.12 + 0.4\left[\log_{10}(f/10)^{0.8}\right] & f \geq 10\ GHz \\ 0.12 & f < 10\ GHz \end{cases}$$

3. Physical Phenomena. Hydrometeors: Rain Absorption

- The effective length calculation depends on the specifics of the radiocommunication system.
- Two examples: LOS Links and Satellite Links

- LOS Links (ITU-R P.530-14, updated 2012)

wtf

$$r = \frac{1}{0.477 d^{0.633} R_{0.01}^{0.073\cdot\alpha} f^{0.123} - 10.579(1 - \exp(-0.024d))}$$

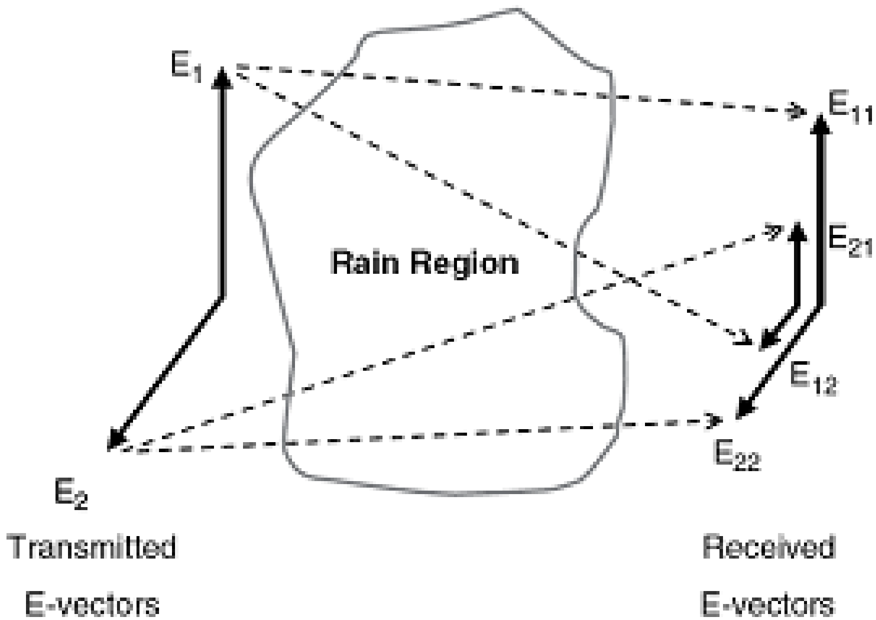
d, link distance (km)

R, rain rate (mm/h)

f, frequency (GHz)

The effective path length: $L_{Eff} = d\ r$

3. Physical Phenomena. Hydrometerors: De-Polarization



$$XPD = 20\log\frac{|E_{11}|}{|E_{12}|}$$

E_{11}	is the component received with the original transmitted polarization
E_{12}	is the component received with the orthogonal polarization caused by cross-polarization

3. Physical Phenomena.

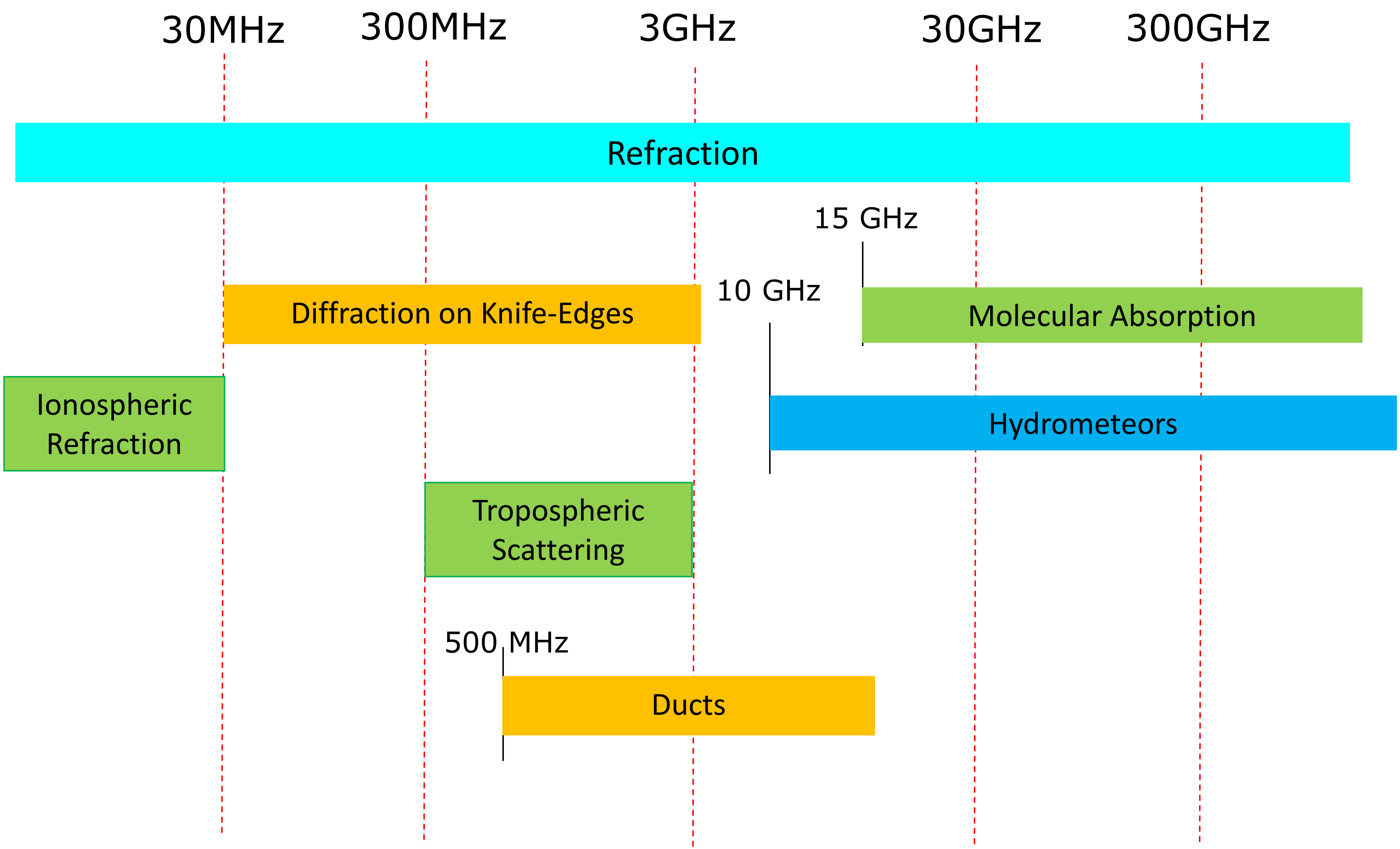
1. Free Space Loss Review
2. Propagation Modes
3. Physical Phenomena
   - Refraction
   - Diffraction
   - Reflection
   - Scattering
   - Molecular Absorption
   - Hydrometeors
4. **Summary**

4. Summary: Physical Phenomena and Propagation Modes

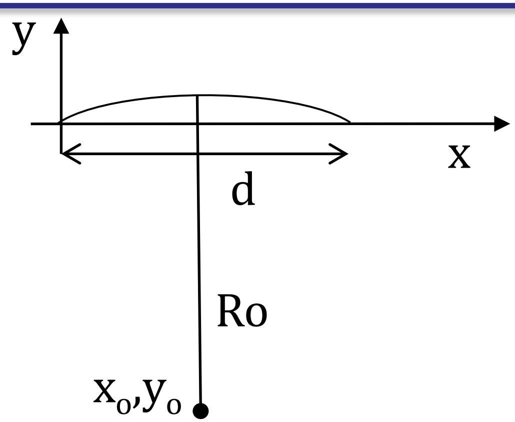
Summary

Propagation Mode	Components	Physical Phenomena	Frequencies
Surface Wave	Surface Wave	Absorption Diffraction	< 3 MHz // < 30 MHz (Depends on the Radiating System and Cov. Area)
Space Wave	Direct Wave Reflected Wave	Refraction Reflection Absorption Diffraction Scattering Hydrometeor Absorption De-Polarization	> 100 MHz
Sky Wave	Ionospheric Wave	Absorption Refraction De-Polarization (Faraday)	3 MHz < f < 30 MHz
Ground Wave	Surface Wave Direct Wave Reflected Wave	*See above*	3 MHz < f < 30 MHz (Depends on the Radiating System and Cov. Area)

4. Summary: Physical Phenomena and Propagation Modes



Annexe: calculation of k fictitious radius factor



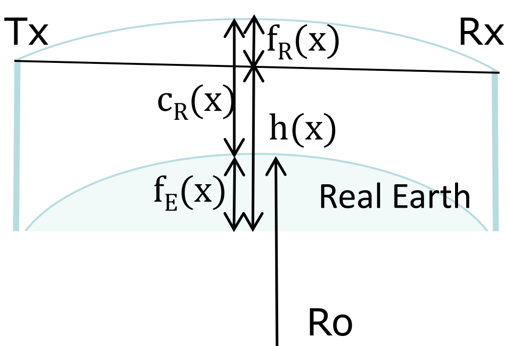
$$(x - x_o)^2 + (y - y_o)^2 = {R_o}^2$$
$$x_o = d \ \text{and} \ \ y_o \approx -R_o$$
$$(x - d/2)^2 + (y + R_o)^2 = {R_o}^2$$
$$x^2 - dx + 2R_o y = 0$$
$$y \approx \frac{x(d-x)}{2R_o}$$

R *ray bending radius*

$$\frac{1}{R} = -\Delta N \cdot 10^{-6}$$

Same distance from ray to Earth:

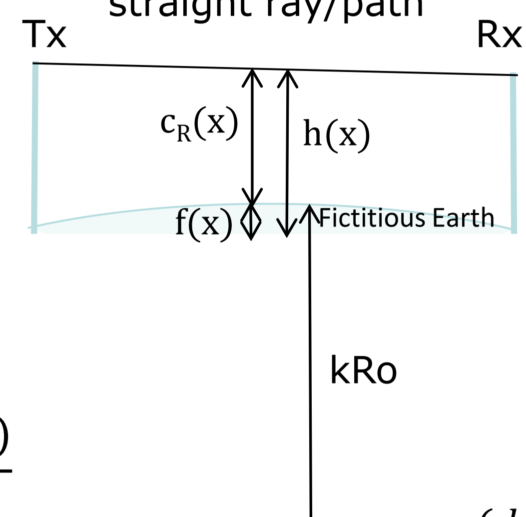
ray bending



$$c_R(x) = h(x) - f_E(x) + f_R(x)$$

$$c_R(x) = h(x) - f(x)$$

straight ray/path



$$h(x) - f_E(x) + f_R(x) = h(x) - f(x)$$
$$f(x) = f_E(x) - f_R(x)$$

$$f_E(x) = \frac{x(d-x)}{2R_o}$$

$$f_R(x) = \frac{x(d-x)}{2R}$$

$$\frac{x(d-x)}{2kR_o} = \frac{x(d-x)}{2R_o} - \frac{x(d-x)}{2R}$$

$$\frac{1}{kR_o} = \frac{1}{R_o} - \frac{1}{R} \Longrightarrow k = \frac{R}{R - R_o}$$

$$\boxed{k = \frac{157}{157 + \Delta N}}$$

$$f(x) = \frac{x(d-x)}{2kR_o}$$

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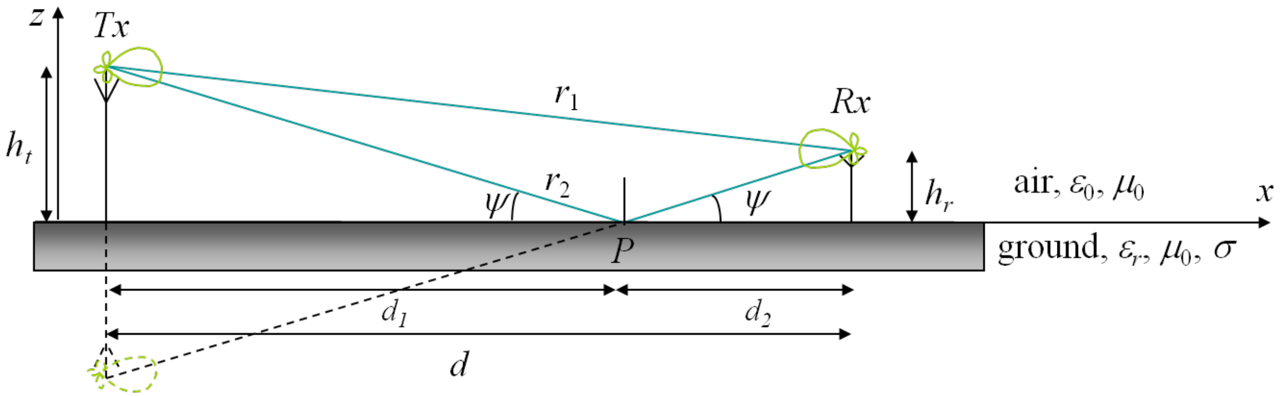
Annexe: Reflection. Two-ray model

Reflection Coefficient $\rho = |\rho| \cdot e^{-j\beta}$



$$\Delta = \frac{2\pi}{\lambda}(r2 - r1)$$

$$\vec{E} = \overrightarrow{Eo} \cdot e^{-j\frac{2\pi}{\lambda}r1} + \overrightarrow{Eo} \cdot \rho \cdot e^{-j\frac{2\pi}{\lambda}r2} = \overrightarrow{Eo} \cdot e^{-j\frac{2\pi}{\lambda}r1}\left[1 + \rho \cdot e^{-j\frac{2\pi}{\lambda}(r2-r1)}\right]$$

$$\vec{E} = \overrightarrow{Eo} \cdot e^{-j\frac{2\pi}{\lambda}r1}\left[1 + \rho \cdot e^{-j\beta} \cdot e^{-j\frac{2\pi}{\lambda}(r2-r1)}\right] = \overrightarrow{Eo} \cdot e^{-j\frac{2\pi}{\lambda}r1}\left[1 + |\rho| \cdot e^{-j(\Delta+\beta)}\right]$$

$$\overrightarrow{|E|} = \overrightarrow{|Eo|} \cdot \left|1 + |\rho| \cdot e^{-j(\Delta+\beta)}\right| = \overrightarrow{|Eo|} \cdot |1 + |\rho|\cos(\Delta+\beta) + j|\rho|\sin(\Delta+\beta)|$$

$$\overrightarrow{|E|} = \overrightarrow{|Eo|} \cdot \sqrt{[1 + |\rho|\cos(\Delta+\beta)]^2 + [|\rho|\sin(\Delta+\beta)]^2} = \overrightarrow{|Eo|} \cdot \sqrt{1 + |\rho|^2 + 2|\rho|\cos(\Delta+\beta)}$$