School on Digital Radio Communications for Research and Training in Developing Countries
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Radio-wave Propagation Basics

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Note: These are preliminary notes, intended only for distribution to participants. Beware of misprints!

Purpose

- The purpose of the lecture is to refresh basic concepts related to EM and radio wave propagation physics that are needed to understand better the operation and design of microwave digital radio links
  - Note: Due to time limitations, we will focus here only on these propagation mechanisms that are critical for wanted signals in microwave LAN/ WAN applications.

Main topics for discussion

- What is the EM field and why consider propagation?
- What are the Free-space, Propagation Losses, and Fresnel zone?
- What are long-term and short term propagation effects?
- What do wave reflections?
- What is DTM?

EM Field = EM Forces

- EM field is a spatial distribution of forces acting on an electric charge
  - The force is a vector. It can be described in terms of its magnitude, direction, orientation, and spatial and temporal coordinates
  - The EM forces propagate with the speed of light and fill-in the whole space without limits
  - They interact with the matter
    - Magnetic forces and electric forces act differently (e.g. the magnetic field interact with electric charges only when the charges move).

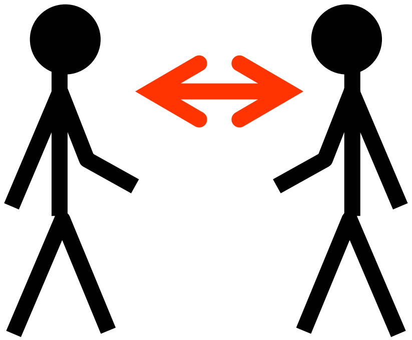
Classical physics

- For many years Electric and Magnetic fields were considered as being different phenomena and different branches of physics. Only in the 19 century it was realized that they both are different faces of the same Electro-Magnetic Field
- Coulomb (1736-1806), Galvani (1737-1798) Volta (1745-1827), Ampere (1775-1836), Faraday (1791-1867), Maxwell (1831-1879), Hertz (1857-1894), Marconi (1874-1937), Popov (1874-1937)

Modern physics

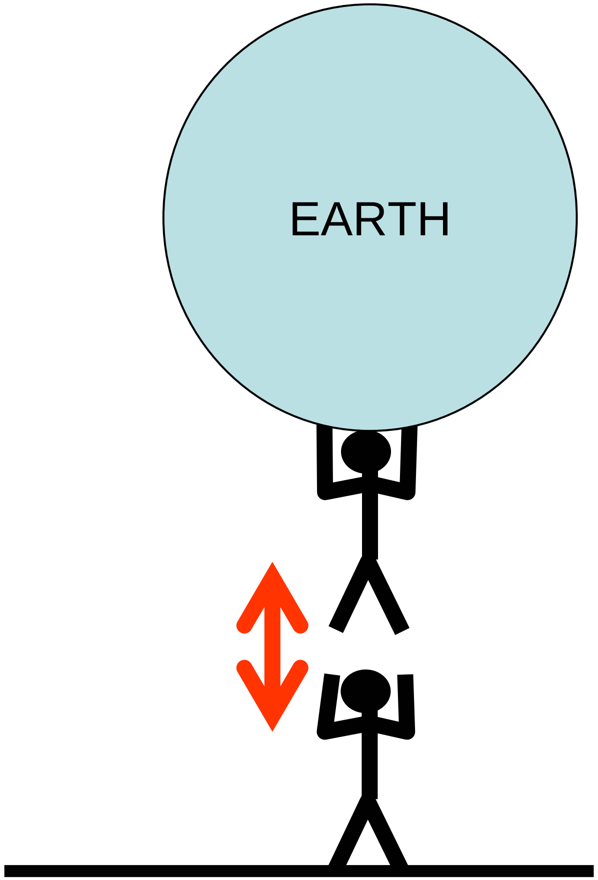
- Richard P Feynman (1918-1988), 1965 Nobel Prize Laureate, shown that laws of classic electromagnetics do not apply to small-scale events – they only approximate more general laws of quantum electrodynamics
- Abdus Salam, (1926-1996), the co-founder of ICTP and 1979 Nobel Prize Laureate, shown further that electromagnetism and weak nuclear interactions known from quantum physics are various facets of the same phenomenon

How strong are the EM forces?



- Imagine 2 persons at 1 m distance. By some magic, we decrease the number of protons by 1% in each, so that each has more electrons than protons
- They would be no more electrically neutral, but would repulse each other.
- How strong would be the repulsive force? Could it be enough to move a hair? Or a sheet of paper? Or this computer?

How strong?



- According to Feynman, the force would be strong enough to lift the whole Earth!
- EM forces generated in far galaxies can move electrons on the Earth
- Arno A Penzias & Robert W Wilson, of Bell Telephone Labs (Nobel Prize Laureates 1978) observed in 1965 such forces as residual EM noise at microwaves
- According to the Bing-Bang theory, that force (= EM noise field) propagated billions of years!

Why consider propagation?

1. Will the wanted signal of my radio communication system be appropriate?
   - Isolated radio-system design/ analysis

- Signal intensity?
- Signal coverage?
- Accounting for
  - Required quality of service
  - Required coverage/ distance
  - Required time period
  - Given geographic/climatic region

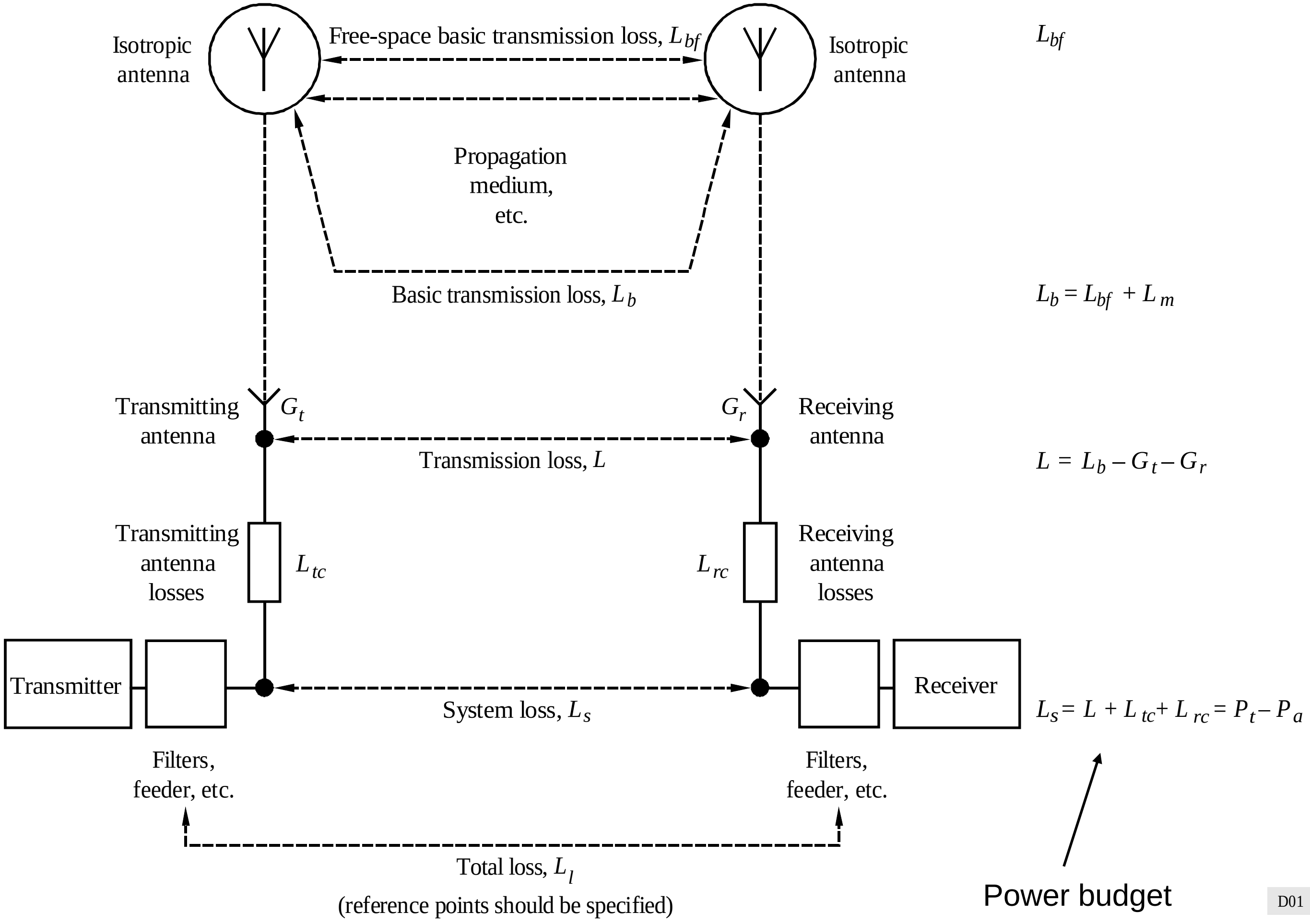
2. …

Why consider propagation?

2. Will my system operation be compatible with the operation of the neighboring systems?
   - Electromagnetic compatibility

- Probability of harmful interference
  - Interfering signal ***radiated*** by the system
  - Interfering signals ***received*** by the system
- Degradation in quality of wanted signal?
- Physical area of potential interference?
- Time period of potential interference?

Transmission loss



Free space propagation

- Propagation of an electromagnetic wave in a homogeneous ideal dielectric medium which may be considered of infinite extent in all directions.

$$PFD = \frac{P_T}{4\pi d^2}$$

$$E_0 = \sqrt{120\pi PFD} = \frac{\sqrt{30 PFD}}{d}$$

PFD : free-space power flux density, W/m^2

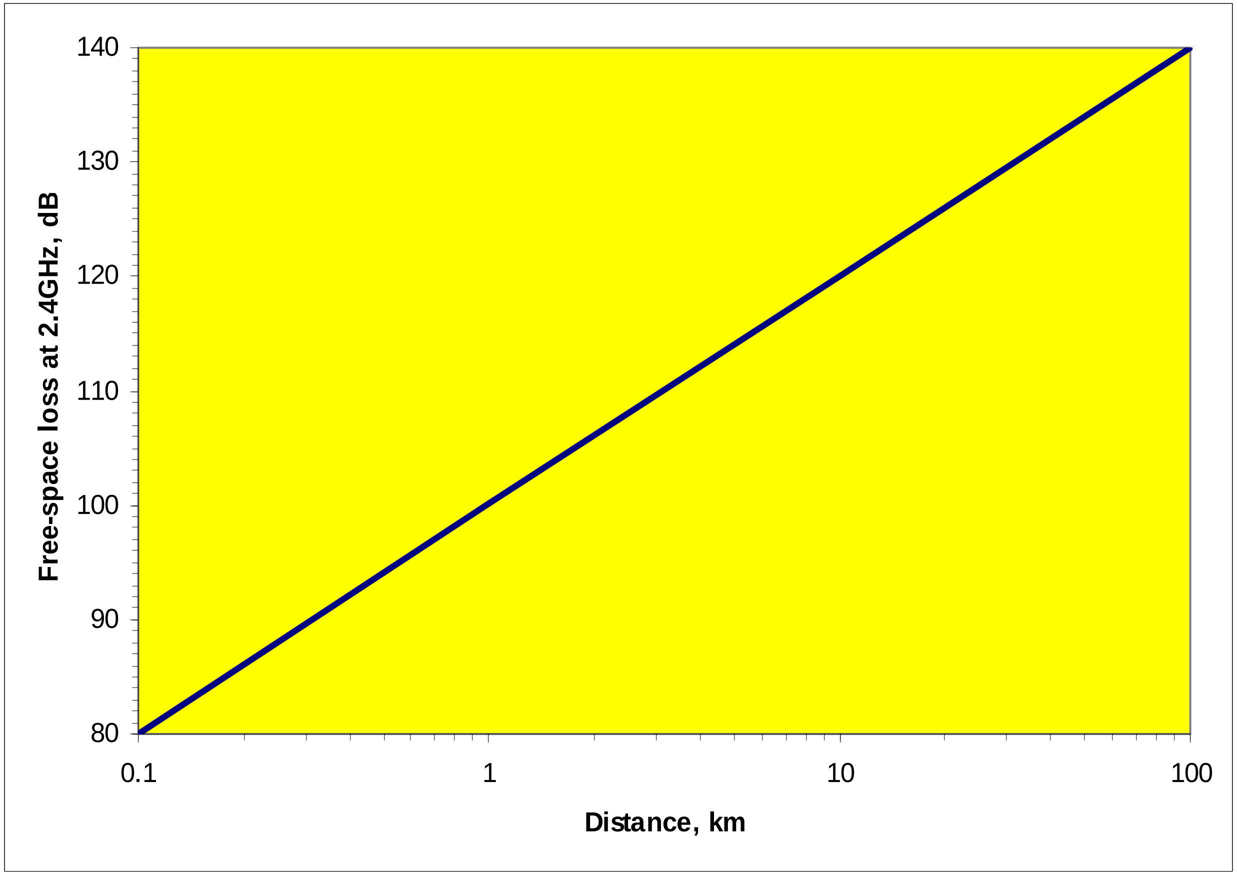
P_T : power radiated (isotropic antenna), W

d : distance between antennas, m

E_0 : free space field strength (isotropic antenna), V/m

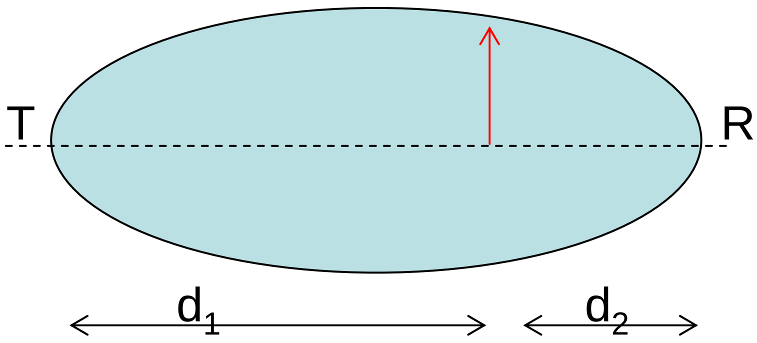
Note: With real antennas, use e.i.r.p. instead of power

Free-space propagation loss



$$L_{bf[dB]} = 32.44 + 20\log(F_{[MHz]}) + 20\log(d_{[km]})$$

Fresnel zone



$$r_1 = \sqrt{\frac{\lambda d_1 d_2}{d}} \le \frac{1}{2}\sqrt{\lambda d}$$

r_1 : radius of the 1st Fresnel zone, m

$d = d_1 + d_2$: distance T-R, m

λ : wavelength, m

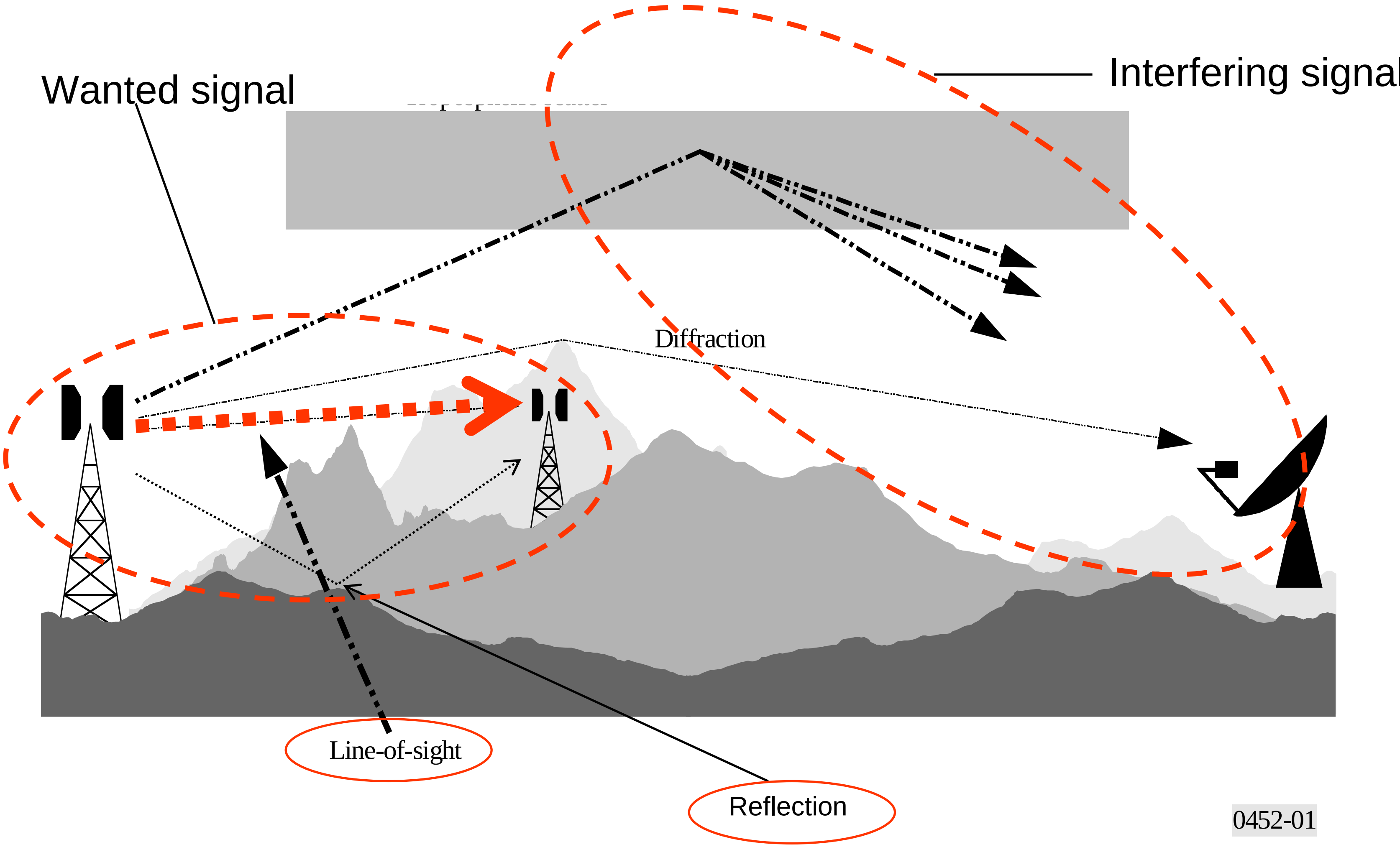
d_1, d_2 : distance to R and to T, m

- Energy transmission from T to R concentrates in the 1st Fresnel zone.
- Fresnel zones = loci of points of constant path-length difference of $\lambda/2$ (ellipsoids)
- The 1st Fresnel zone corresponds to $\lambda/2$. The n-th zone is the region enclosed between the 2 ellipsoids giving path-length differences $n(\lambda/2)$ and $(n-1)(\lambda/2)$

Fresnel zone (cont.)

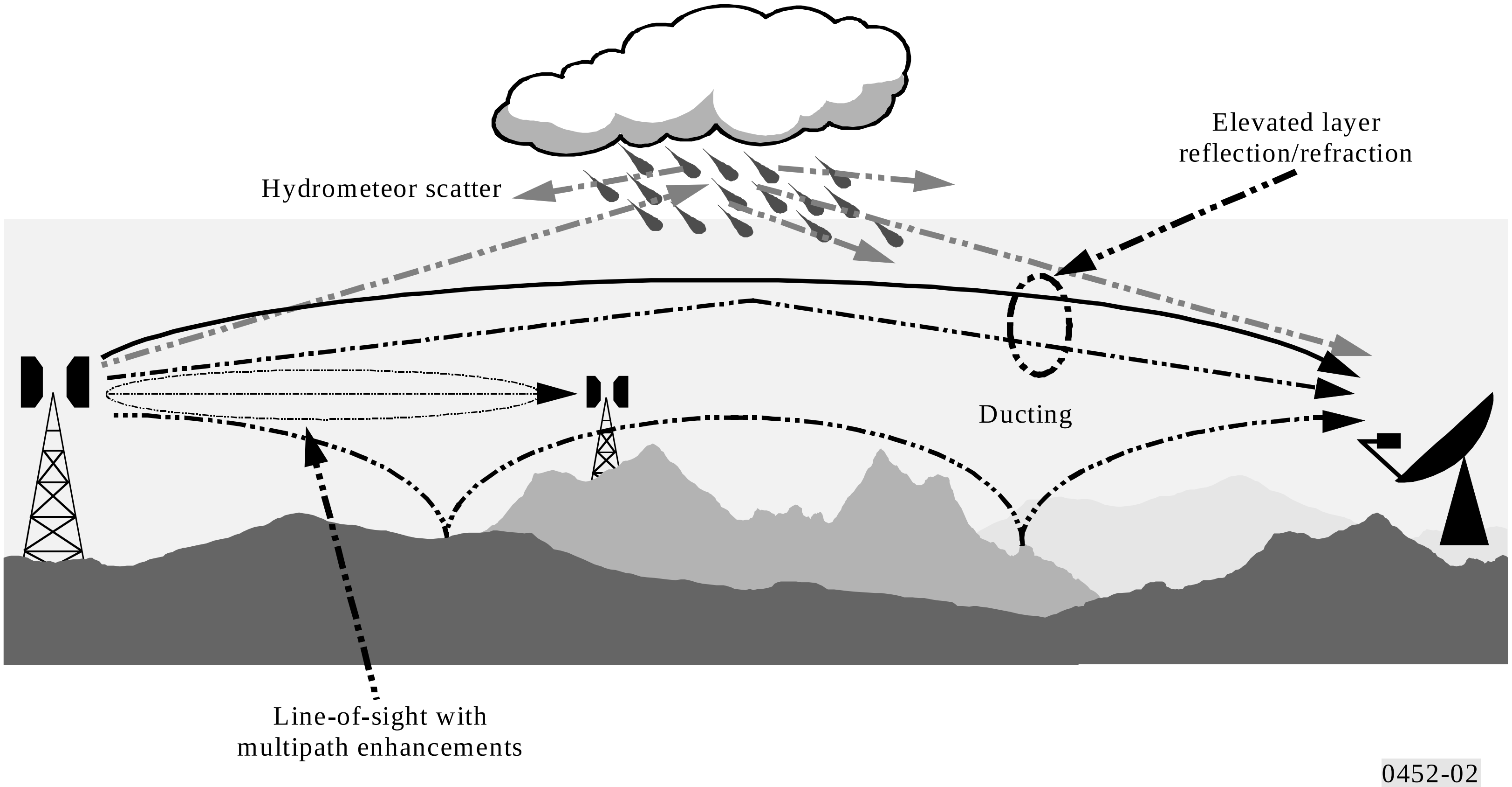
- If the 1st zone is not obstructed, the energy transmitted approximates energy transmitted in free-space. Sometimes obstructions up to ½ of the 1st Fresnel zone are ignored.
- An obstruction may lie to the side, above, or below the path.
  - Examples: ridges, bridges, cliffs, buildings, and trees

Long-term propagation modes



Short-term propagation modes

Anomalous (short-term) interference propagation mechanisms



Main components of radio wave

Component	*Comments*
Direct wave	Free-space propagation, LOS systems
Reflected wave	Reflection from a passive antenna, ground, wall, object, ionosphere, etc.
Refracted wave	Standard, Sub-, and Super-refraction, ducting, ionized layer refraction (<~100MHz)
Diffracted wave	Ground-, mountain-, spherical earth- diffraction (<~5GHz)
Scatter wave	Troposcatter wave, precipitation-scatter wave, ionized-layer scatter wave

Propagation Models

- Different dominating propagation mechanisms
  - For wanted signal and for interfering signals
  - For various frequencies and polarizations
  - For various applications/ services
  - For various environments (climates/ geographic regions)
- Variability due to randomly changing factors

Variability

- Changing environment
- Climate & weather
  - temperature, pressure, water vapor
  - rain intensity
  - cloud cover
- Dependent on region, season and time
  - e.g. temperate, tropical, equatorial
- Probabilistic approach

Principal propagation effects

- Effects of the ground and obstructions
- Tropospheric effects:
  – clear air
  – non-clear air
- Ionospheric effects

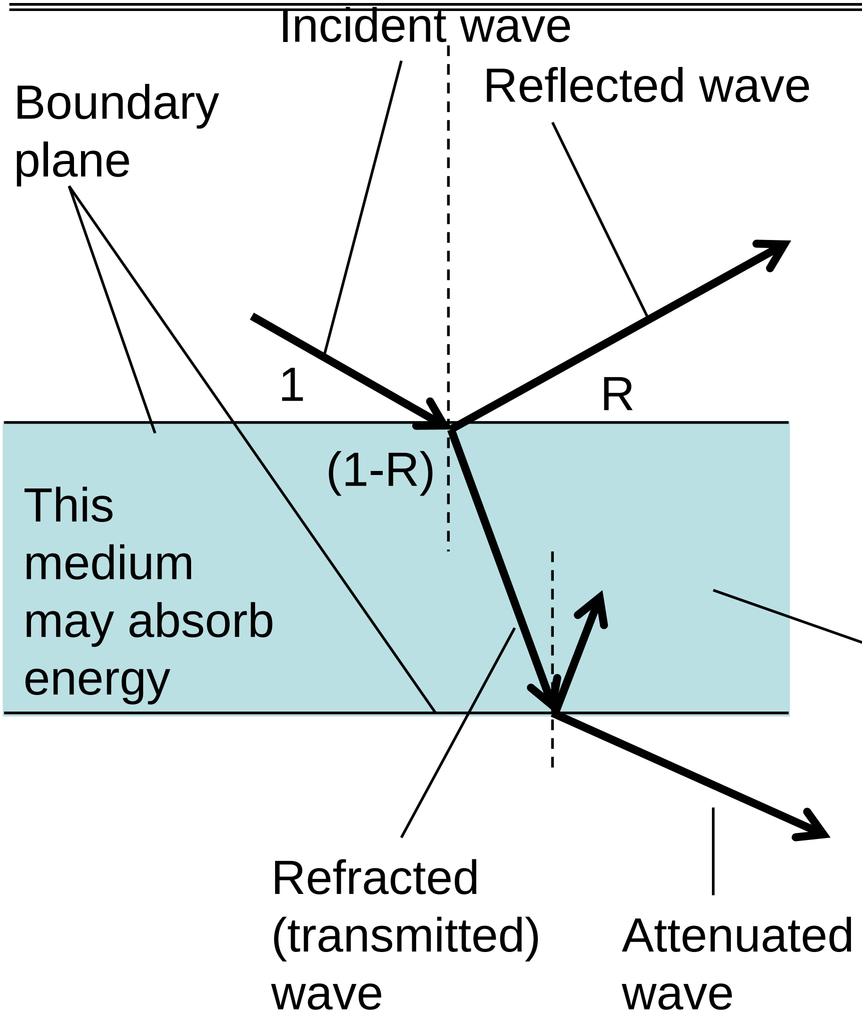
Ground and Obstacles

- Buildings (outside and inside)
  - Reflection, diffraction, scattering, absorption
- Terrain (smooth Earth, hills and mountains)
  - Reflection, diffraction, scattering
- Vegetation
  - Reflection, shadowing/ attenuation, scattering

Reflection

- = the abrupt change in direction of a wave front at an interface between two dissimilar media so that the wave front returns into the medium from which it originated. Reflecting object is large compared to wavelength.

Plane wave: reflection



Boundary conditions: Tangential components of the field are continuous at the boundary plane

E.g. wall between 2 rooms

Experiment with the laser pointer

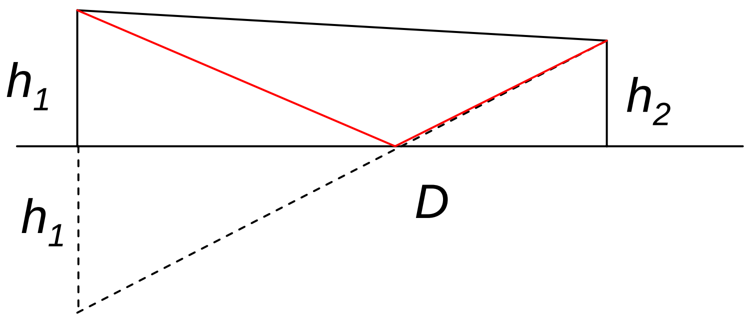
What does the reflection?

- changes the magnitude and phase of the reflected wave. The change depends on:
  - The nature of the media (reflection coefficient)
  - The shape of the interface
- Reflection may be specular (*i.e.,* mirror-like) or diffuse (*i.e.,* not retaining the image, only the energy) according to the nature of the interface.

Path-length difference

- Path-lengths difference of the reflected and direct rays introduces:
  - Relative phase delay (in addition to the phase change due to the reflection) dependent on frequency and distance (phase change of 360^0 at distance of λ)
  - Relative amplitude change (which is usually insignificant and may be disregarded)

Path-length Difference (cont.)



Direct ray: $d_d = \sqrt{D^2 + (h_1 - h_2)^2} = D\sqrt{1 + \left(\frac{h_1 - h_2}{D}\right)^2} \approx D\left[1 + \frac{1}{2}\left(\frac{h_1 - h_2}{D}\right)^2\right]$

Reflected ray: $d_r = \sqrt{D^2 + (h_1 + h_2)^2} = D\sqrt{1 + \left(\frac{h_1 + h_2}{D}\right)^2} \approx D\left[1 + \frac{1}{2}\left(\frac{h_1 + h_2}{D}\right)^2\right]$

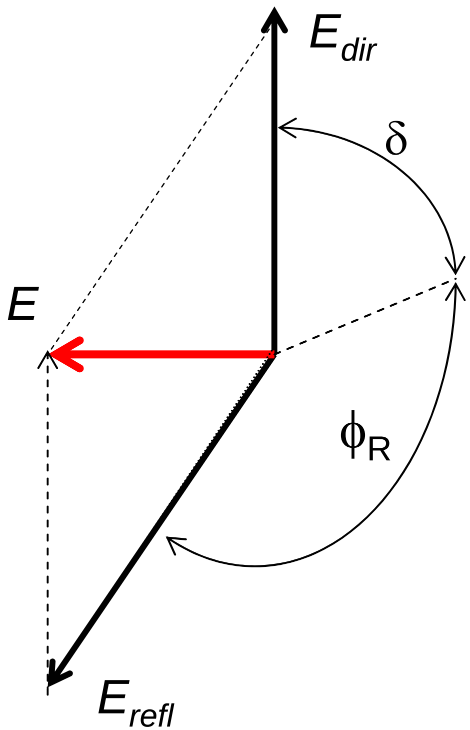
$$\sqrt{(1+x)} = 1 + \frac{1}{2}x - \frac{1}{2}\frac{1}{4}x^2 + \frac{1}{2}\frac{1}{4}\frac{3}{6}x^3 - \ldots$$

$$\Delta = d_r - d_d \approx \frac{(h_1 + h_2)^2}{2D} - \frac{(h_1 - h_2)^2}{2D} = \frac{2h_1h_2}{D}, \text{ if } \frac{h_1 + h_2}{D} \ll 1$$

Antenna contributions

- The magnitude and phase of the signal radiated in the direction of the receiver and those radiated in the direction of the reflection point may be different
- The receiving antenna gain may have different magnitudes and phases for the direct signal and for the reflected signal

Summing 2 vectors (rays)



$$|E| = \sqrt{E_{dir}^2 + E_{refl}^2 - 2E_{dir}E_{refl}\cos(\delta + \phi_R - \pi)}$$

$$= E_{dir}\sqrt{1 + |R|^2 - 2|R|\cos(\delta + \phi_R - \pi)}$$

$$\frac{E_{refl}}{E_{dir}} = |R|e^{-j\phi_R}$$

$\phi_R =$ lagging angle due to reflection

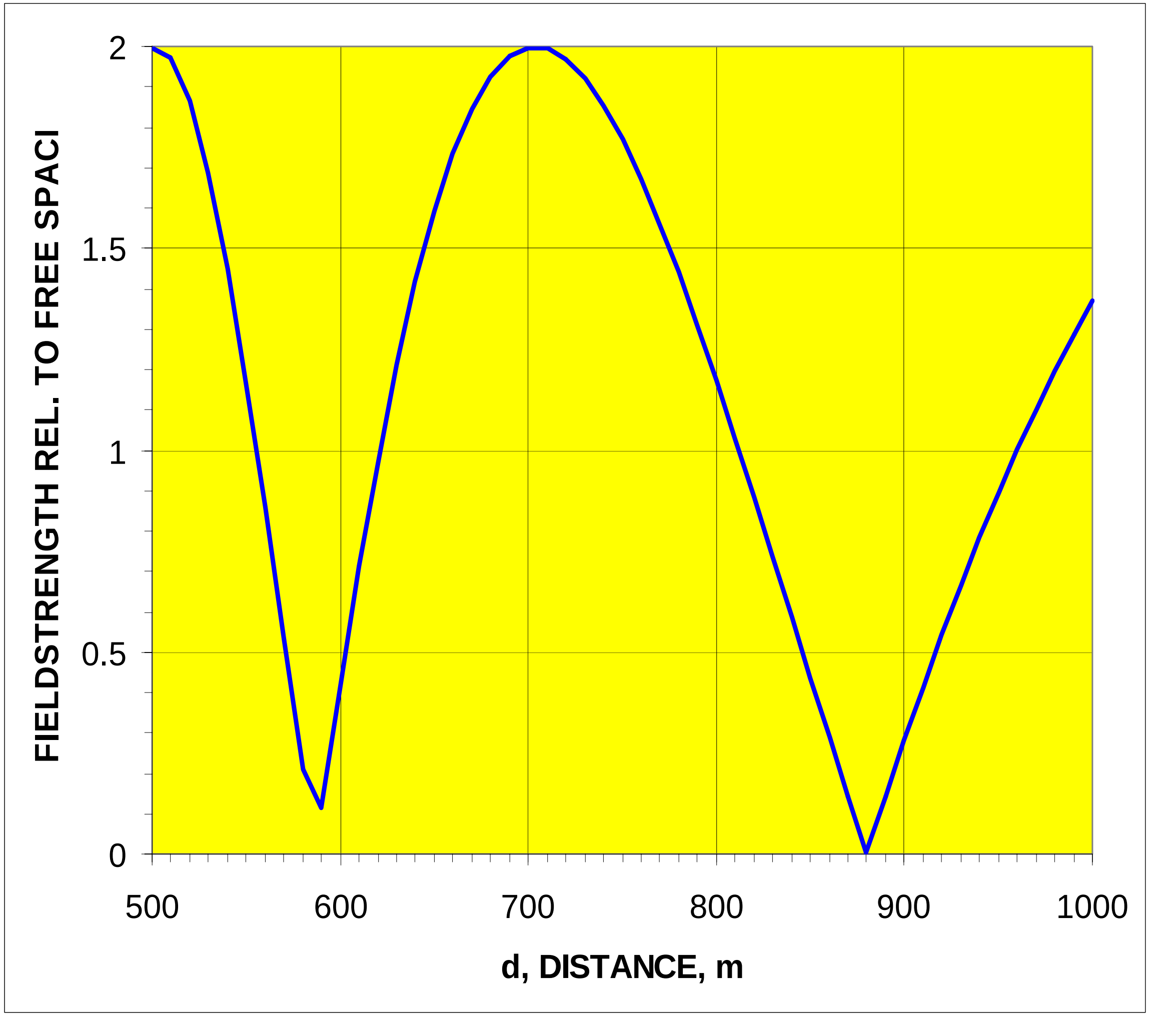
$\delta =$ lagging angle due to path-length difference

$= \ 2\pi\Delta/\lambda \ \ (\delta \approx 4\pi h_1 h_2 / \lambda D$, if D >> $h_1 + h_2$)

Sum: $\max|E| = E_{dir}(1 + |R|)$: when $(\delta + \phi_R - \pi) = 2(k+1)\pi$

Difference: $\min|E| = E_{dir}(1 - |R|)$: when $(\delta + \phi_R - \pi) = 2k\pi$

Example 1: distance

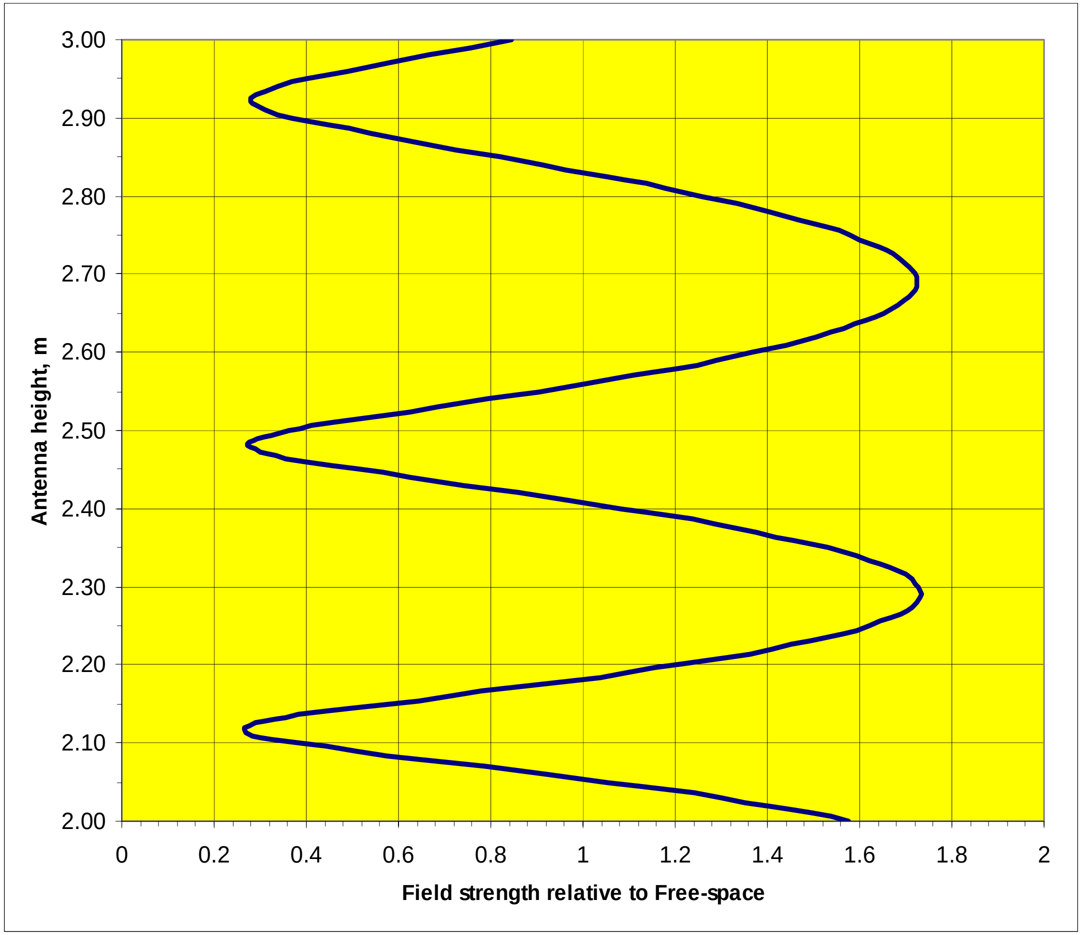


Variable:
d = 500-1000m
Step = 10m

Fixed parameters:
F = 2.4 GHz
H1 = 11m
H2 = 10m
|R| = 1
Arg(R) = 180^0

Diversity reception

Example 2: heigth



Variable:

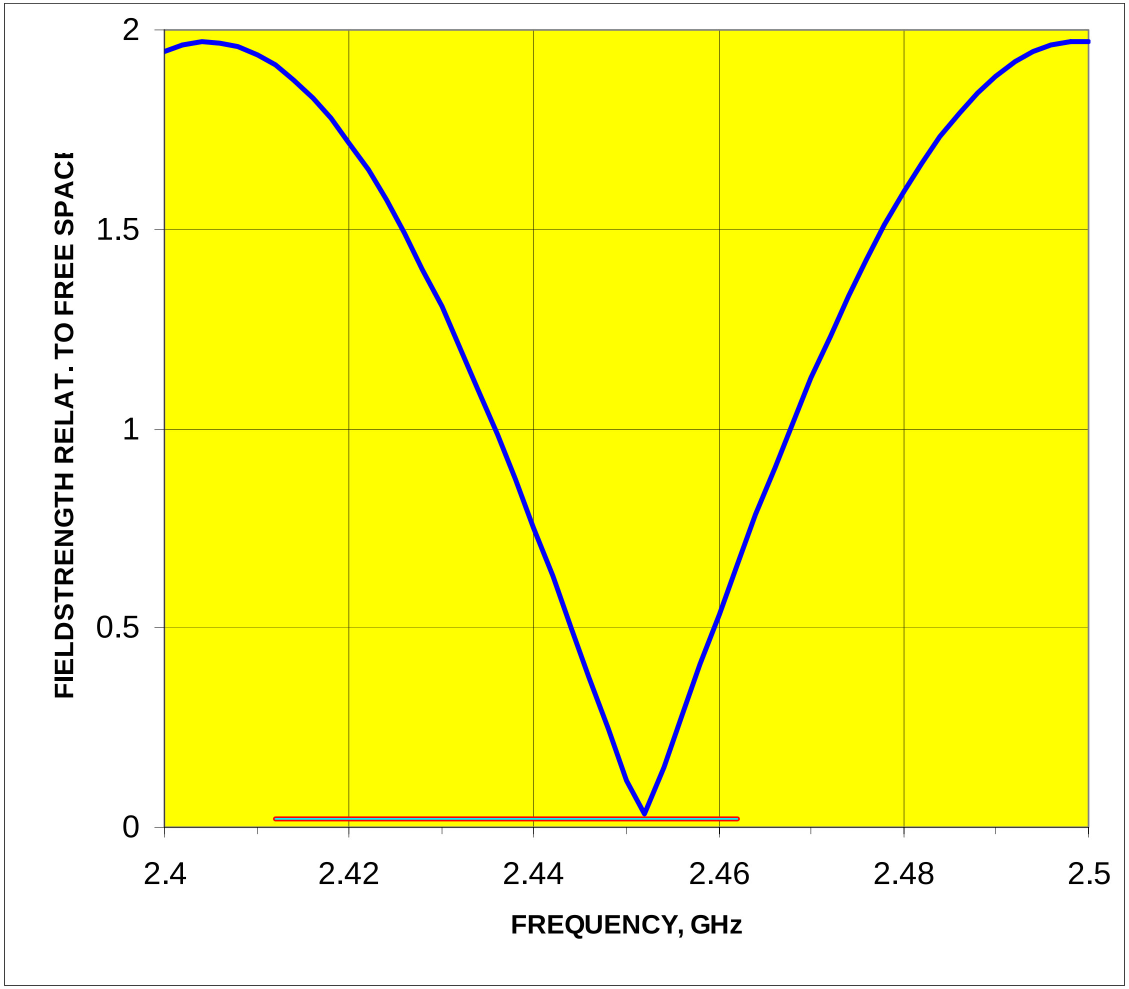
- H2 = 2 - 3m
- Step = 1 cm

Fixed parameters:

- F = 2.4GHz
- H1 = 1m
- D = 3m
- |R| =1
- Arg(R) = 180^0

Diversity reception

Example 3: frequency



Variable:
- F = 2.4 - 2.6 GHz Step = 2 MHz

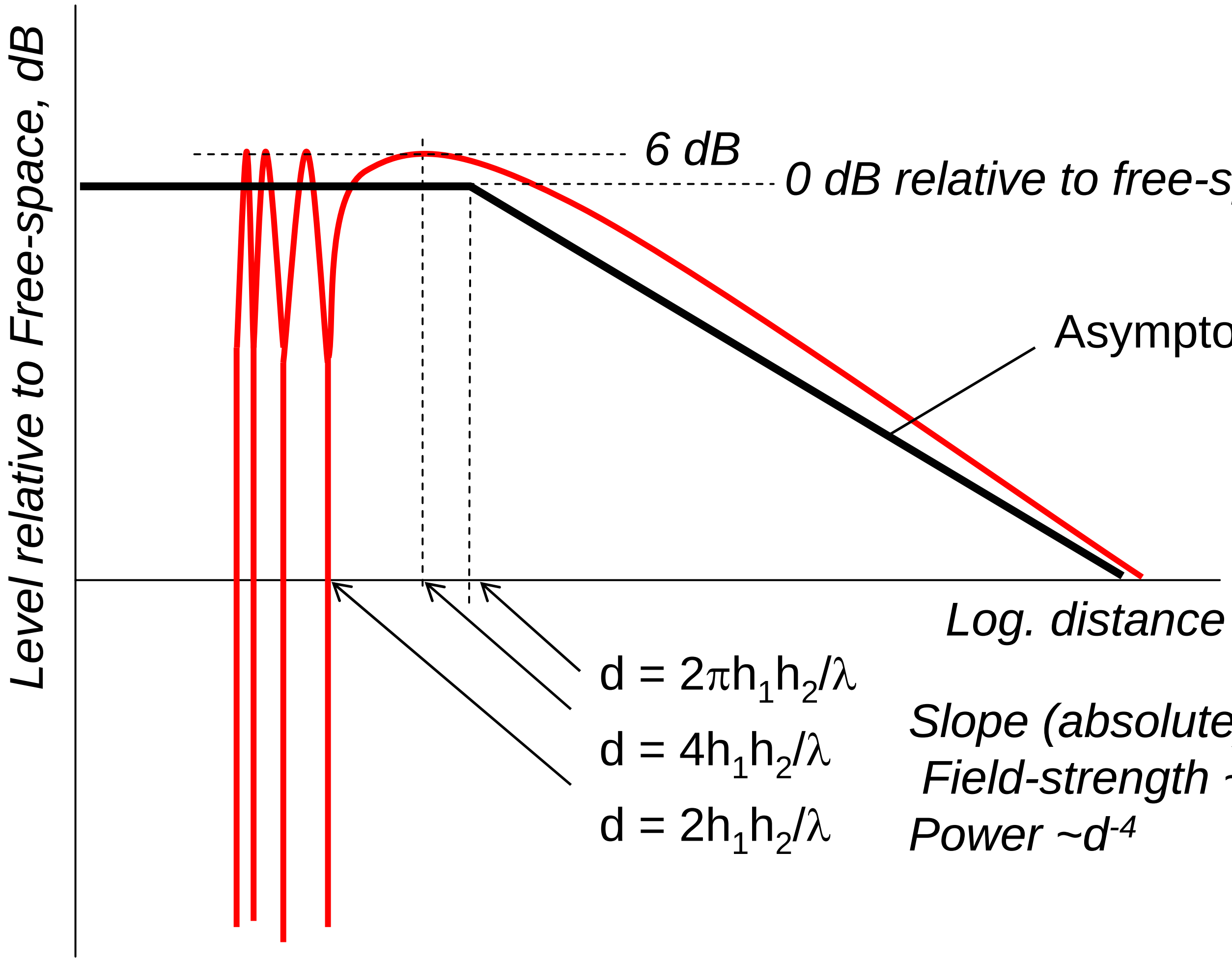
Fixed parameters:
- H1 = 14 m
- H2 = 12 m
- D = 104 m
- |R| =1
- Arg(R) = 180^0

Diversity reception

Field measurements

- Changing height, distance, direction, polarization

Distance Dependence



Slope (absolute): -40 dB/dec

Field-strength ~d^{-2}

Power ~d^{-4}

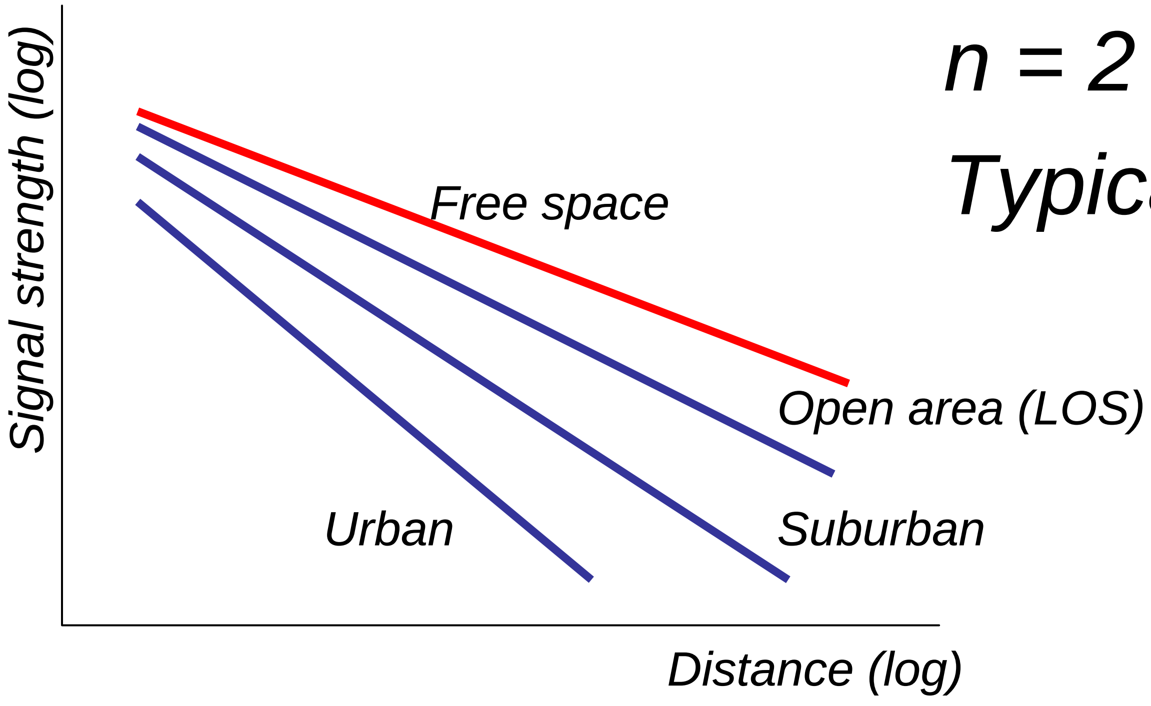
Outdoor Propagation

Received power

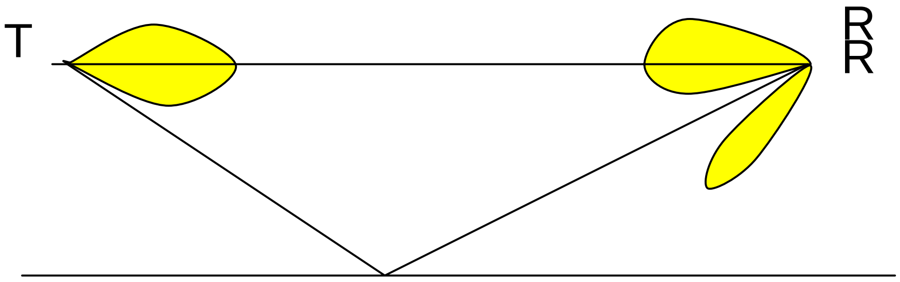
$P_R = Kd^{-n}$

n = 2 in free space

Typically $3 \leq n \leq 4$

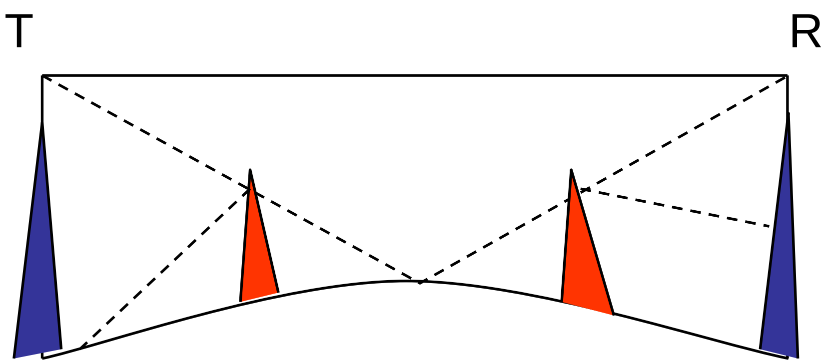


Avoiding reflection effects



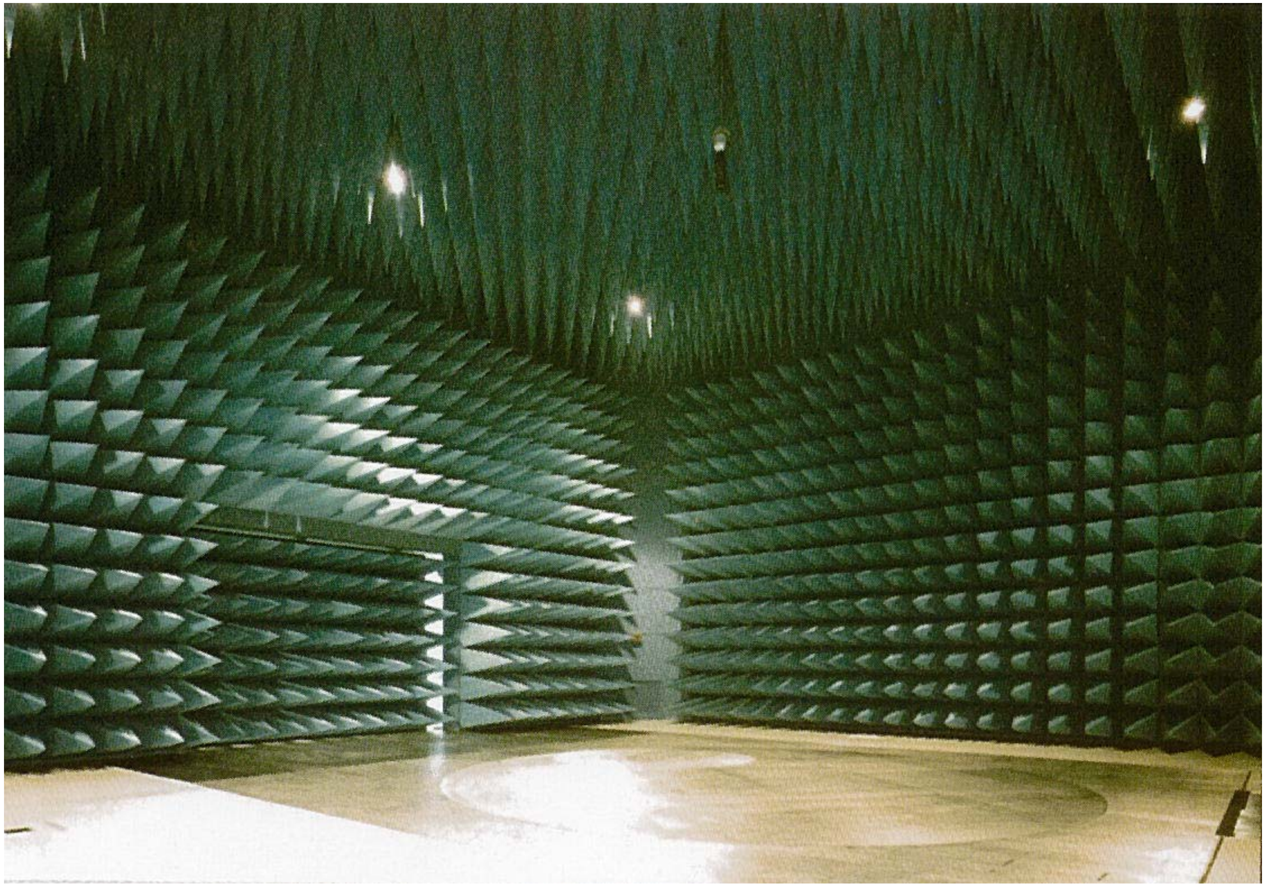
- At the transmitting antenna
  - Controlling the power radiated towards the reflection object
- At the receiving antenna
  - Controlling the power received from the reflection object
- At both antennas

Blocking reflections



- The transmitter-reflection region ray
- The reflection region – receiver reflected ray
- Blocking both rays

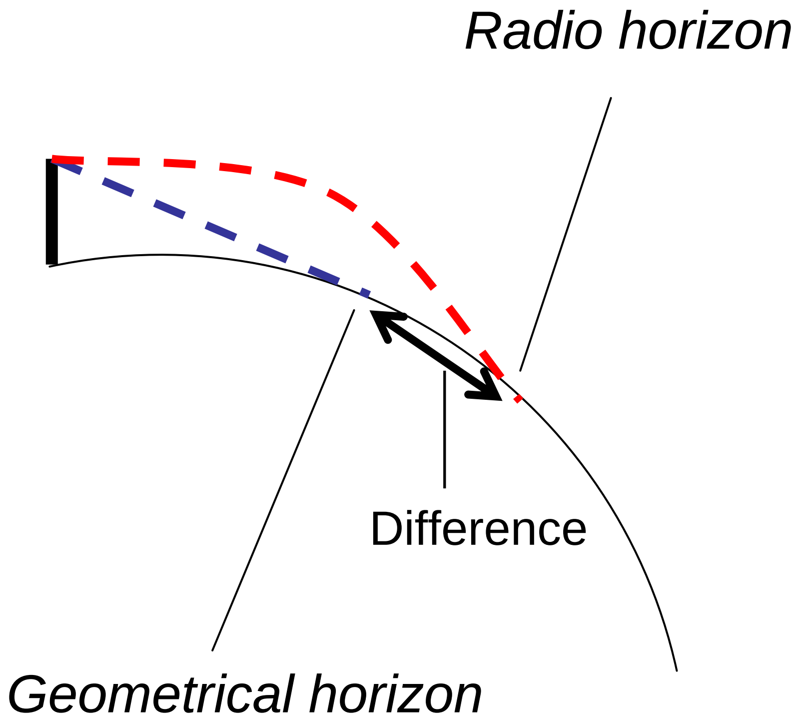
Absorbing reflections



- Cover the reflecting objects by non-reflecting (absorbing) material (Black-body in optics)

Source: Rohde & Schwarz

LOS – Radio Horizon

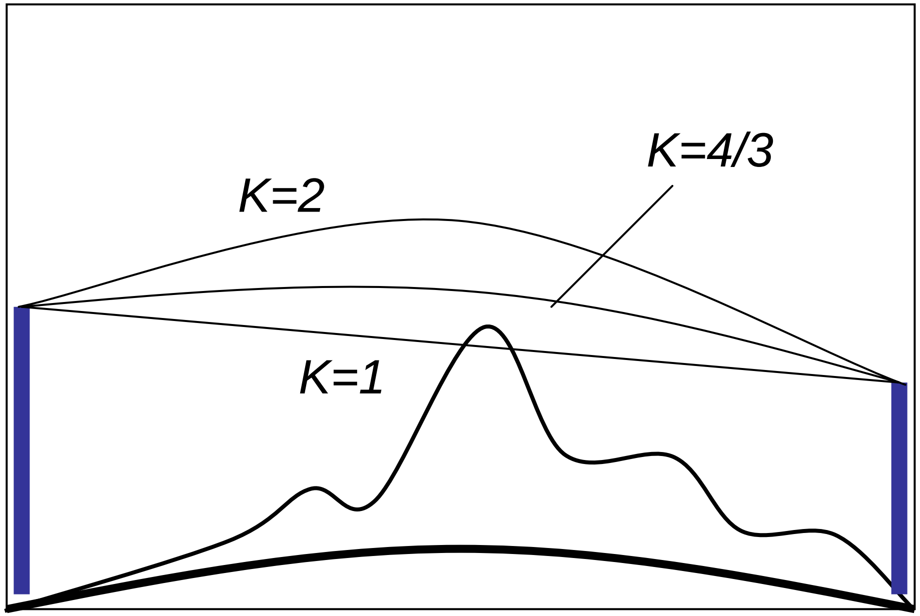


- *Radio horizon:* The locus of points at which direct rays from a point source of radio waves are tangential to the surface of the Earth.
- Radio waves go behind the geometrical horizon due to refraction in the air

Refraction

- = redirection of a wavefront passing through a medium having a refractive index that is a continuous function of position (*e.g.,* a graded-index optical fibre, or earth atmosphere) or through a boundary between two dissimilar media or
- For two media of different refractive indices, the angle of refraction is closely approximated by Snell's Law.

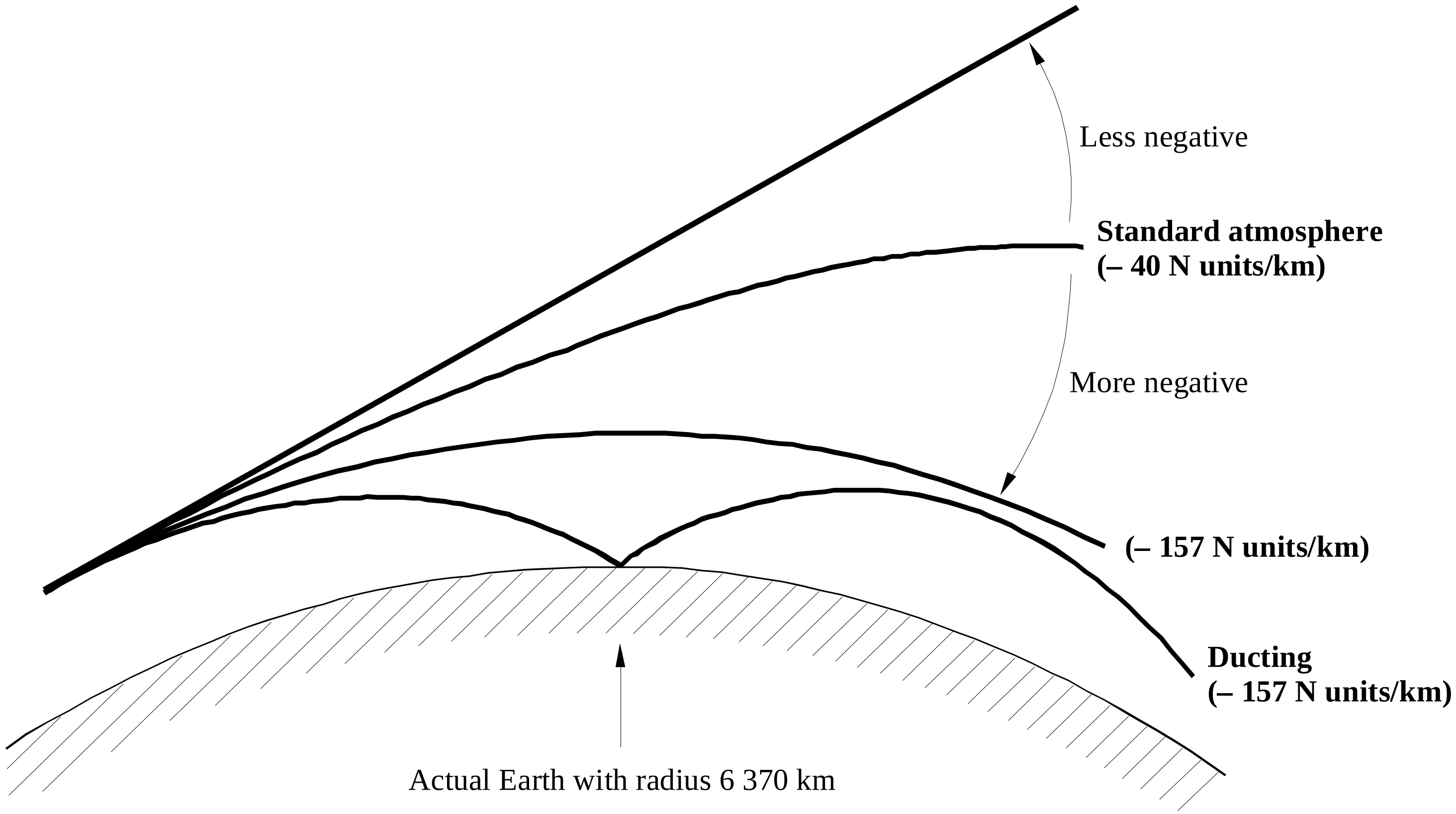
Example



Depends on the contents of water vapor in the air. Long paths over water or desert may show ducting phenomena, - surface ducts or elevated ducts.

Refraction effects
(Troposphere - clear air)

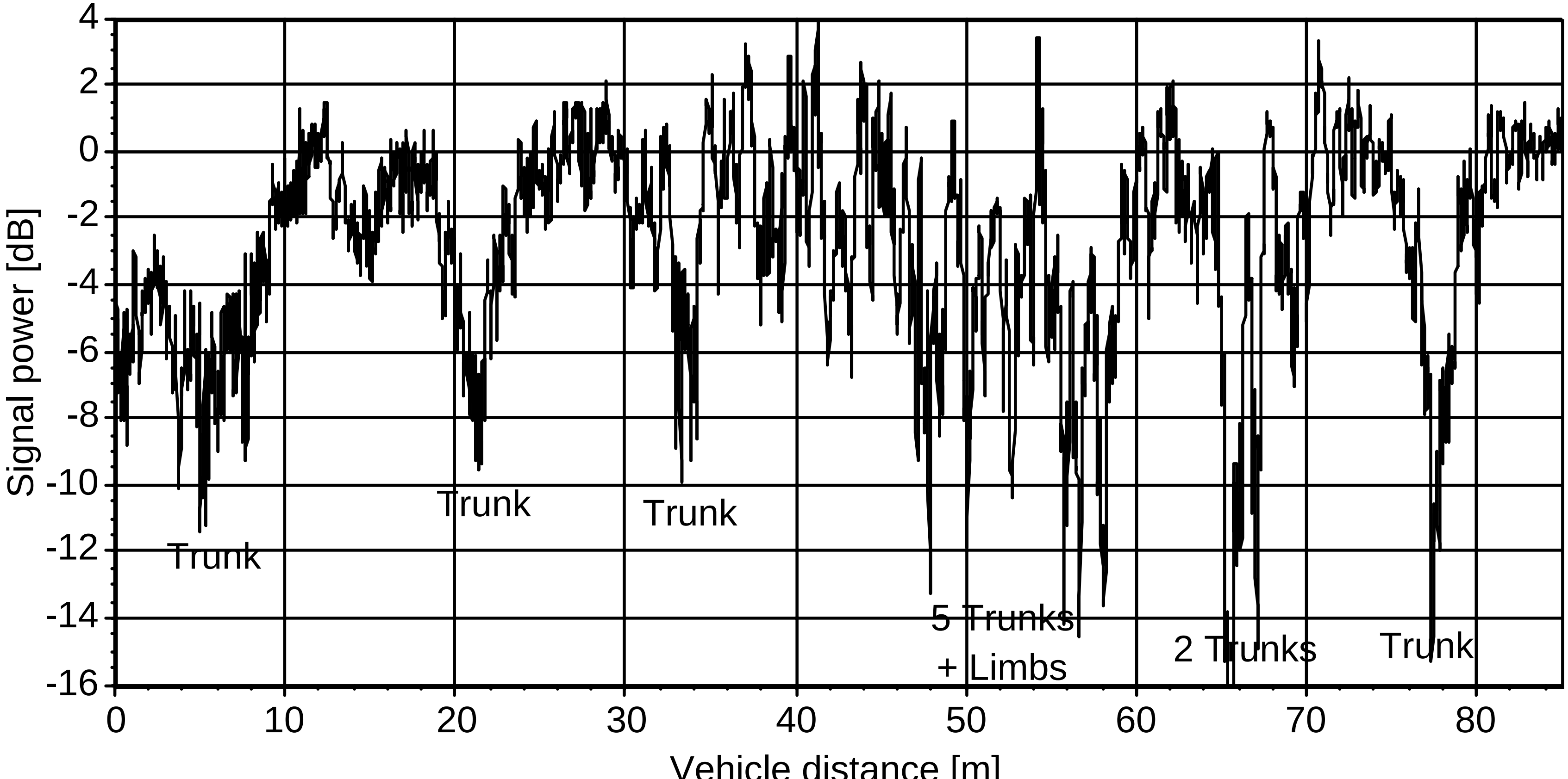
Atmospheric refraction effects on radio signal propagation



Effects of vegetation

- Shadowing/ attenuation can reach 20 dB
- Depends on
  - Season
  - Species of tree
  - Density and structure of foliage
  - Movement of branches and foliage

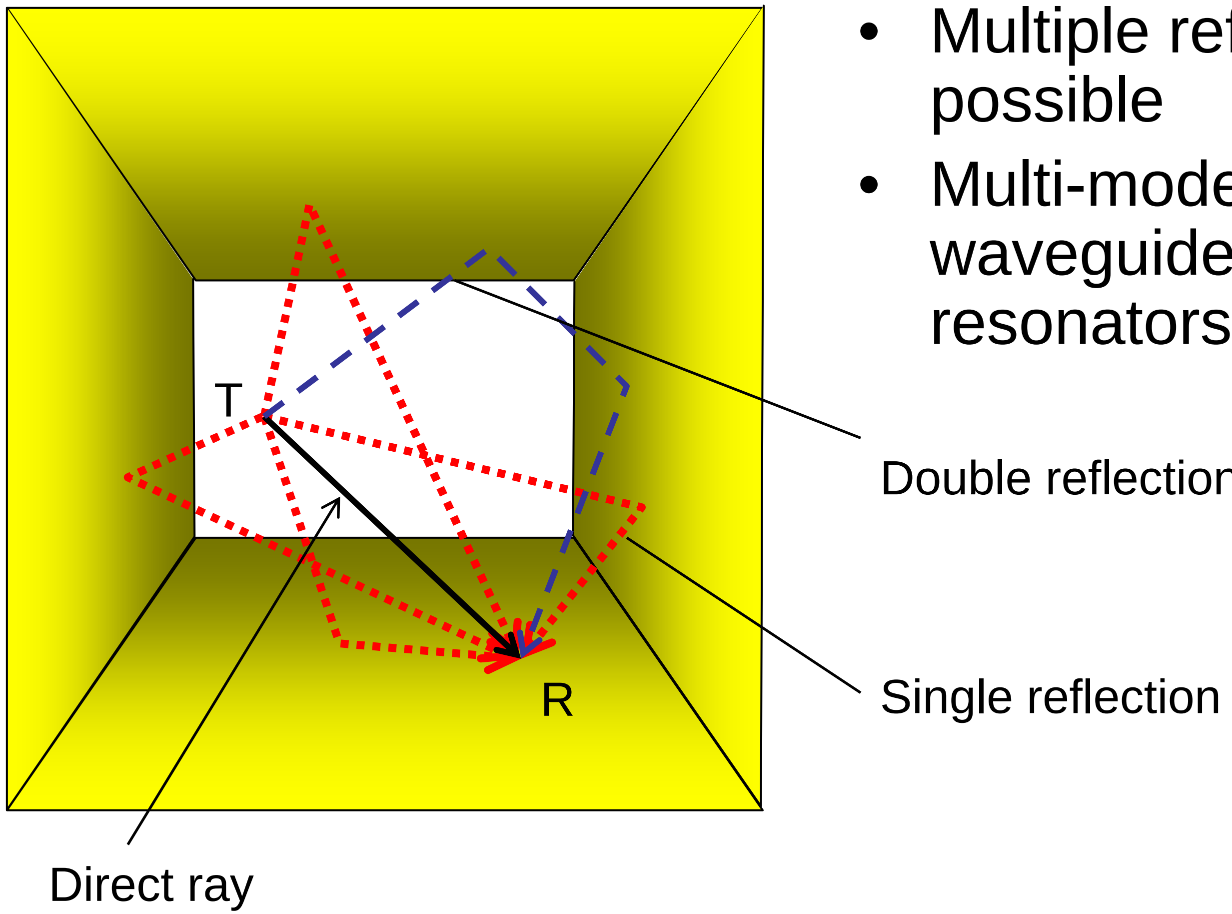
Vegetation
(shadowing by a pine tree)



Ray Tracing

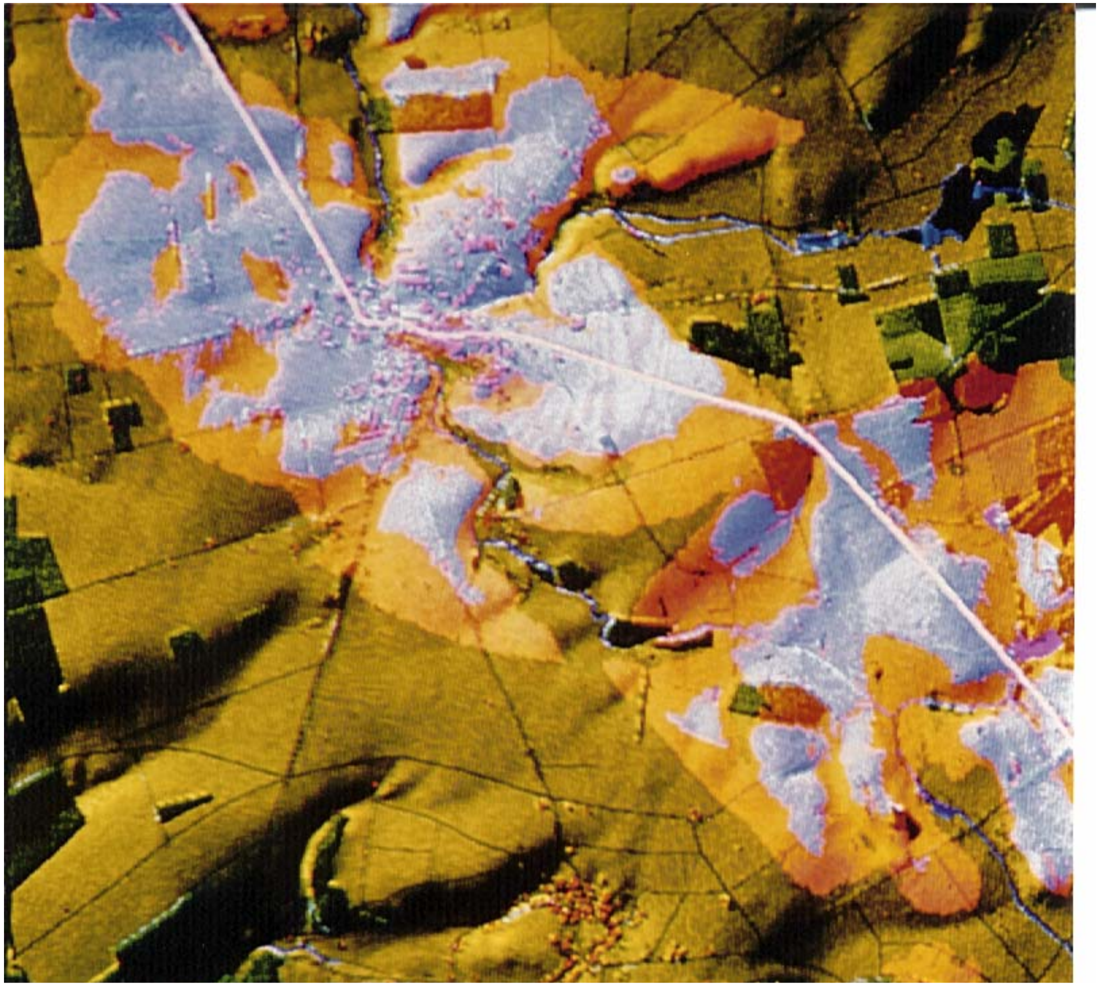
- SISP – Site Specific propagation models based on deterministic analysis of reflection, diffraction, scattering on all objects between the transmitter and receiver
- Requires exact data on the actual environment
  - Indoor: detailed 3D data on building, room, equipment
  - Outdoor: 3D data on terrain infrastructure, streets, buildings, etc. requiring satellite/ aerial photographs or radar images
  - Large databases

Ray tracing: indoors



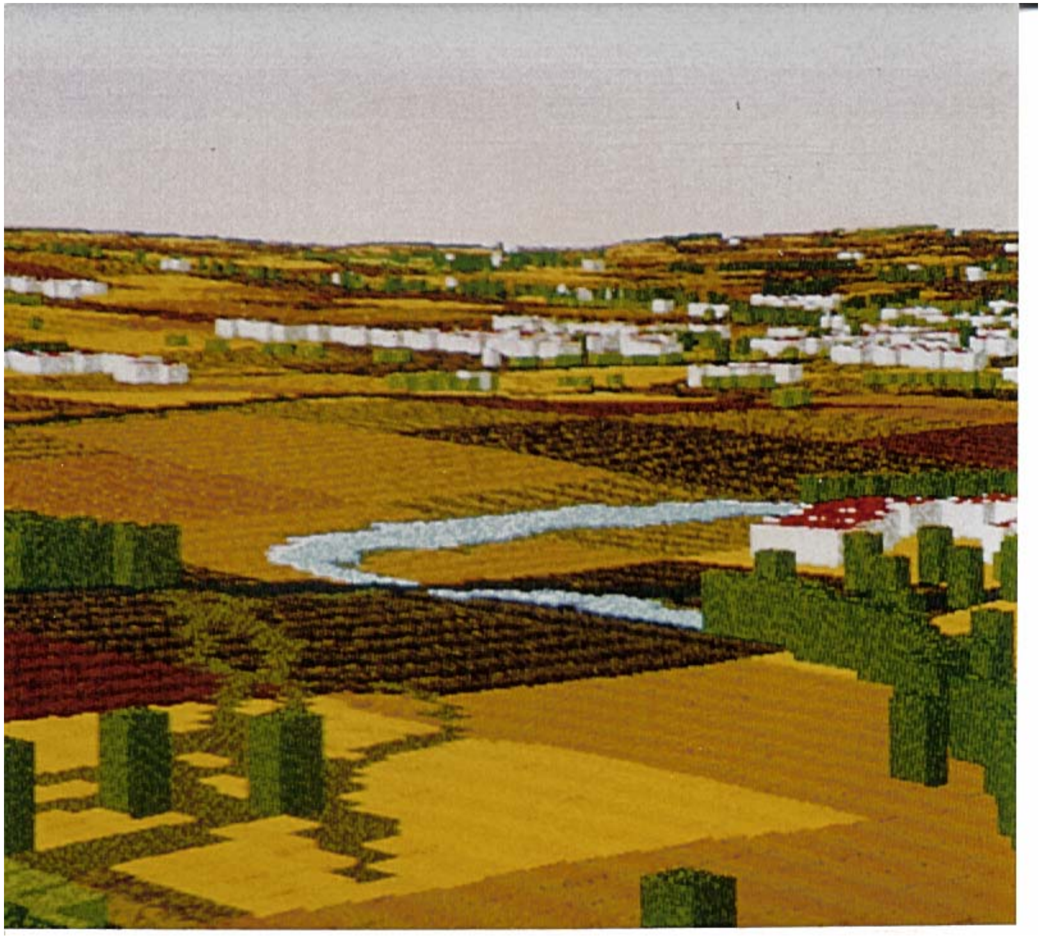
- Multiple reflections possible
- Multi-mode waveguides & resonators

Signal coverage map



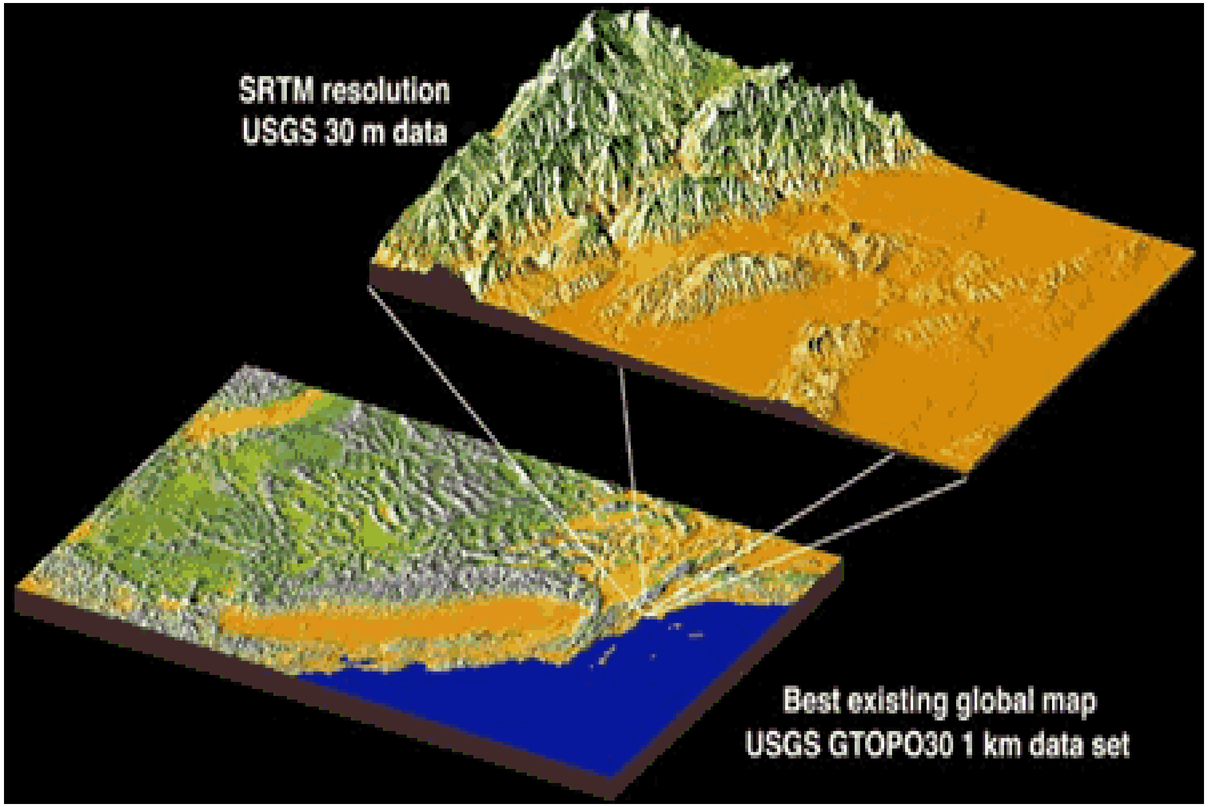
- This is an example of computer-generated signal-level distribution over a geographical region

DTM



- Application of propagation prediction models requires topographical information, called often Digital Terrain Model (DTM)

Digital terrain elevation maps

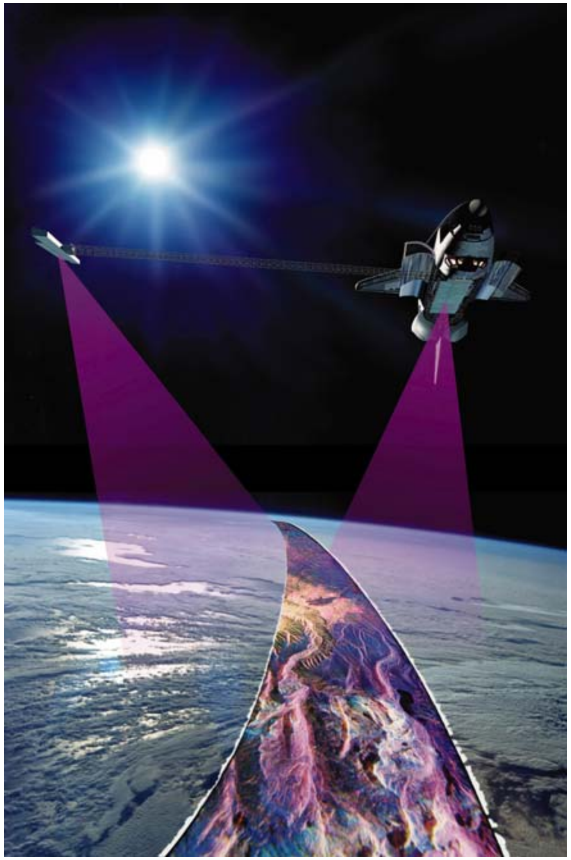


Source: NASA (http://www2.jpl.nasa.gov/srtm/)

One of the most accurate Digital Terrain Elevation Data of the Earth ever assembled is being produced from radar data collected from satellite.

Resolution: 1 arc-sec (~30 m), or 30 times as precise as the best global maps in use today. First such maps will be available in 2004.

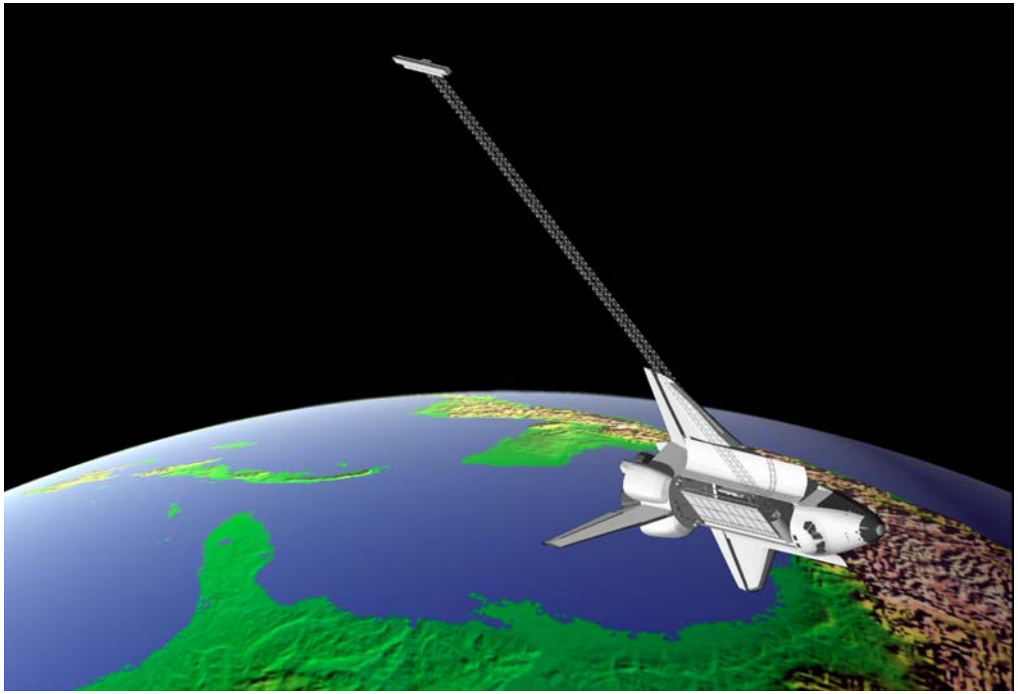
Radar Topography



Radar interferometry compares two radar images taken at slightly different locations to obtain terrain elevation information. Unlike earlier missions, SRTM used single-pass interferometry, which means that the two images were acquired at the same time -- one from the radar antennas in the shuttle's payload bay, the other from the radar antennas at the end of a 60-meter mast extending from the shuttle. Combining the two images produces a single 3-D image.

Source: NASA

Shuttle Radar Topography Mission 2000



- Mission: 11-22 Feb. 2000
- Collected: 9 terabytes of raw data (~15,000 CDs)
- More than 80 hours data recording

- Orbiter**:** Shuttle Endeavour (7.5km/sec)
- Nominal altitude: 233 km (with orbital adjustment once per day)
- Inclination**:**57 degrees
- 6-member crew
  - to activate payload, deploy and stow mast, align inboard and outboard structures, monitor payload flight systems, operate on-board computers & recorders, & handle contingencies

Source: NASA

Simulated experiments

- Experiments with Two-ray Propagation Model (single reflection)
- How the resultant signal depends on
  - Frequency?
  - Distance between the antennas?
  - Height of the antennas?
  - Reflection coefficient?
  - Antenna radiation patterns?

What we have learned

- The radio propagation conditions decide on the system performance so that propagation paths of the wanted signal and unwanted signals should be carefully analyzed/ designed
- The best transmitter, receiver, antennas, cables, etc. may not work as expected if the relevant propagation effects are ignored or incorrectly taken into consideration
- Dependence on environmental variables, including meteorological phenomena, make propagation prediction and measurements difficult and imprecise
- Increasing spectrum congestion requires more sophisticated propagation models and more detailed data; improved knowledge required!

Selected references

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- Free software
  - MLINK (simple software to design microwave radio links)
  - MSAM (Microcomputer spectrum analysis models, including propagation predictions)
  - SEAMCAT (software integrating major propagation models, http://www.ero.dk/seamcat)

Any questions?

Thank you for your attention

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