天线与电波传播
ANTENNASAND WAVE PROPAGATION

LECTURE 15

Qingsha Cheng 程庆沙

雨课堂

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4	时运祥	17.7
5	陈运旺	17.6

课程评价 COURSE EVALUATION

- Surveys （https://tis.sustech.edu.cn/）

方法1

方法2

2019-2020-2本科期末评价-实验课(Teaching Evaluation-Experimental Courses)	期末评价
2019-2020-2本科期末评价-理论课(Teaching Evaluation-Theoretical Courses)	期末评价

CERTIFICATE EXAM

全国应用型人才培养工程岗位证书220元/科目（高频电磁仿真助理工程师）

https://www.uec.org.cn/

工业和信息化人才专业知识测评证书200元/科目（Ansys分析）

https://www.ncie.org.cn/

FINAL PROJECT SUBMISSION CHECKLIST

1. A report in TAP paper format use the provided (.docx template)

   describe design theory, your implementation details, and your results

   all figures should be clear and all text in figures are in proper size

   individual contributions

   discussions

2. Project presentation PPT

3. Modeling Tutorial (算例)

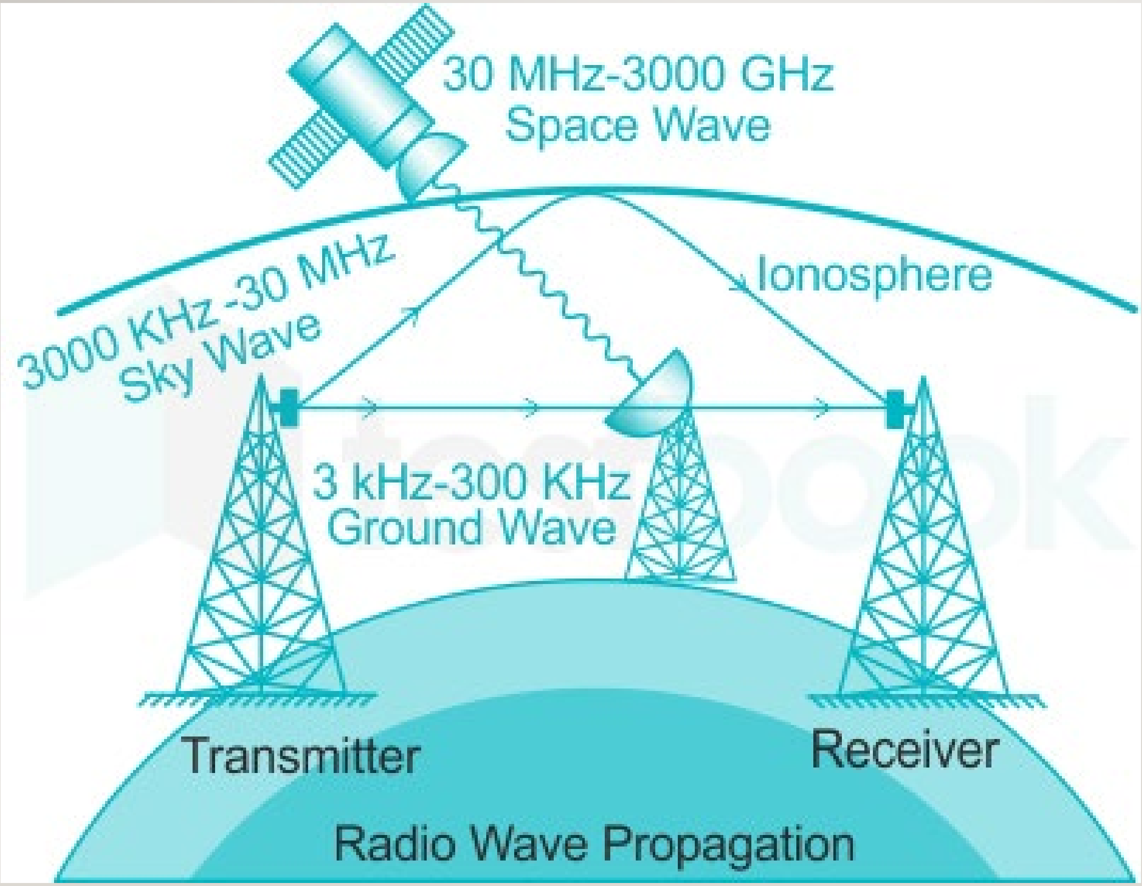
   - HFSS files
   - PPT (see template)
   - Word document (see template)
   - Video demonstration

- Due: **11:55pm, Sunday, June 9 (Week 16)**

WAVE PROPAGATION

- Electromagnetic wave
- Wave front
- Wave not in free space
- Ground wave
- Space wave
- Sky wave
- Satellite Communication

WAVE PROPAGATION



- Ground wave
- Sky Wave
- Space Wave

RANGE OF WAVE PROPAGATION

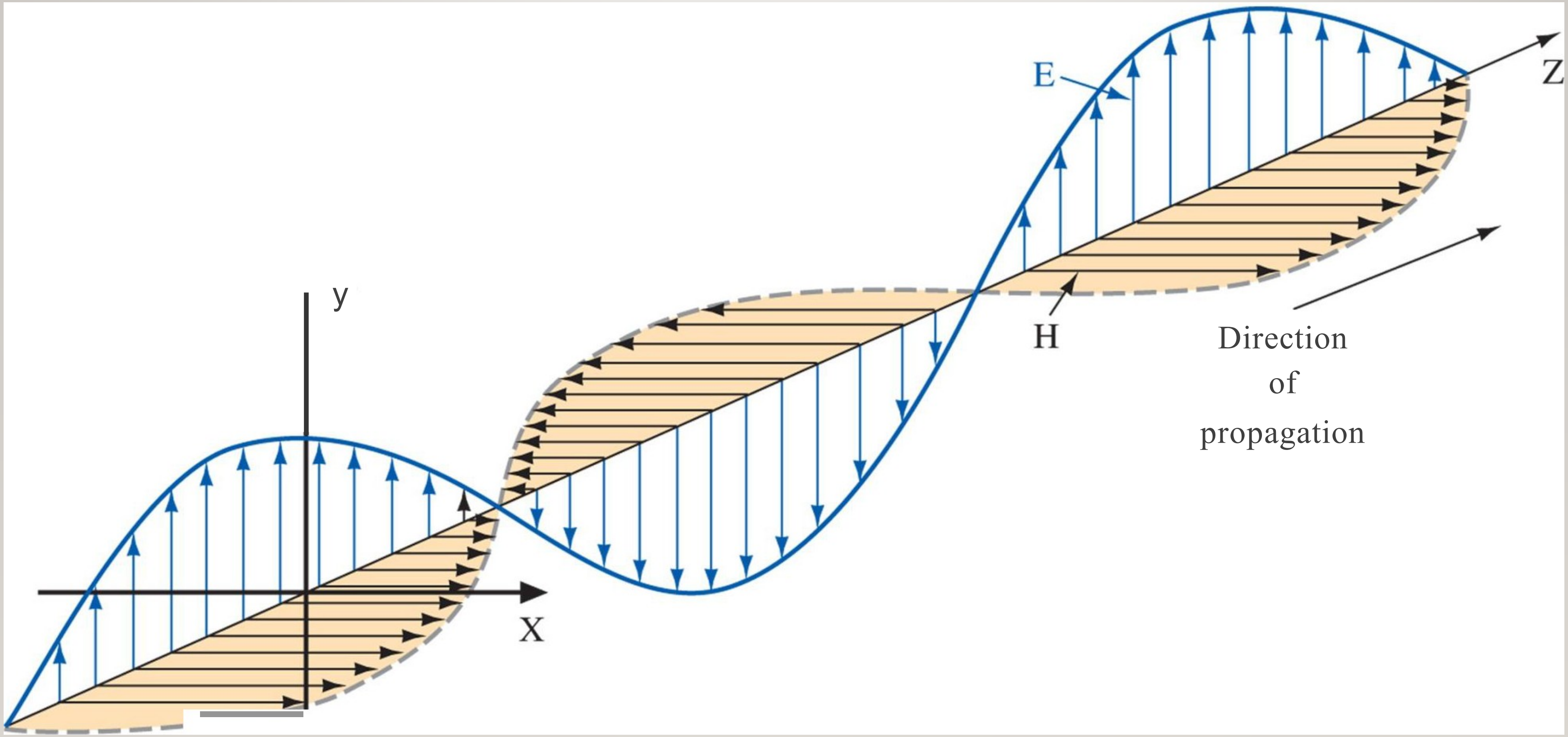
Classification Band	Initials	Frequency Range	Characteristics
Extremely low	ELF	< 300 Hz	Ground wave
Infra low	ILF	300 Hz - 3 kHz	
Very low	VLF	3 kHz - 30 kHz	
Low	LF	30 kHz - 300 kHz	
Medium	MF	300 kHz - 3 MHz	Ground/Sky wave
High	HF	3 MHz - 30 MHz	Sky wave
Very high	VHF	30 MHz - 300 MHz	Space wave
Ultra high	UHF	300 MHz - 3 GHz	
Super high	SHF	3 GHz - 30 GHz	
Extremely high	EHF	30 GHz - 300 GHz	
Tremendously high	THF	300 GHz - 3000 GHz	

Frequency Bands	Frequency Ranges	Wavelength Ranges	Propagation Modes
Extremely Low Frequency (ELF)	3 Hz - 30 Hz	10,000 km - 100,000 km	Ground Wave
Very Low Frequency (VLF)	3 kHz - 30 kHz	10 km - 100 km	Ground Wave
Low Frequency (LF)	30 kHz - 300 kHz	1 km - 10 km	Ground Wave
Medium Frequency (MF)	300 kHz - 3 MHz	100 m - 1 km	Ground/Sky Wave
High Frequency (HF)	3 MHz - 30 MHz	10 m - 100 m	Sky Wave
Very High Frequency (VHF)	30 MHz - 300 MHz	1 m - 10 m	Space Wave
Ultra High Frequency (UHF)	300 MHz - 3 GHz	10 cm - 1 m	Space Wave
Super High Frequency (SHF)	3 GHz - 30 GHz	1 cm - 10 cm	Space Wave
Extremely High Frequency (EHF)	30 GHz - 300 GHz	1 mm - 1 cm	Space Wave
Tremendously High Frequency (THF)	Above 300 GHz	Below 1 mm	Space Wave

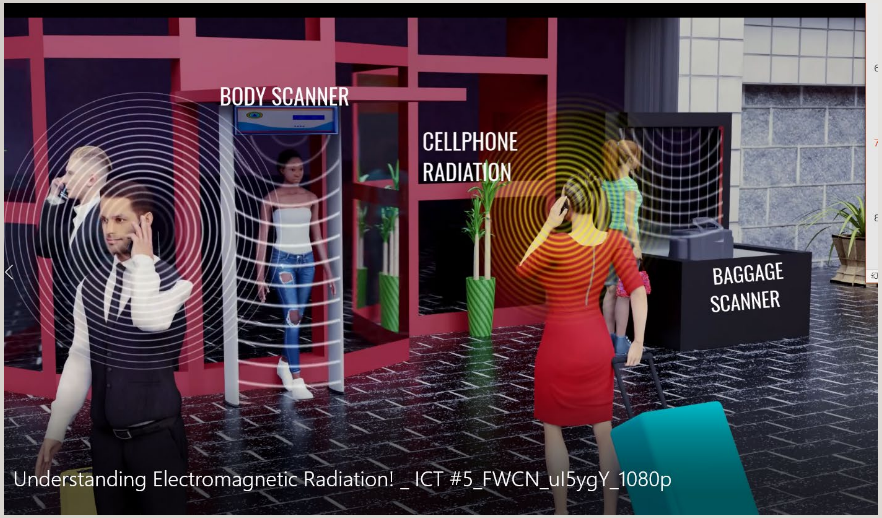
Electromagnetic Waves

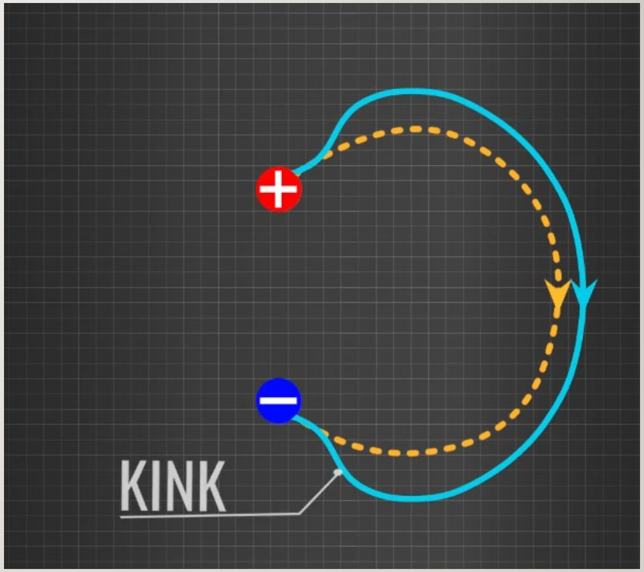
- **In free space, an oscillating electric field creates and oscillating magnetic field, which creates an oscillating electric field, and so on.**
- **These two fields contain energy:**
  - **In circuits, the energy is returned to the circuit when the fields collapse (e.g., inductor and capacitor)**
  - **In a radio transmitter, the antenna is designed not to allow the energy to collapse back into the circuit, but instead to be radiated (or set free) into the form of an *electromagnetic (EM) wave* (aka radio wave)**

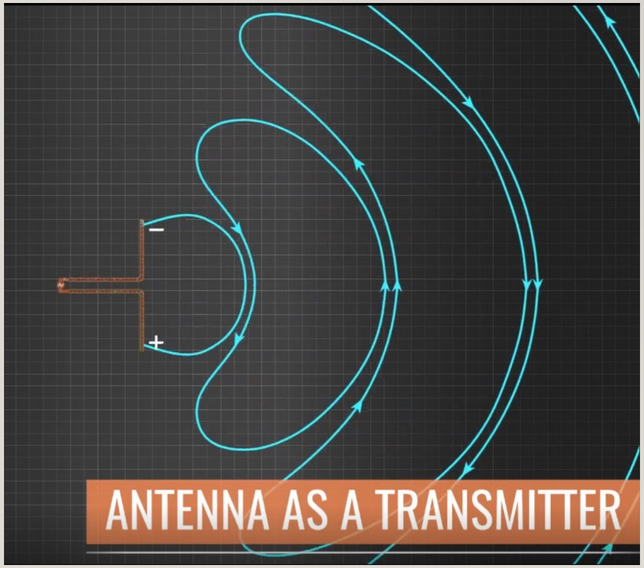
Figure 13-1 Electromagnetic wave.



- **An EM wave electric field, magnetic field and direction of propagation are mutually orthogonal**



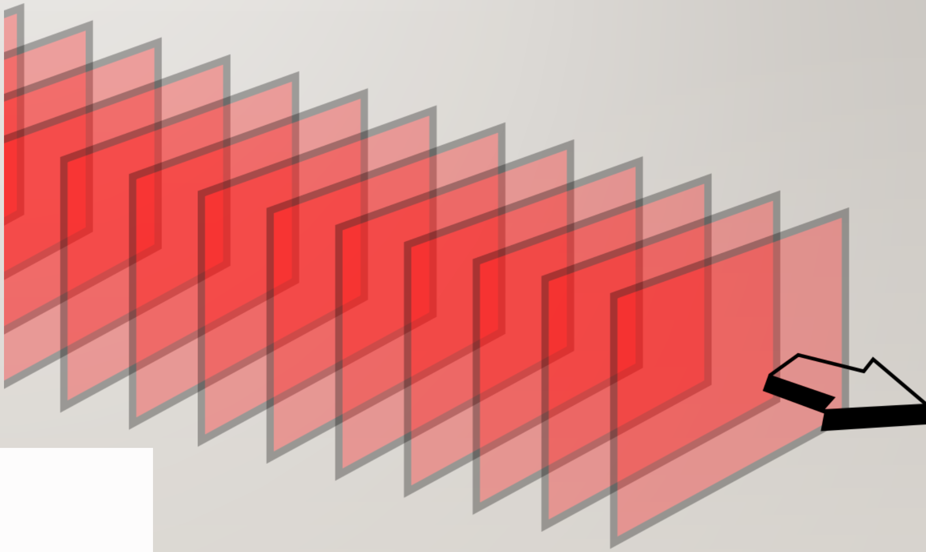


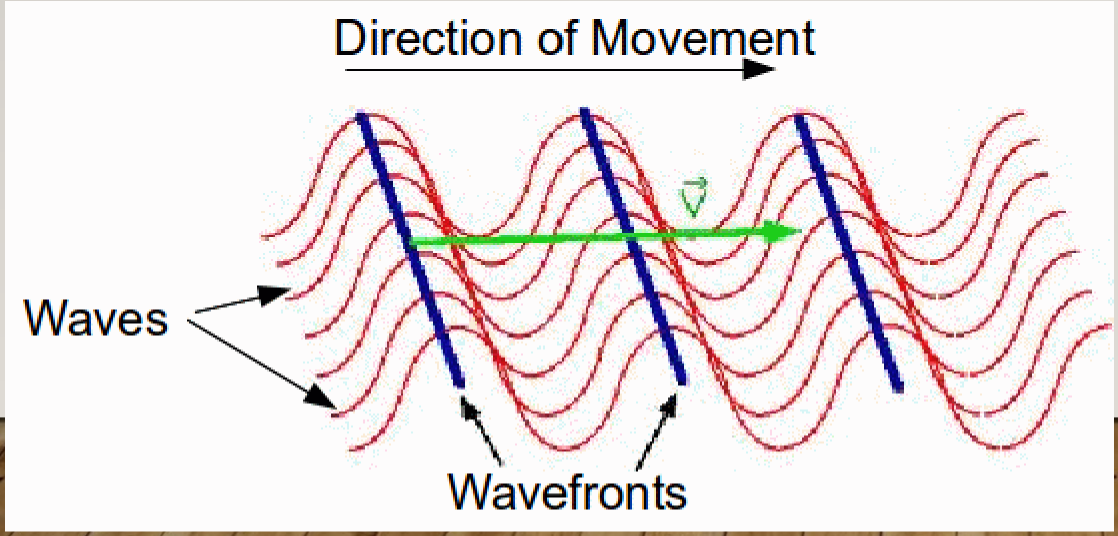


Understanding EM radiation (7’26”)

WAVEFRONT

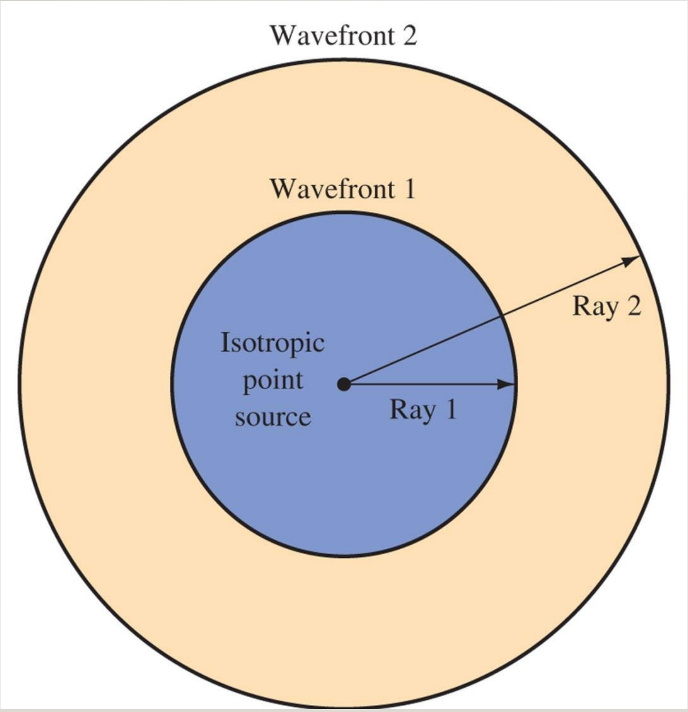
- A *wavefront* is a surface joining all points of equal phase in an electromagnetic wave

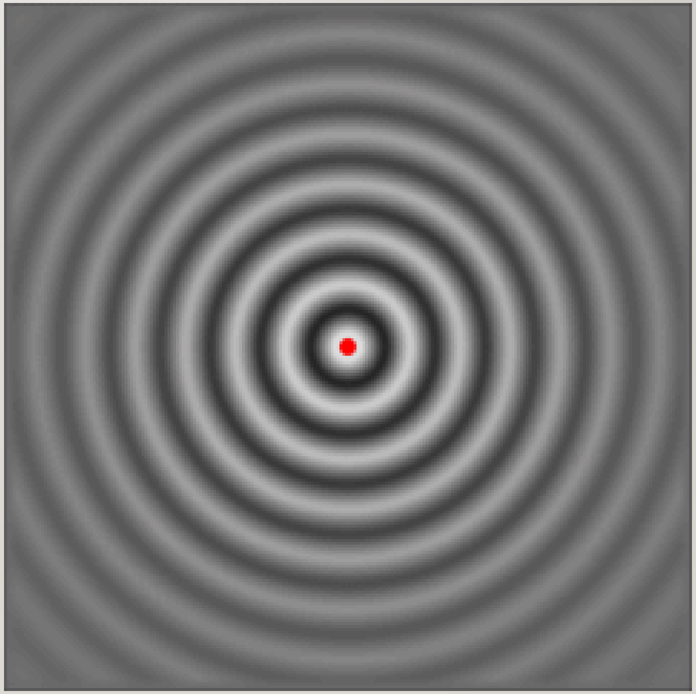




WAVEFRONT OF AN ISOTROPIC POINT

- An *isotropic point source* is a point in space that radiates electromagnetic radiation in all directions





WAVEFRONT OF AN ISOTROPIC POINT

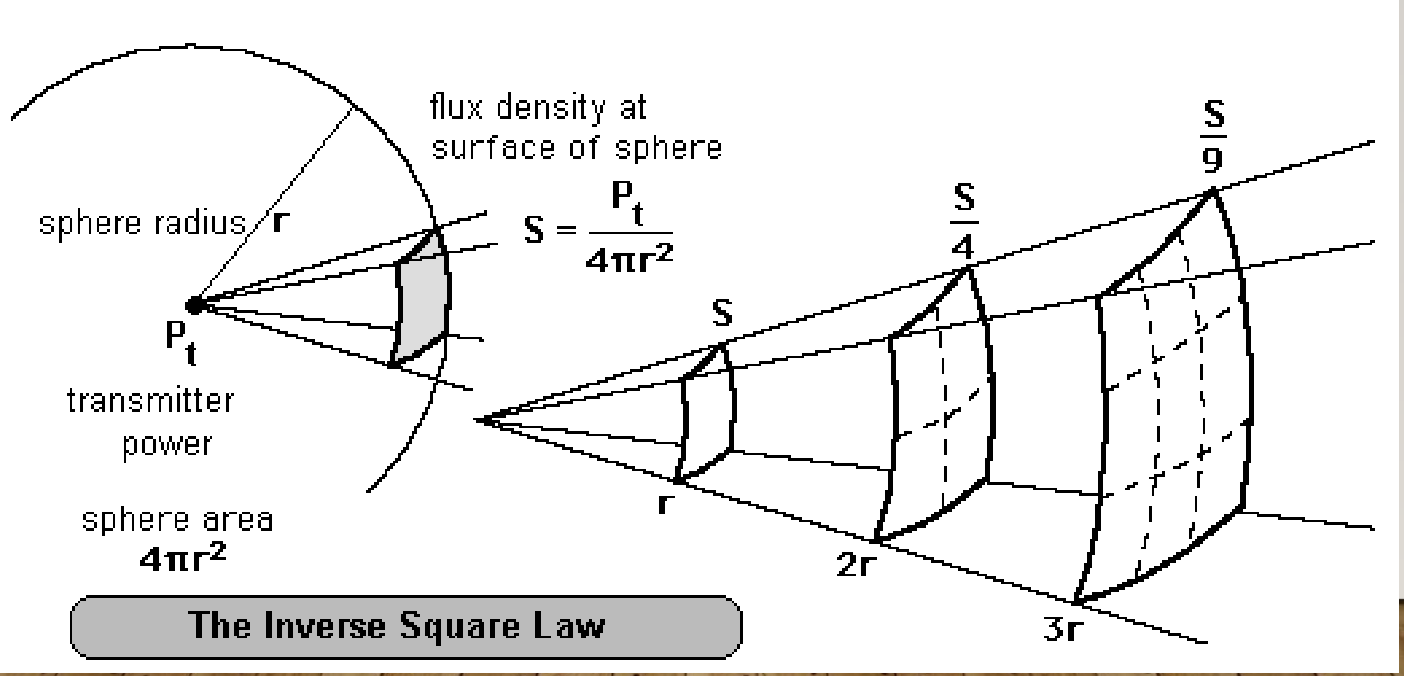
- **The power density at a waveform is given by:**

$$S = \frac{P_t}{4\pi r^2}$$

Where:

P_t = transmitted power (Watts)

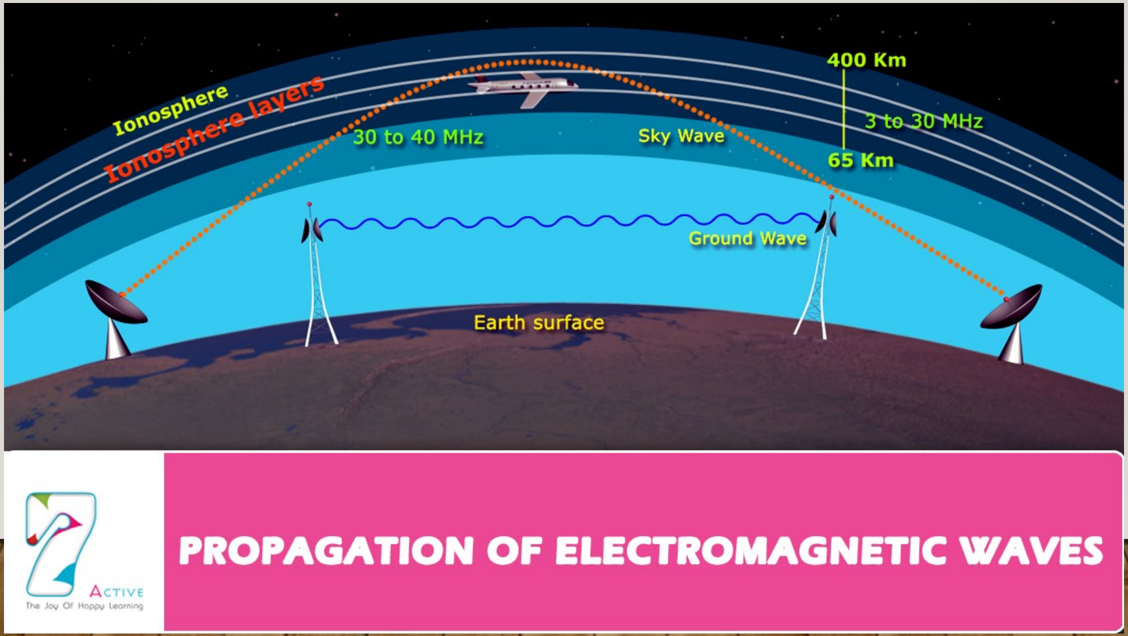
r = distance from source (meters)



WAVES NOT IN FREE SPACE

EM waves affected by atmosphere and earth

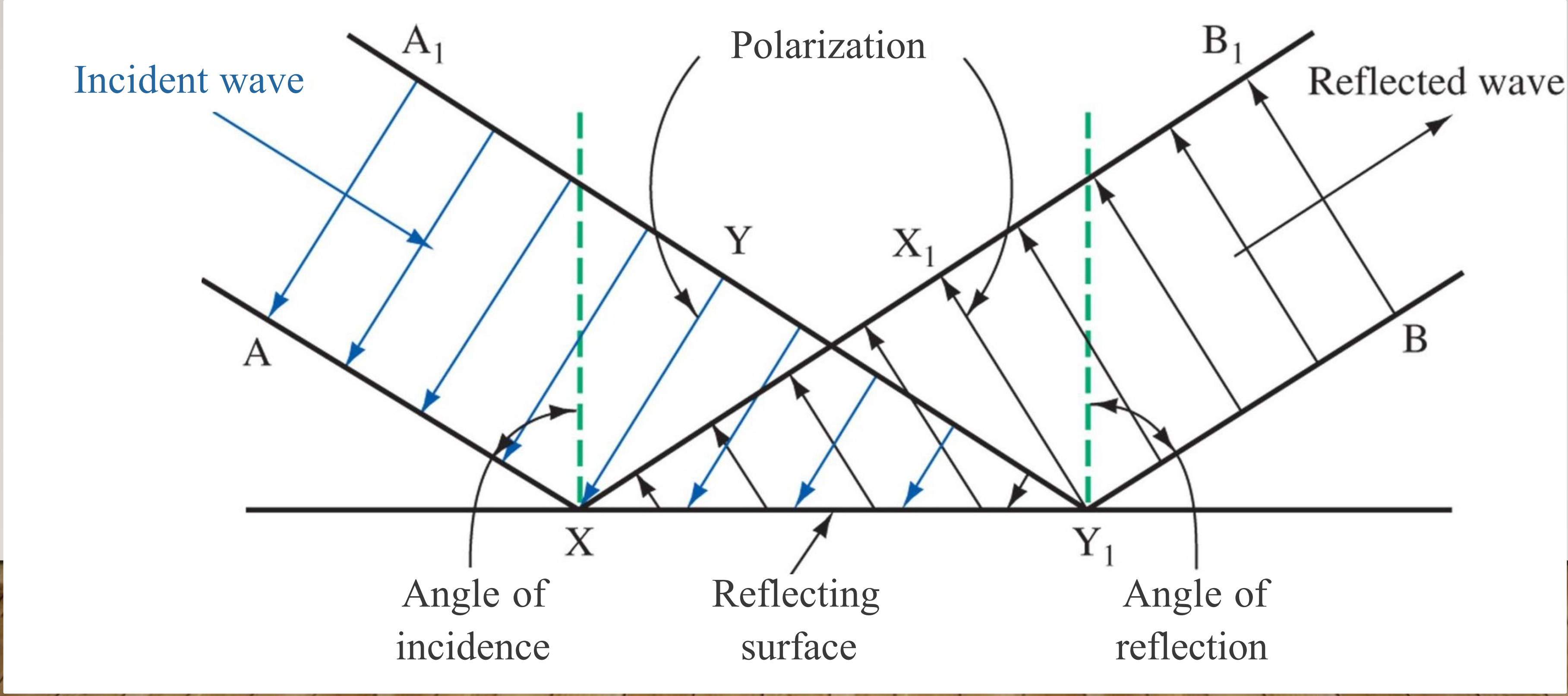
- **Reflection (反射)**
- **Refraction (折射)**
- **Diffraction (衍射)**



WAVES NOT IN FREE SPACE

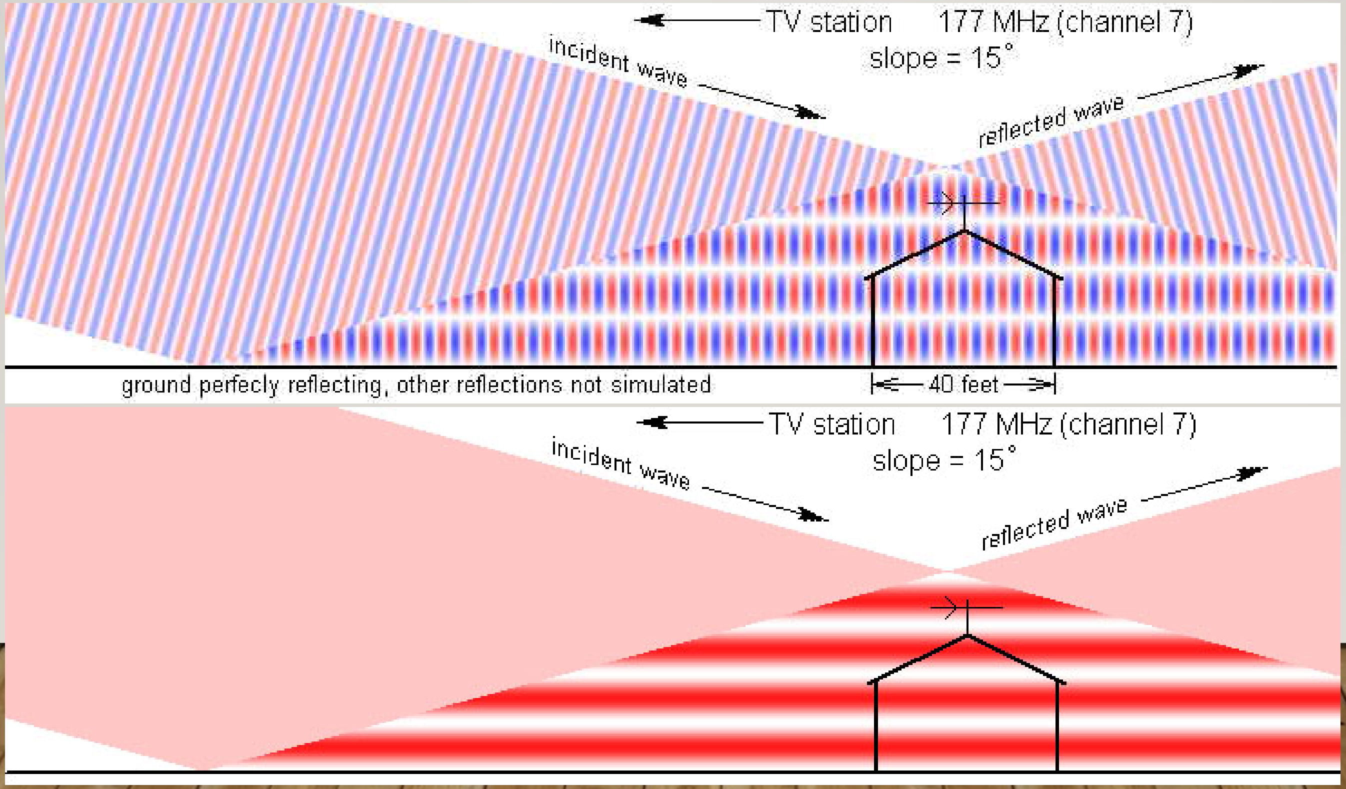
Reflection occurs when a radio wave bounces off an object or a surface of a different medium

- Similar to light waves reflected in a mirror
- Angle of incidence equals angle of reflection



WAVES NOT IN FREE SPACE

Reflection and Interference: Incident waves from a TV station reflect off the ground and interfere with each other.
Standing Waves: This interference creates standing waves with alternating strong (constructive) and weak (destructive) signal areas.
Signal Impact: The standing waves cause variations in signal strength, affecting TV reception quality near the house.



WAVES NOT IN FREE SPACE

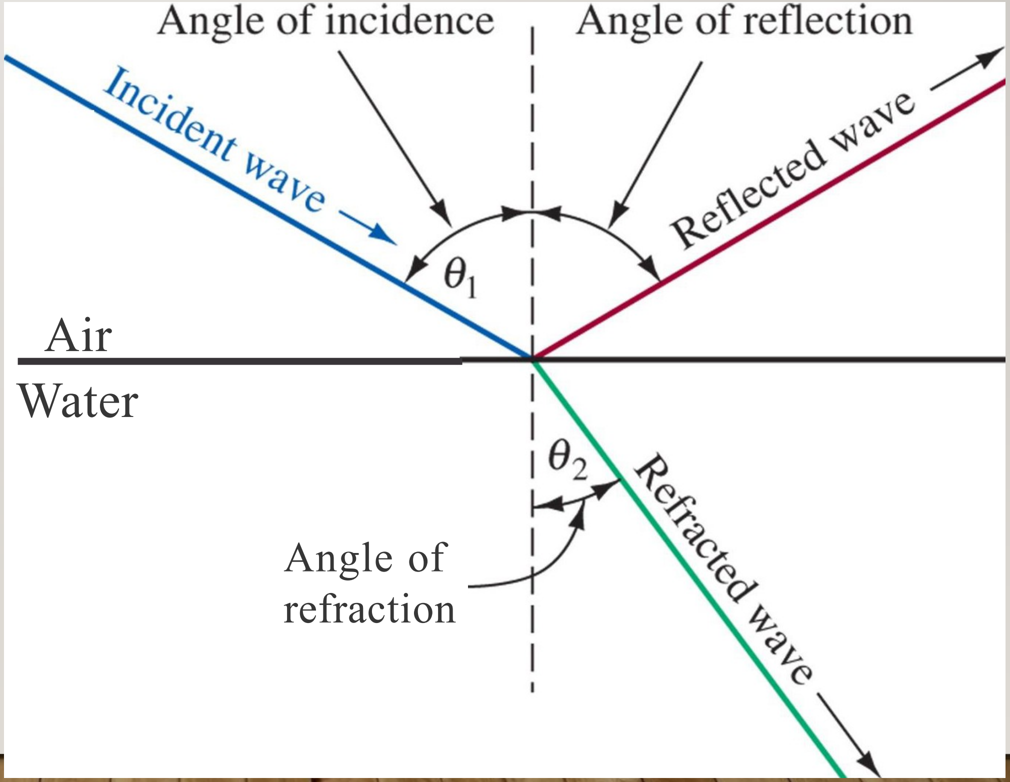
Refraction occurs when radio waves pass from a medium of one to another of different density

The angle of incidence (θ_1) and the angle of refraction (θ_2) are related by

the <u>Snell's Law</u>:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

n_x: refractive index for medium x (water: 1.33, glass: 1.5)



ATMOSPHERIC REFRACTION

Atmospheric refraction is the bending of light or radio waves as they pass through layers of the Earth's atmosphere with varying densities.

Supra-refraction occurs when atmospheric conditions, such as increased moisture, cause radio waves to bend more than usual, closely following the Earth's curvature.

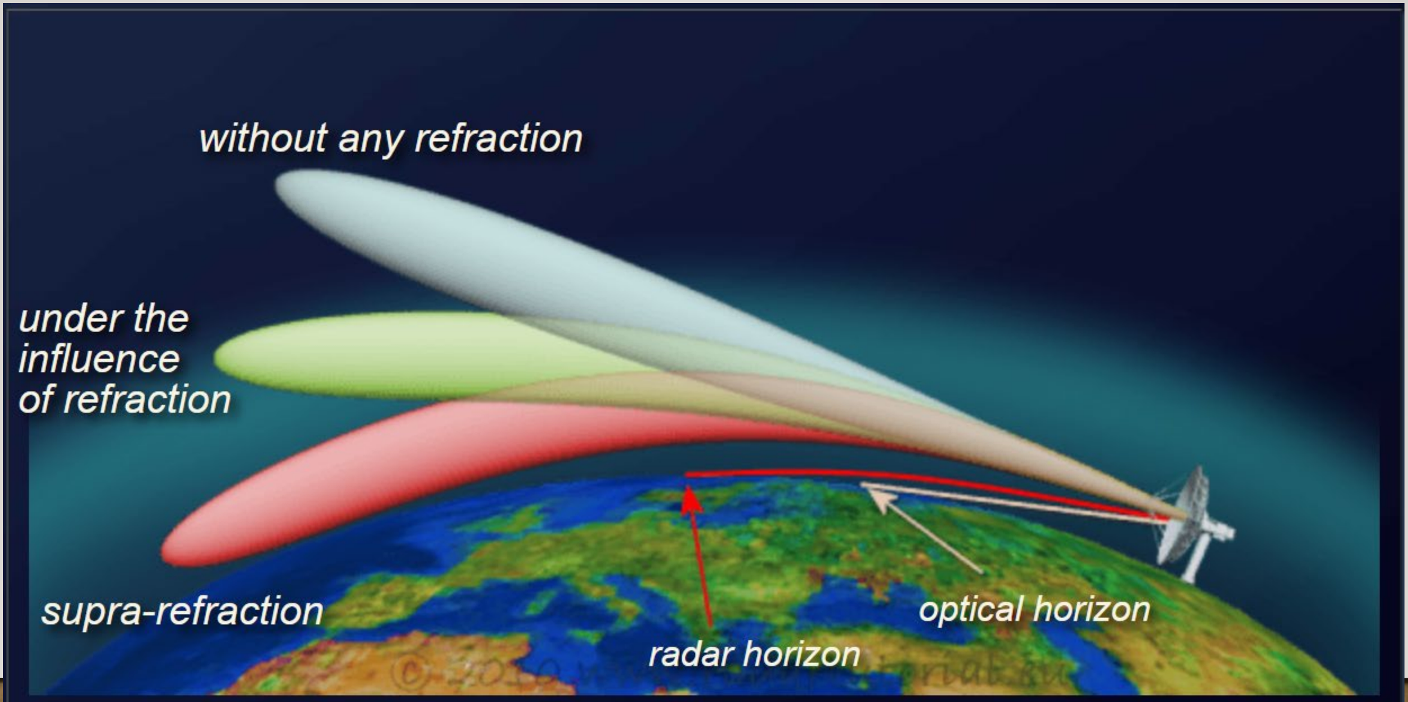
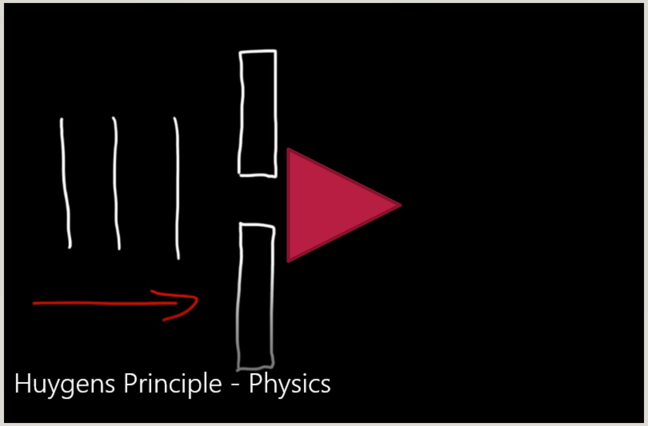


Figure 1: The refractions influence on the range of the radiohorizon

WAVES NOT IN FREE SPACE

Diffraction is the phenomenon whereby radio waves traveling in straight paths "bend" around an obstacle

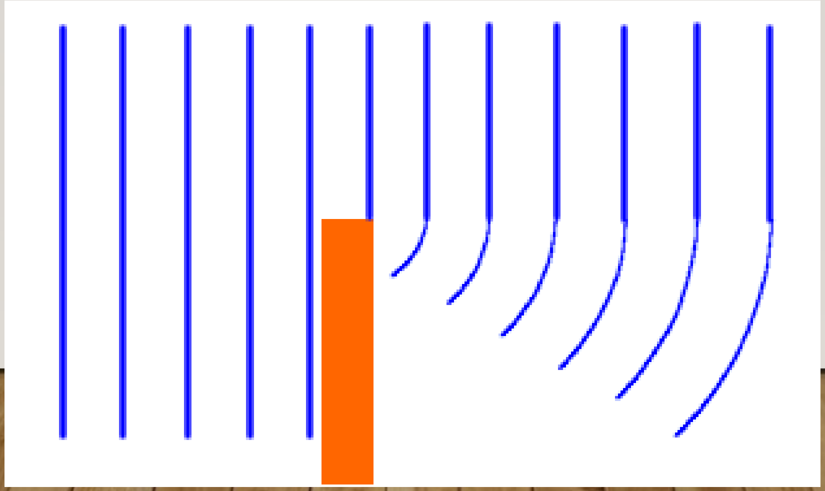
– Result of **Huyges's principle**: each point in a wavefront may be considered as the source of a secondary spherical wavefront



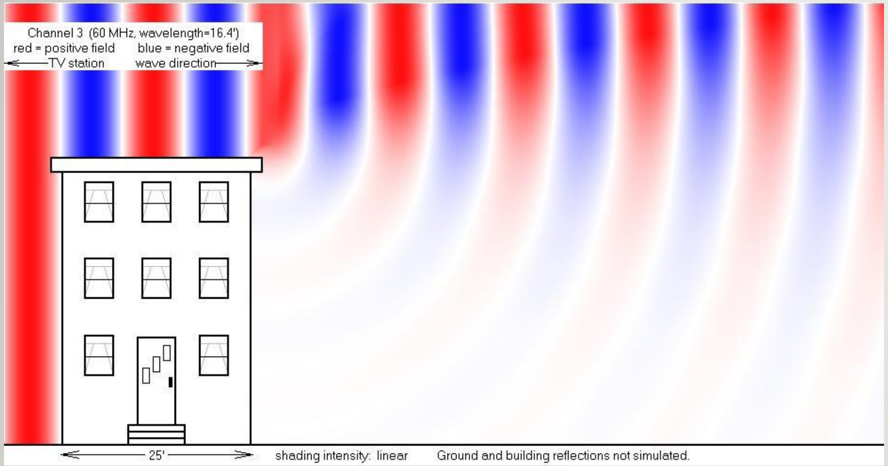
1'39''

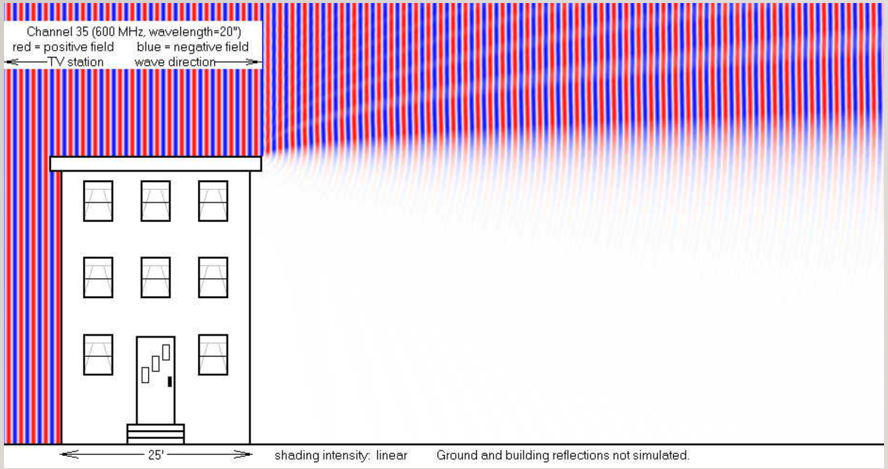
WAVES NOT IN FREE SPACE

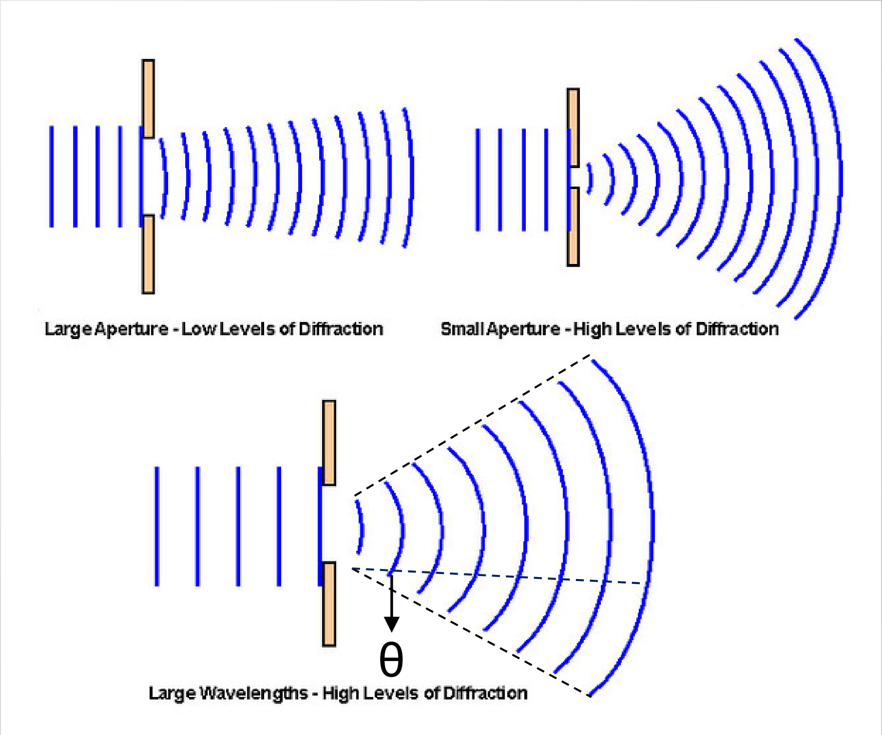
- **Diffraction explains radio reception behind a mountain or tall building**
- The amount of **diffraction** (the sharpness of the bending) **increases** with **increasing wavelength** and **decreases** with **decreasing wavelength**. In fact, when **the wavelength of the waves** is **smaller than the obstacle, no noticeable diffraction occurs.**



Diffraction around a building for 60MHz and 600MHz







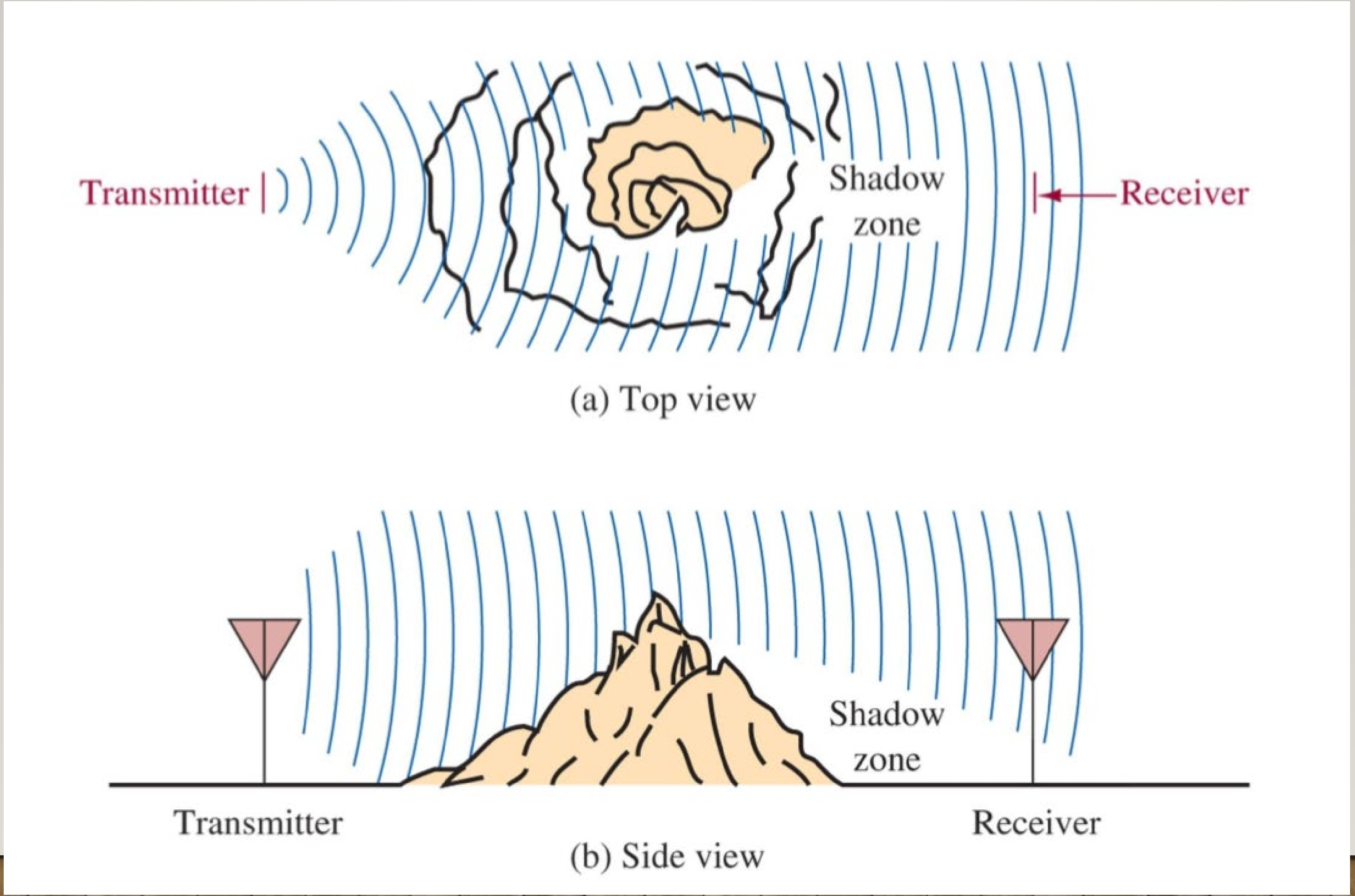
angle of diffraction

$$\theta = \sin^{-1}\left(\frac{\lambda}{d}\right)$$

λ – wavelength

d – aperture width

Diffraction around a mountain



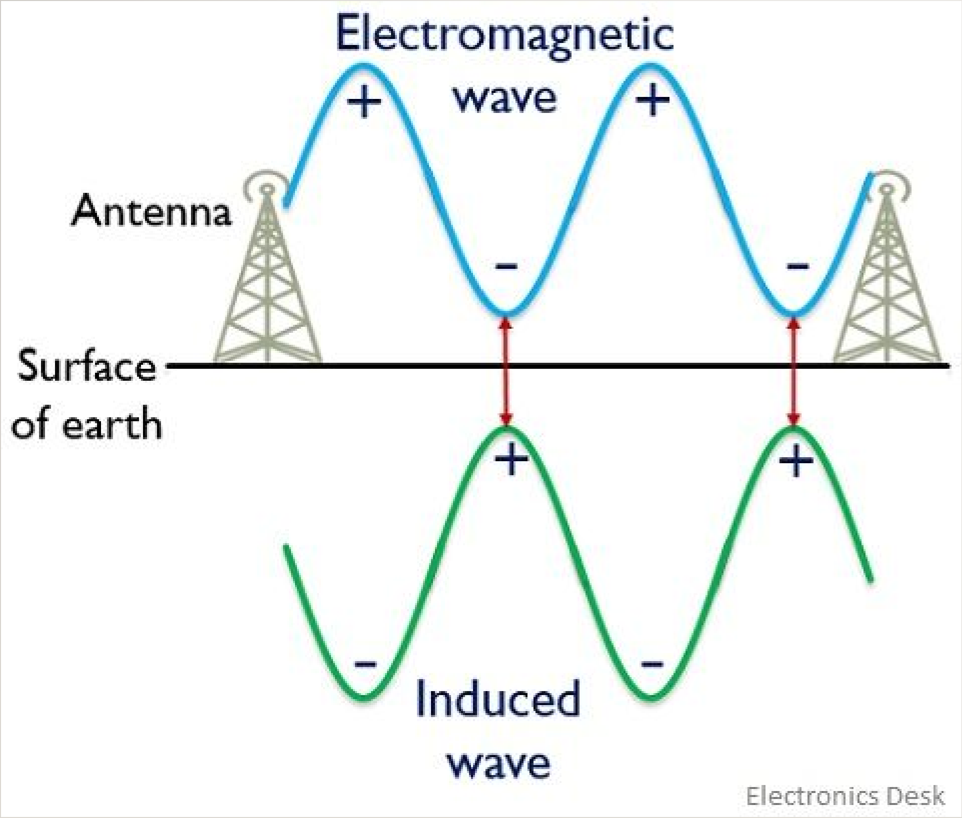
GROUND AND SPACE PROPAGATION

- **Four basic modes** of transmitting a radio wave to a receiving antenna:
  - **Ground Wave**
  - **Space Wave**
  - **Sky Wave**
  - **Satellite Communication** (**SATCOM**)
- The **frequency** of the radio wave is of primary importance in considering the performance of each type of propagation

GROUND-WAVE PROPAGATION

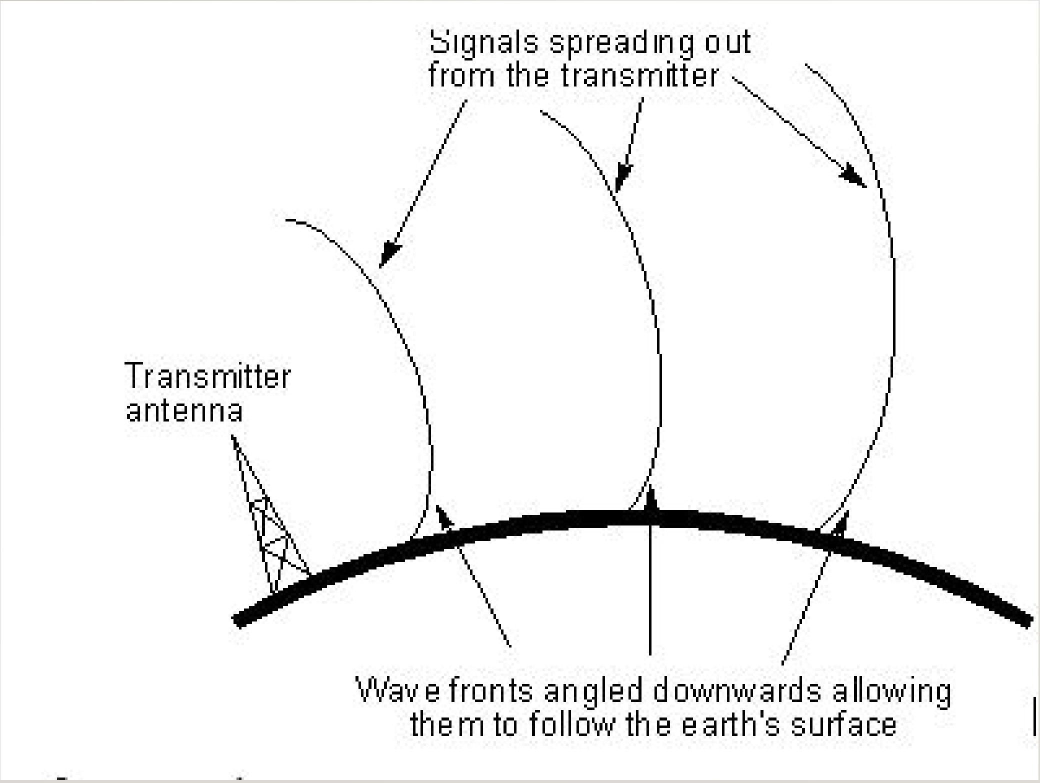
- a.k.a. Surface Wave
- a radio wave that travels along earth's surface due to diffraction
- travels better over a conductive surface such as sea water
- losses increase with increasing frequency
  - not very effective above 2 MHz
- only way to communicate with submarines
  - Extremely Low Frequencies (ELF) propagation is used
  - ELF range from 30 to 300 Hz

GROUND-WAVE PROPAGATION



- Parallel to ground
- Induced wave in ground attenuate EM wave at a shorter range for high frequency
- Used for low frequency, high frequency attenuate fast
- A few KHz to a few MHz
- Bend around obstruction because of diffraction

GROUND-WAVE PROPAGATION



guided along with a **refractive index gradient** or along an **interface between two media** having different dielectric constants

following the curvature of the earth

currents are induced in the surface of the earth

slows down the wave-front in this region

field tilt downwards towards the Earth

GROUND-WAVE PROPAGATION

Typical HF Ground Wave Range as a function of Frequency

- propagate a **considerable distance** over the earth's surface
- particularly in **the low and medium frequency** portion of the radio spectrum.

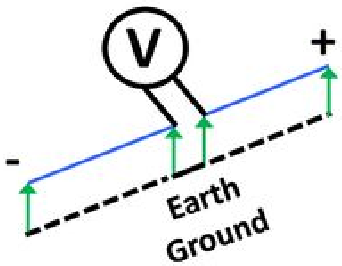
GROUND-WAVE PROPAGATION

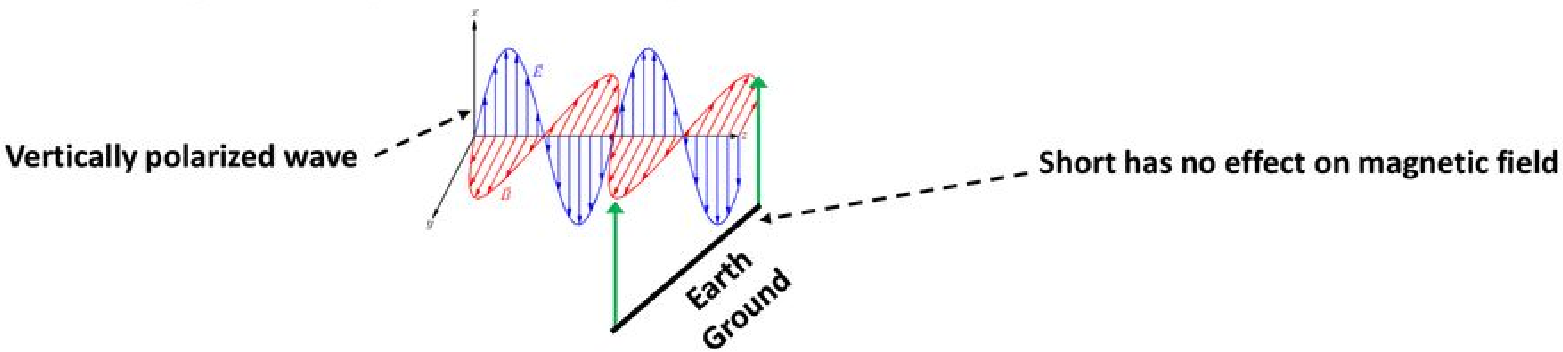
Why Are Ground Waves Vertically Polarized?

- Polarization of a linear EM wave is defined by the E field
- Horizontally polarized wave has the E field in contact with the Earth
  - A conductive surface will act like a short to an E field

  Ex: Dipole antenna laying on highly conductive ground plane
- Magnetic fields are unaffected by conductive materials
  - Magnetic fields are affected by ferromagnetic materials

  Ex: Magnetic loop antenna near ground





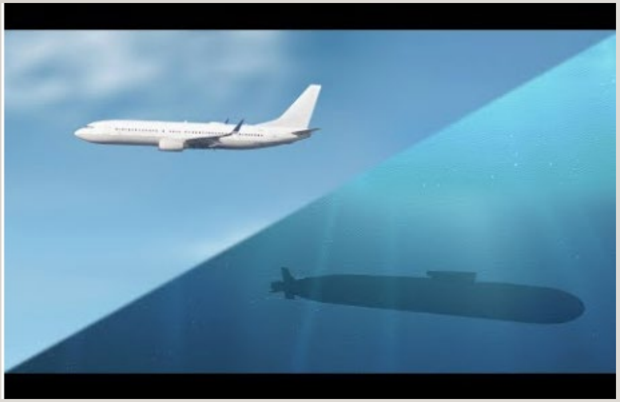
GROUND-WAVE PROPAGATION

Ground conductivity, **terrain roughness** and the **dielectric constant** all affect the signal attenuation. Good conductivity is desirable

- ✓ salty sea water is the best
- ✓ agricultural land
- ✓ marshy land
- ✗ dry sandy terrain and city centres

SUBMARINE COMMUNICATION

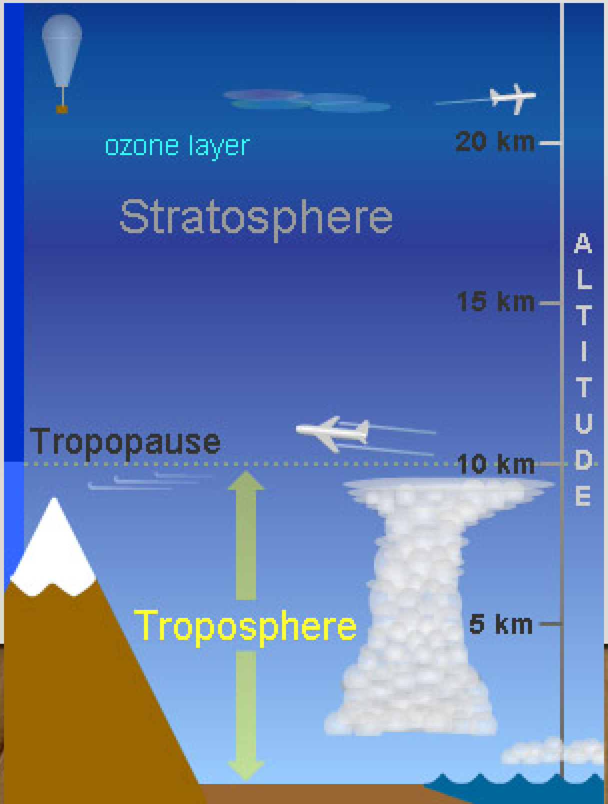
The Radio Network that Communicated with Nazi Subs
3’39”



Getting submarines talking to airplanes, finally
2’12”

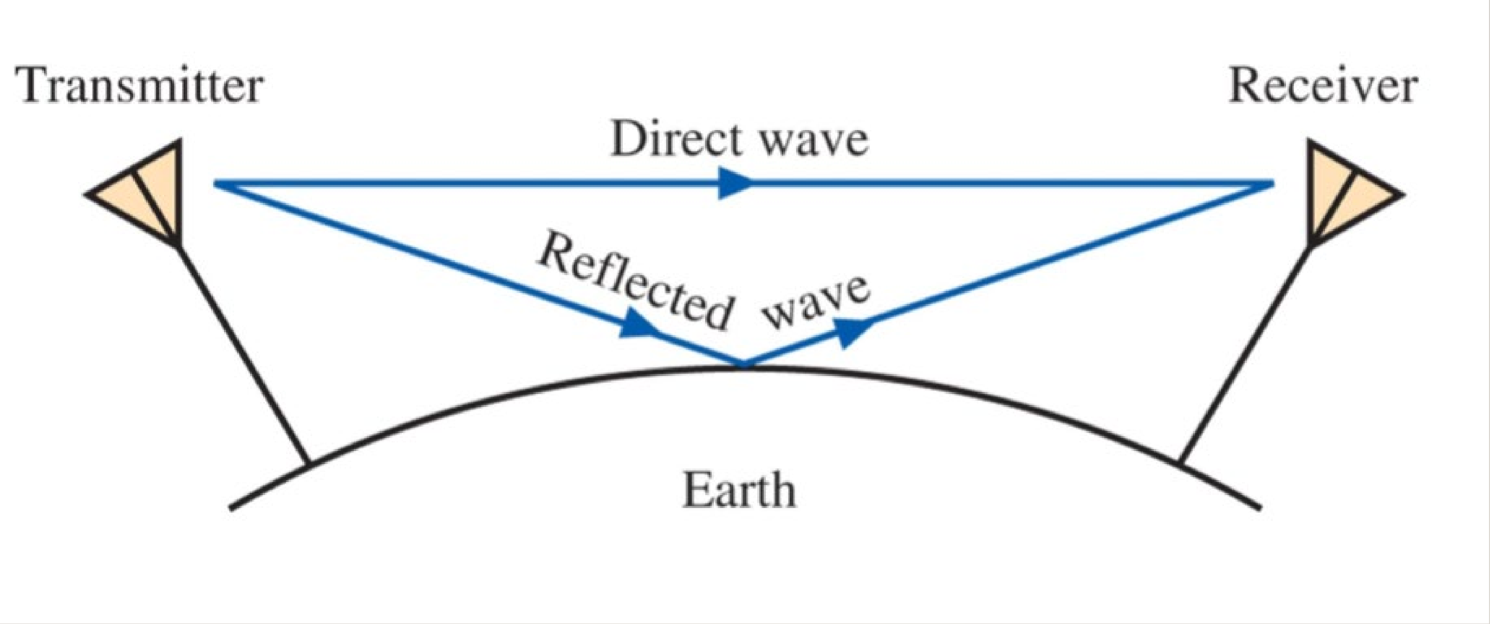
SPACE-WAVE PROPAGATION

- The **space waves** are the radio **waves** of very high frequency (i.e. between 30 MHz to 300 MHz or more). The **space waves** can travel through atmosphere from transmitter antenna to receiver antenna either directly or after reflection from ground in the earth's **troposphere (对流层)** region.



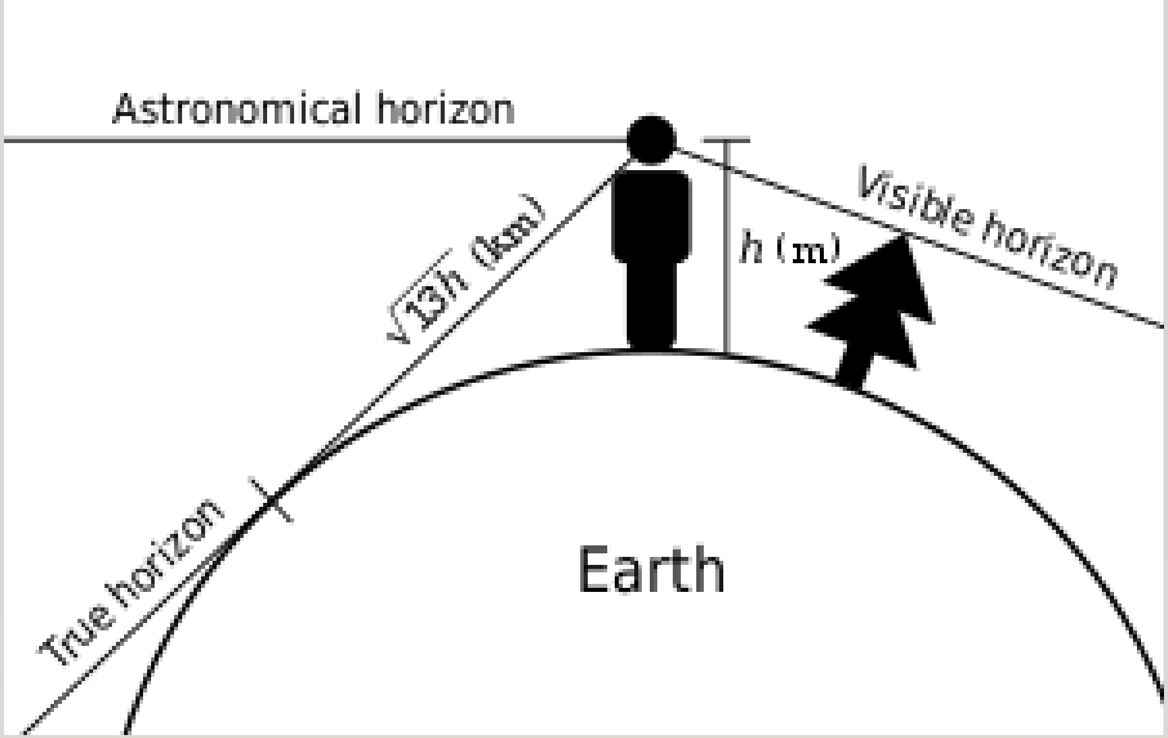
SPACE-WAVE PROPAGATION

- **A *Space Wave* can be classified as**
  - **a direct wave (line-of-sight)**
  - **ground reflected wave**



SPACE-WAVE PROPAGATION (DIRECT)

Assuming no atmospheric refraction and a spherical Earth with radius R=6,371 kilometres (3,959 mi):

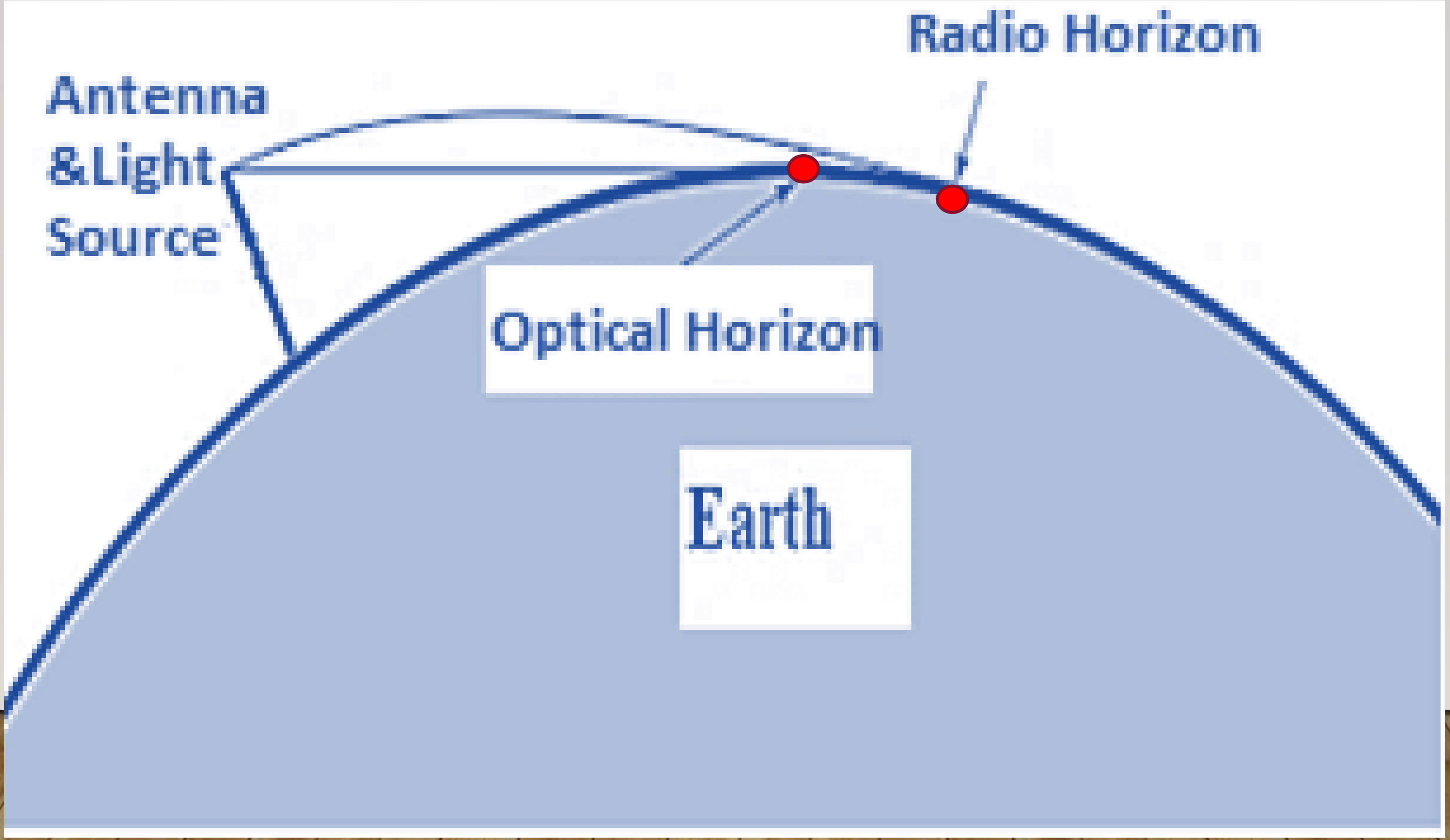


SPACE-WAVE PROPAGATION (DIRECT)

Reference	Altitude of observer	Horizon
Average person standing on the ground with	1.70 metres (5 ft 7 in)	4.7 kilometres (2.9 mi).
Basket ball player	2 metres (6 ft 7 in)	5 kilometres (3.1 mi).
Small hill/tower of 9 stories	30 metres (98 ft) above sea level	19.6 kilometres (12.2 mi).
hill/tower of 30 stories	100 metres (330 ft) above sea level	36 kilometres (22 mi).
on the roof of the Burj Khalifa 163 stories	834 metres (2736 ft) above sea level	103 kilometres (64 mi).
atop Mount Everest	8848 metres (29029 ft)	336 kilometres (209 mi).
Cruise altitude of airplane	12000 meters (39000 ft)	391 kilometres (235 mi)
For a U-2 pilot whilst flying at its service ceiling	21000 metres (69000 ft)	521 kilometres (324 mi)

SPACE-WAVE PROPAGATION (DIRECT)

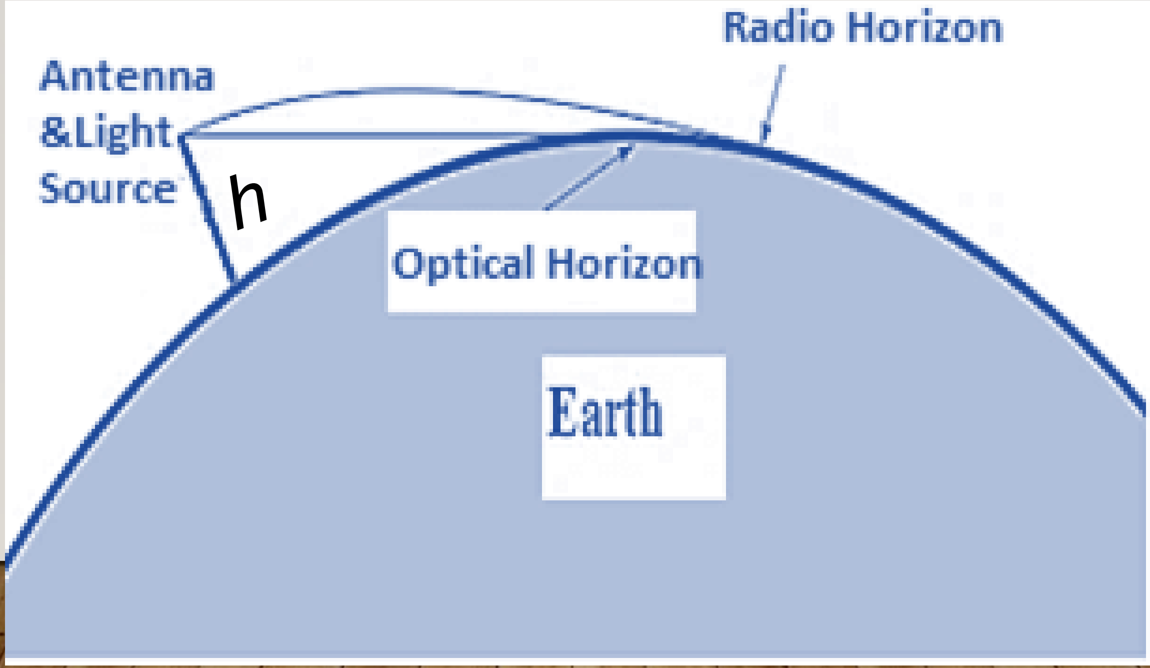
Because of **diffraction**, a direct space wave can travel ~ 4/3 greater than line-of-sight. This distance is known as the *radio horizon*



SPACE-WAVE PROPAGATION (DIRECT)

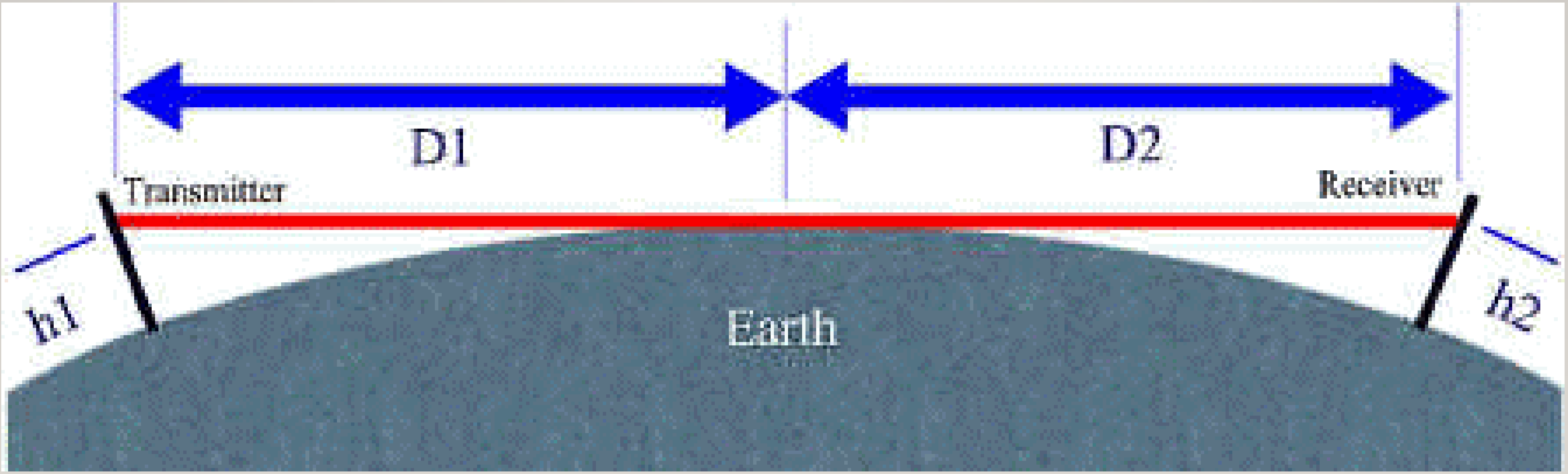
If the height of antenna *h* is known, the ***radio horizon*** can be approximated as:

$$d(km) = 3.57\sqrt{h(in\,m)} \;\; or \;\; d(mi) = 1.22\sqrt{h(in\,ft)}$$



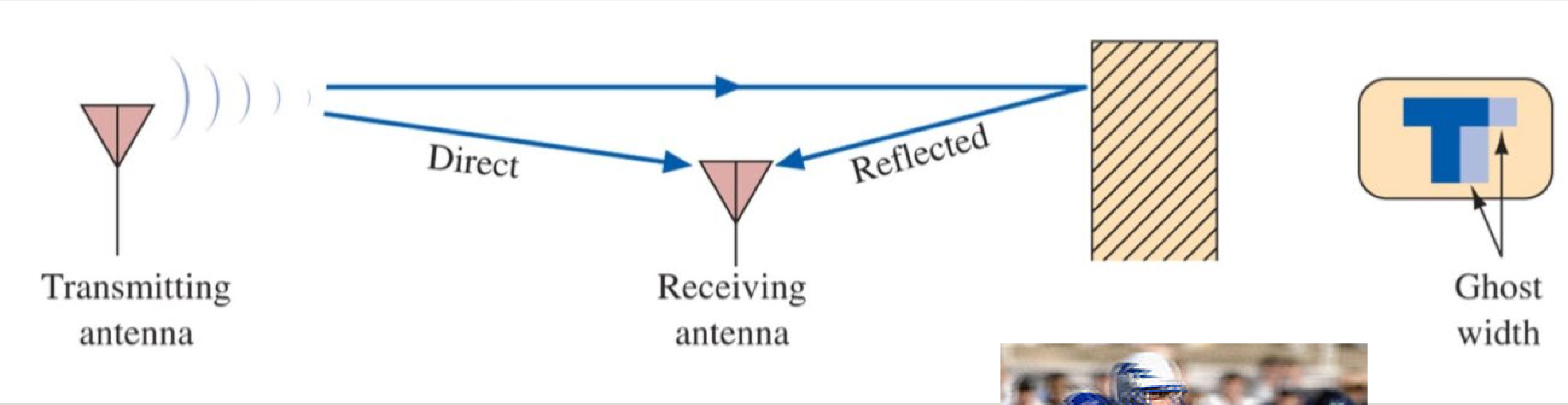
SPACE-WAVE PROPAGATION (DIRECT)

If the heights of transmitting and receiving antennas are known, the *radio horizon* and can be approximated as: D=D1+D2=$3.57(\sqrt{h1}+\sqrt{h2})$ (km)



SPACE-WAVE PROPAGATION

Ghosting is a condition that occurs when the same signal arrives at an early analogy TV receiver at two different times; the reflected signal travels farther and is weaker than the direct signal, resulting in double image (multipath distortion)

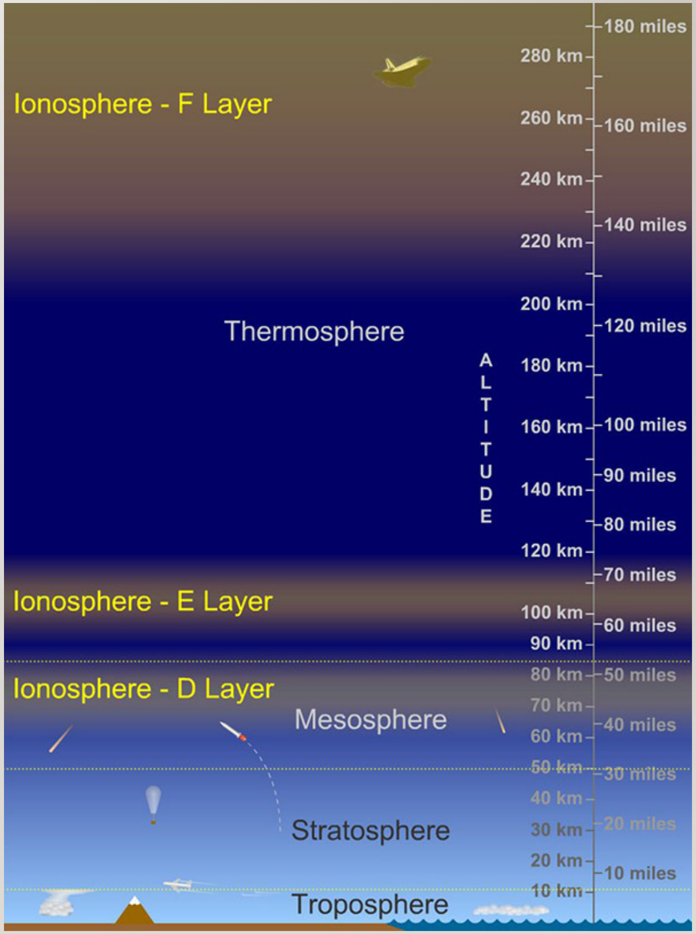


IONOSPHERE AND SKY-WAVE

The *ionosphere* is a layer of atmosphere from 25 to 250 miles above earth's surface

- Contains charged particles

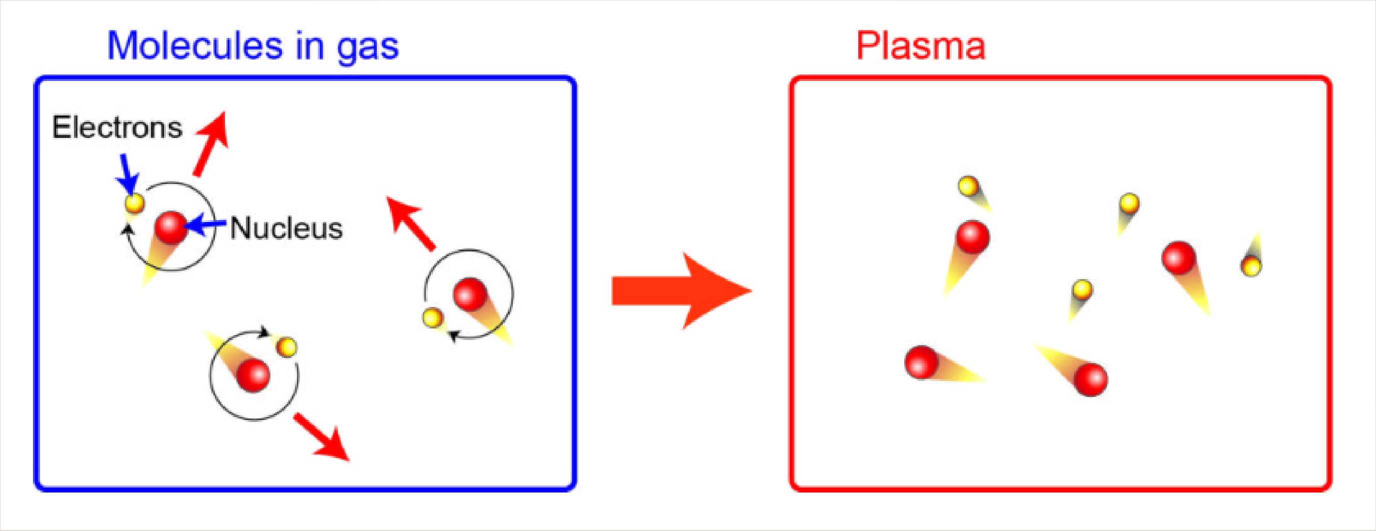
3'00"



IONOSPHERE AND SKY-WAVE

Ionosphere contains a high proportion of free electrons which influence radio propagation.

High Frequency (HF) radio waves hitting the free electrons in the ionosphere cause them to vibrate and re-radiate the energy back down at the same frequency, effectively bouncing the radio wave back towards the Earth.



IONOSPHERE AND SKY-WAVE

Critical frequency: the limiting frequency at or below which a wave component is reflected by, and above which it penetrates through, an ionospheric layer.

Critical Frequency changes with time of day, atmospheric conditions and angle of fire of the radio waves by antenna.

the critical frequency is related to number of free electrons to support reflection at higher frequencies. N_{max} is **maximum electron density** per m^3

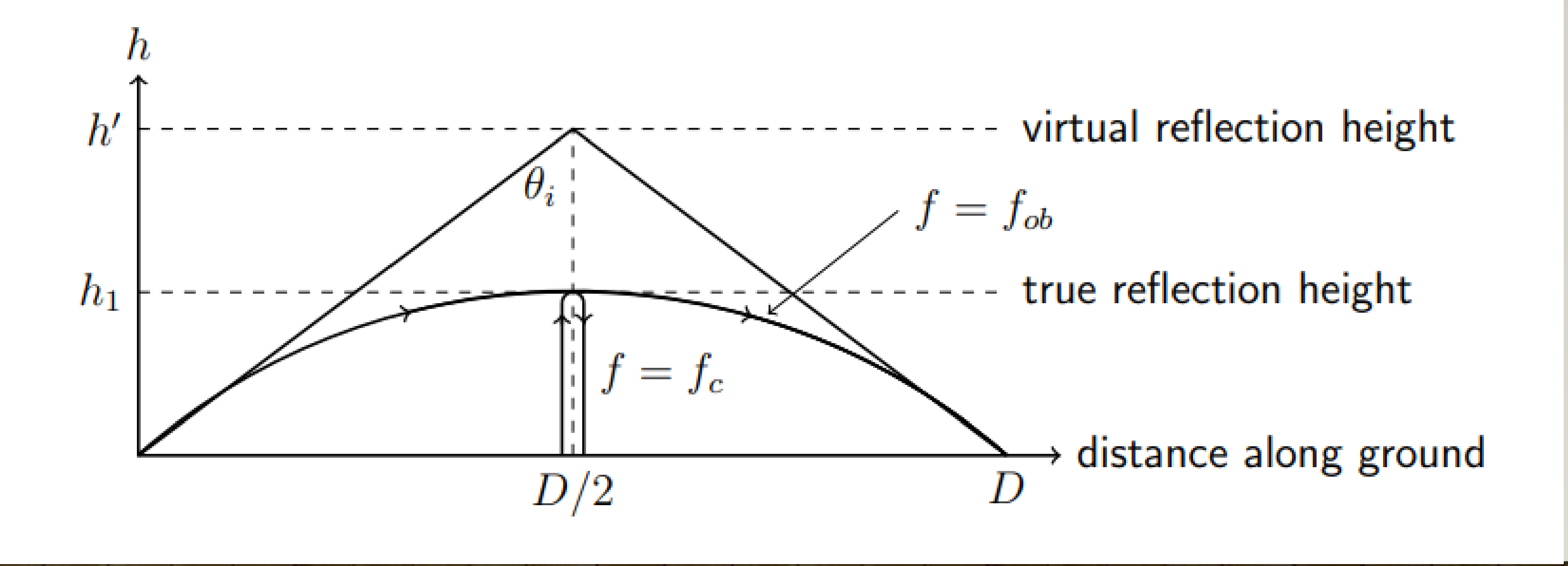
$$f_c = 9\sqrt{N_{max}}$$

IONOSPHERE AND SKY-WAVE

the curved path of a refracted ray associated with frequency f_{ob}

$$f_{ob} = 9\sqrt{N_{max}}\sec\theta_i = f_c \sec\theta_i$$

f_{ob} is called the maximum usable frequency, and is less than 40 MHz

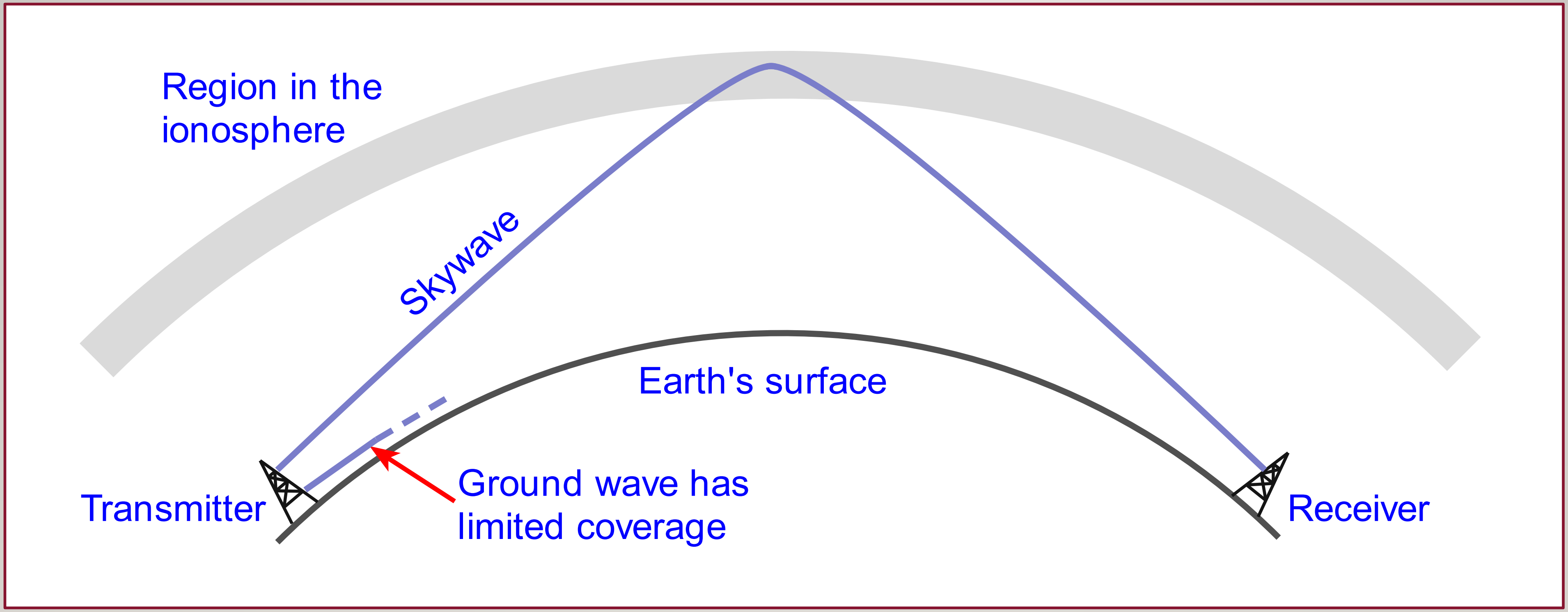


SKY-WAVE PROPAGATION

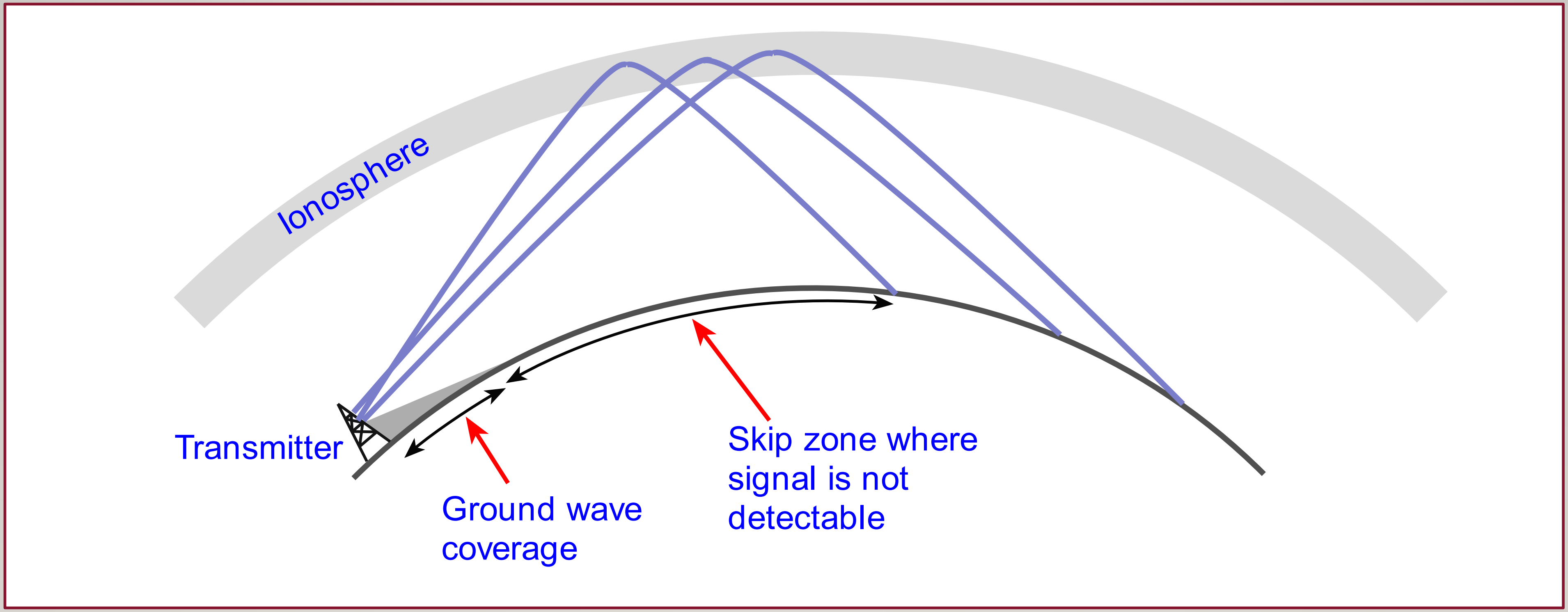
A *Sky Wave* is a radio wave that is radiated from a transmitting antenna in a direction toward the ionosphere

- One of the most frequently used methods for long-distance transmission
- Waves bounce between the ionosphere via refraction and the ground via reflection
- The alternate bouncing is known as *skipping*

SKY-WAVE PROPAGATION

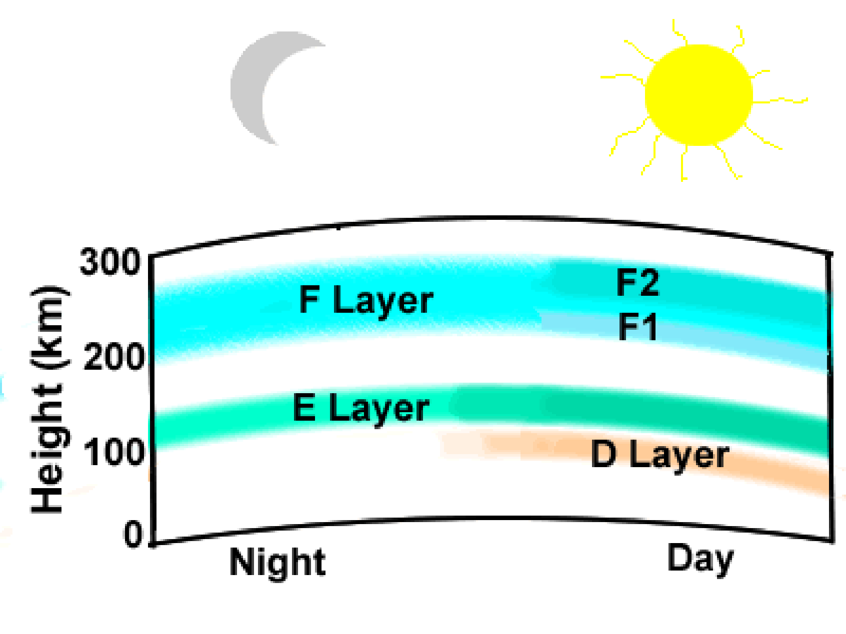


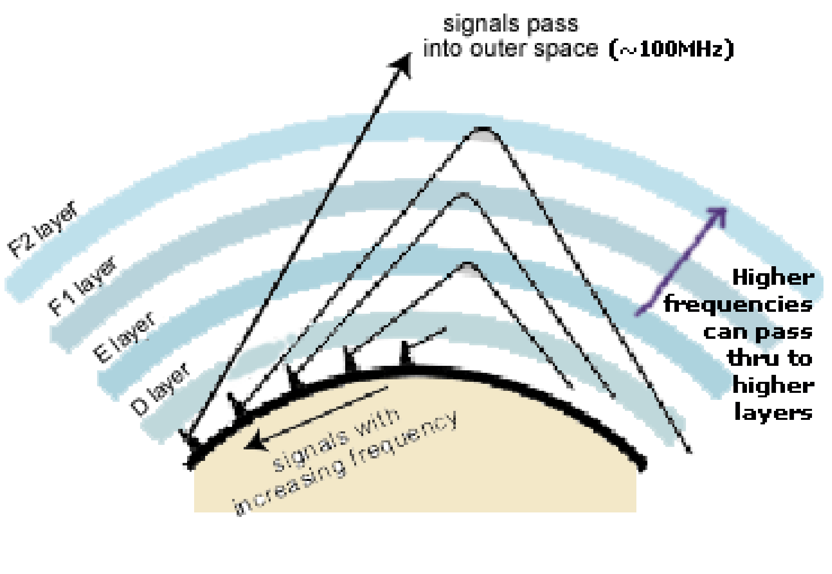
SKY-WAVE PROPAGATION



The **skip zone** is the region between the point where the ground wave signals can no longer be received and the point where the **skywave** first returns to Earth.

SKY-WAVE PROPAGATION

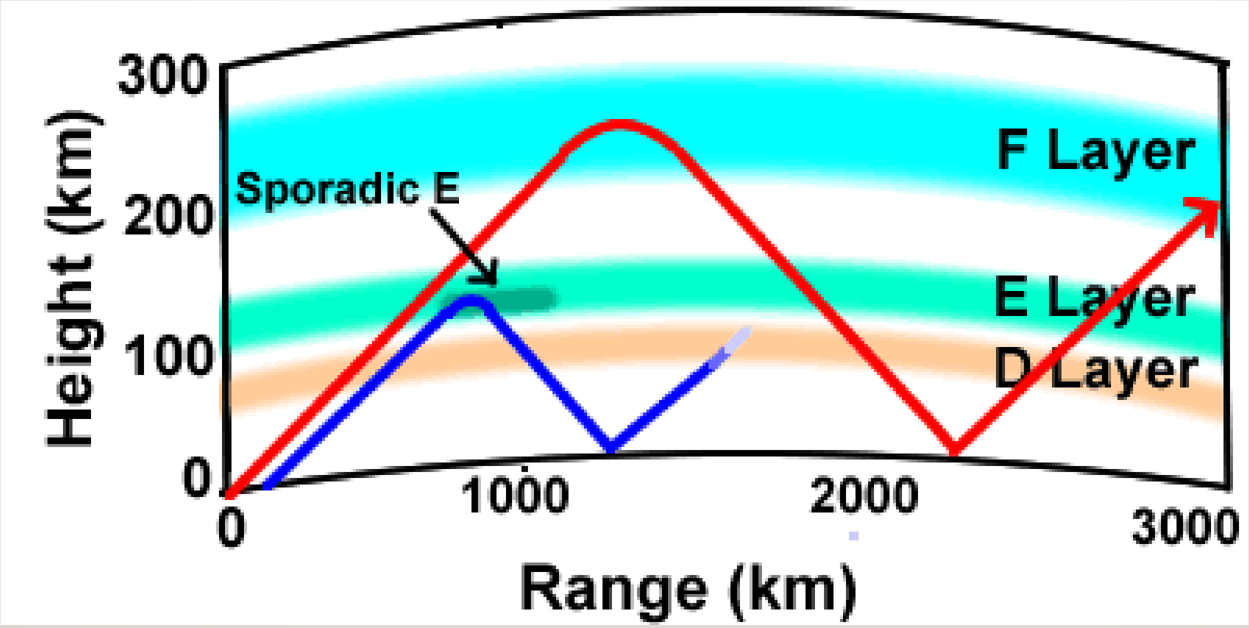




How the ionospheric layers refract different frequencies

each layer having specific behavioral characteristics dependent on solar radiation.

SKY-WAVE PROPAGATION



multi-hop propagation can occur at some layers and under certain condition (Sporadic E).

SKY-WAVE PROPAGATION

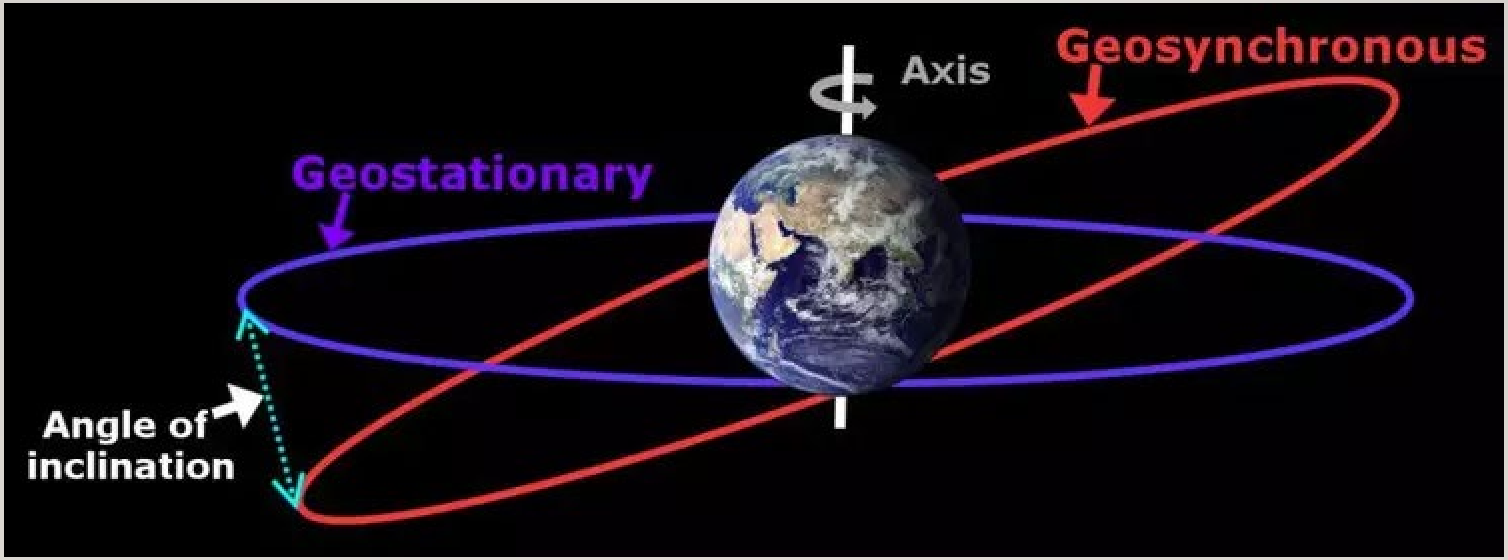
Why Some AM Radio Stations Don't Work at Night 4’58”

SATELLITE COMMUNICATION (SATCOM)

4:22

SATELLITE COMMUNICATION (SATCOM)

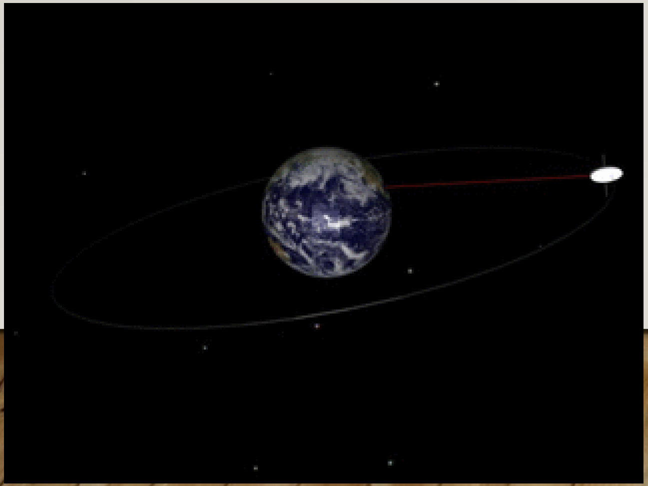
Made possible by placing satellites in geostationary orbit (GEO) (a subset of geosynchronous orbit without inclined orbit)

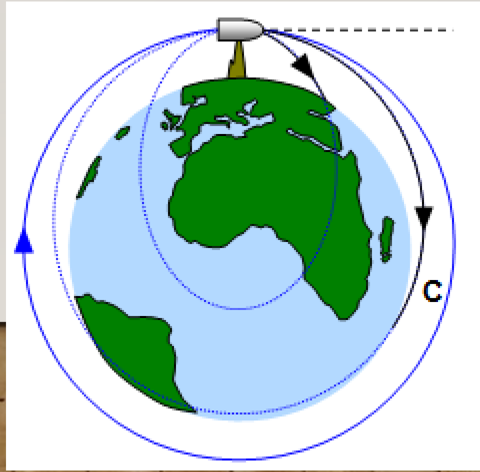


SATELLITE COMMUNICATION (SATCOM)

Made possible by placing satellites in geostationary orbit (GEO) (a subset of geosynchronous orbit without inclined orbit)

- Fixed location at ~22,300 miles above equator
- Keep in place by balance of gravitational forces (earth, sun & moon) and the centrifugal force (rotation around earth)
- A satellite is always falling toward earth, but earth is a moving target

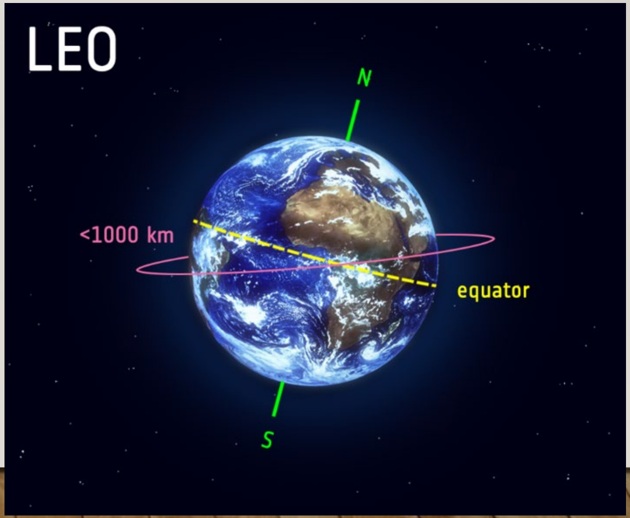




SATELLITE COMMUNICATION (SATCOM)

Communication recently proposed to use Low Earth orbit (LEO)

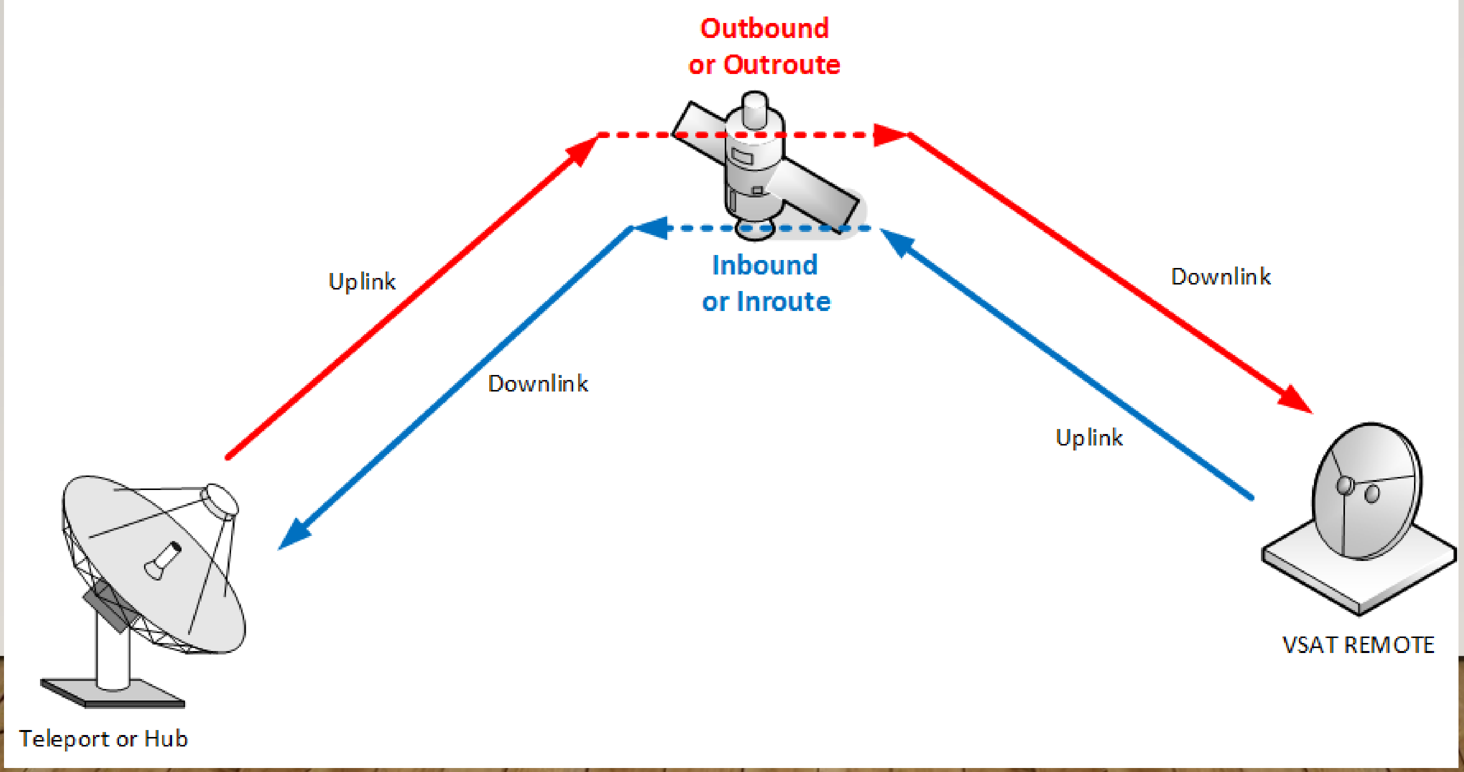
- normally at an altitude of less than 1000 km
- but could be as low as 160 km
- do not always have to follow a particular path around Earth in the same way – their plane can be tilted.
- Commonly used for imaging
- Difficult to track



SATELLITE COMMUNICATION (SATCOM)

Satellite communication system consists of:

- Uplink: sending signal to a satellite
- Orbiting Satellite
- Downlink: satellite sending signal to earth

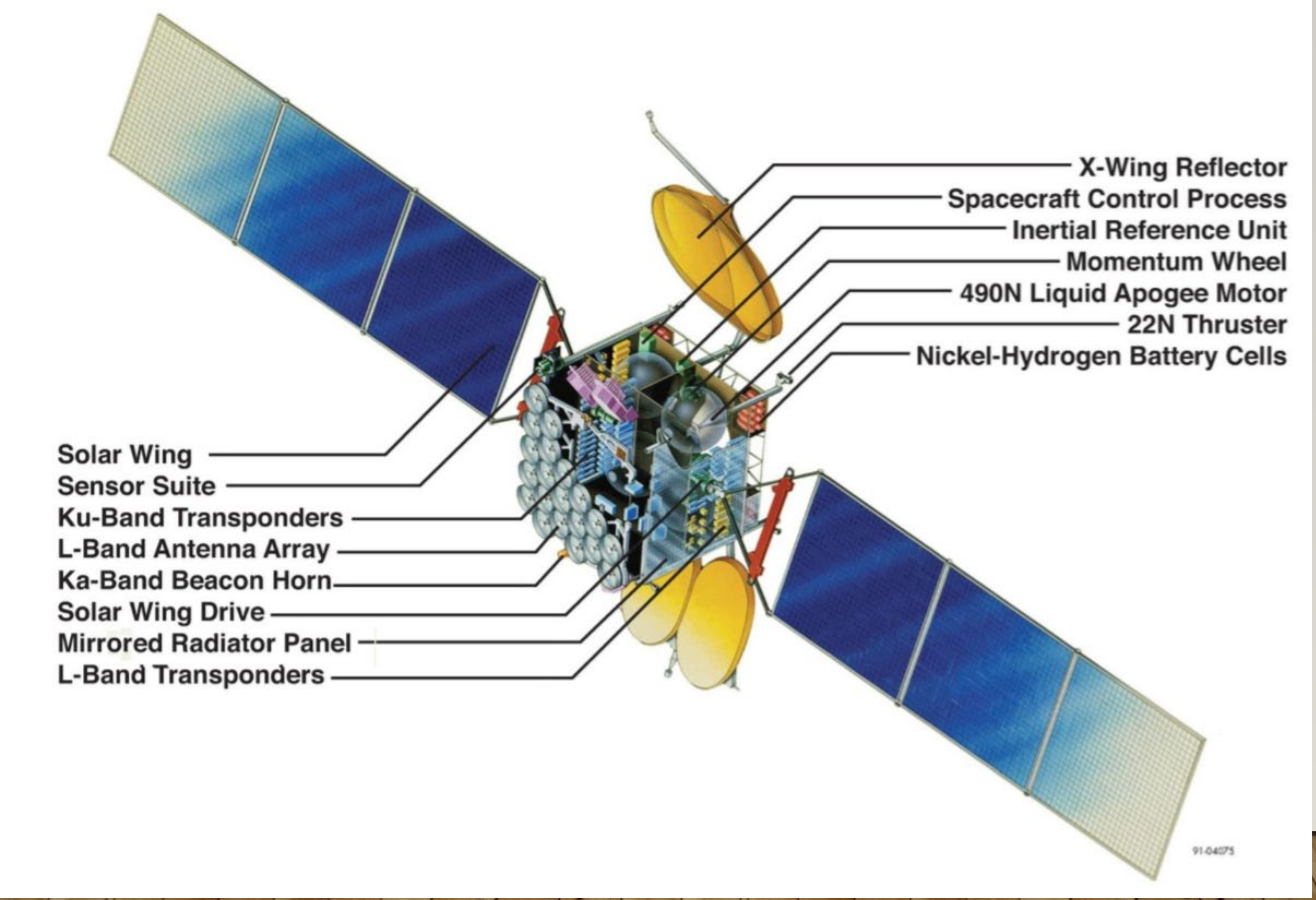


SATELLITE COMMUNICATION (SATCOM)

Satellites require a payload that includes:

- Antennas: transmit and receive signals
- Transponders: performs reception, frequency translation and re-transmission
- Altitude Controls: performs orbital corrections
- See example in the next slide

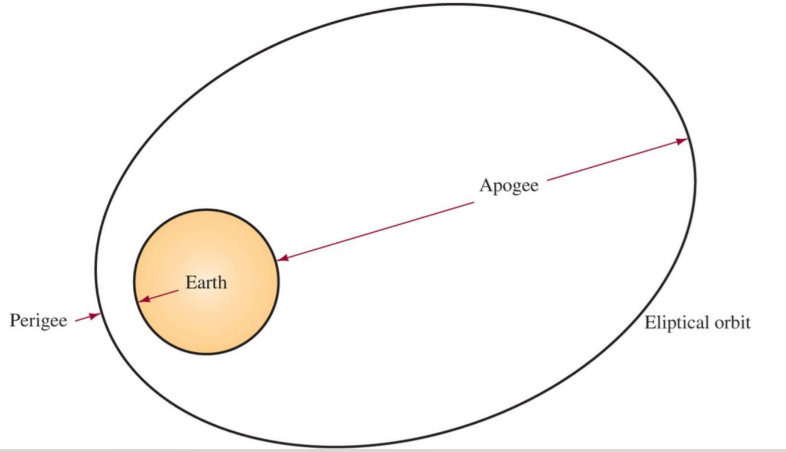
SATELLITE COMMUNICATION (SATCOM)



SATELLITE COMMUNICATION (SATCOM)

The orbital patterns of satellite are elliptical

- Perigee: closest distance of orbit to earth
- Apogee: farthest distance of orbit to earth

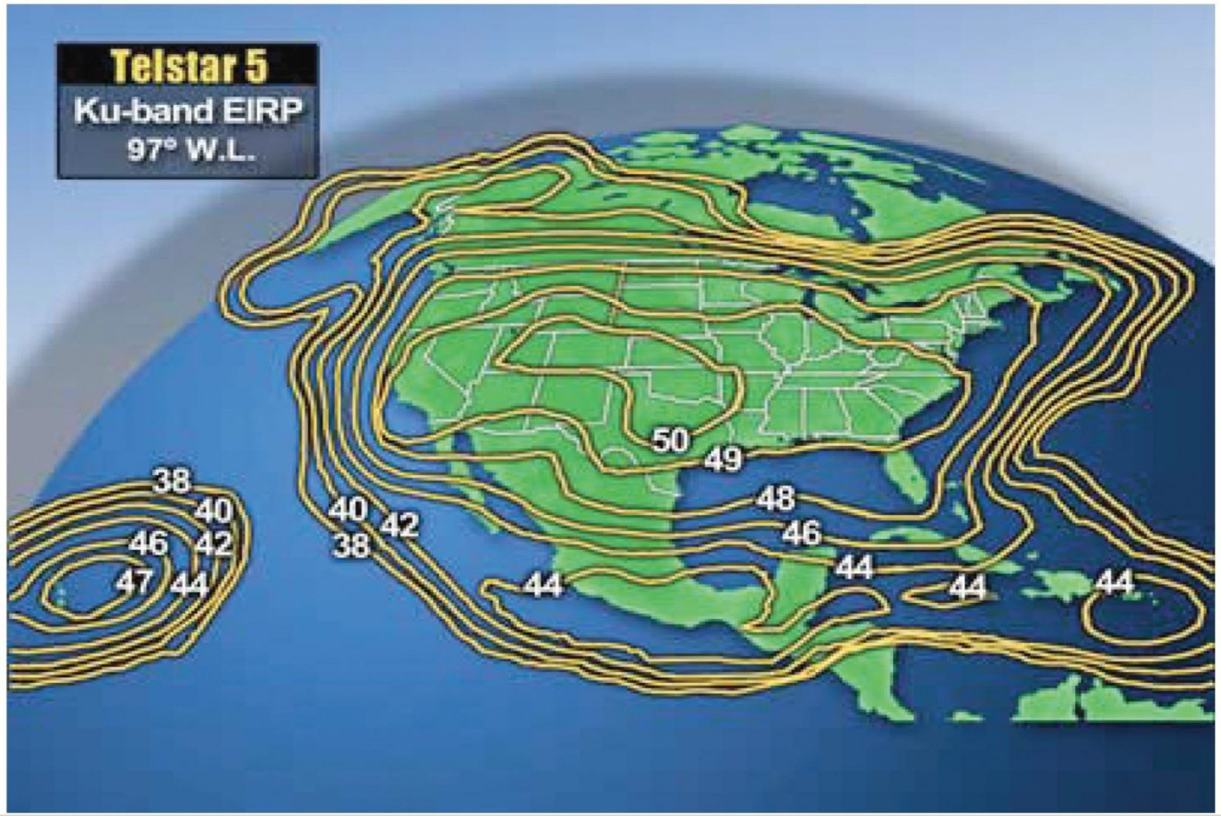


Observation Target		Orbit(km)		
Satellite	NORAD ID	Perigee	Apogee	Eccentricity
ATV 5	40103	368	405	0.0013728
COSMOS 1455	14032	516	543	0.0019497
COSMOS 1726	16495	507	526	0.0013828
COSMOS 2428	31792	845	857	0.0007984
CryoSat-2	36508	712	726	0.0009476
Gravity Probe B	28230	635	638	0.0002320
SEASAT 1	10967	747	749	0.0001213

The **eccentricity** of an **ellipse** is the ratio of the distance from the center to the foci and the distance from the center to the vertices.

SATELLITE COMMUNICATION (SATCOM)

A satellite covers a limited area called a *footprint*



Equivalent Isotropically Radiated Power (**EIRP**) is the product of **transmitter power** and **the antenna gain in a given direction** relative to an isotropic antenna of a radio transmitter.

SATELLITE COMMUNICATION (SATCOM)

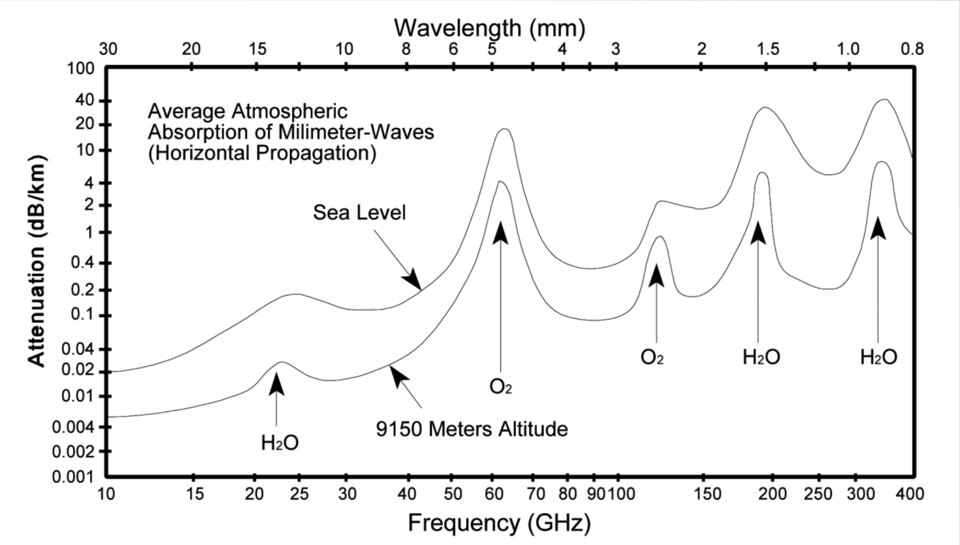
Satellite Frequency Bands:

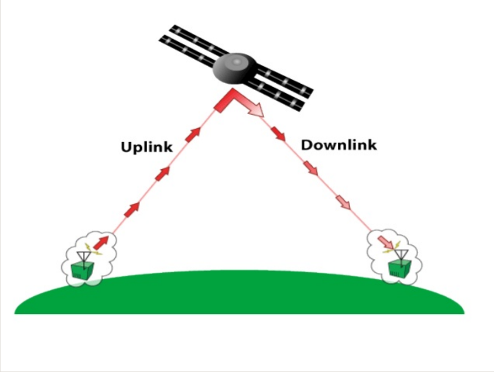
- L-Band (1-2 GHz): relatively low frequency, easier to process (less expensive RF equipment), not much bandwidth available. Used for military & mobile phones
- C-band (4-8 GHz): used for cruise ships and commercial vessels (remember white domes on cruises)
- Ku-Band (12-18 GHz): commonly used for TV, requires pointing accuracy of antennas, subject to rain fade
- Ka-Band (26.5-40 GHz): requires sophisticated (expensive) RF equipment, commonly used for HDTV, requires pointing accuracy of antennas, subject to rain fade

SATELLITE COMMUNICATION (SATCOM)

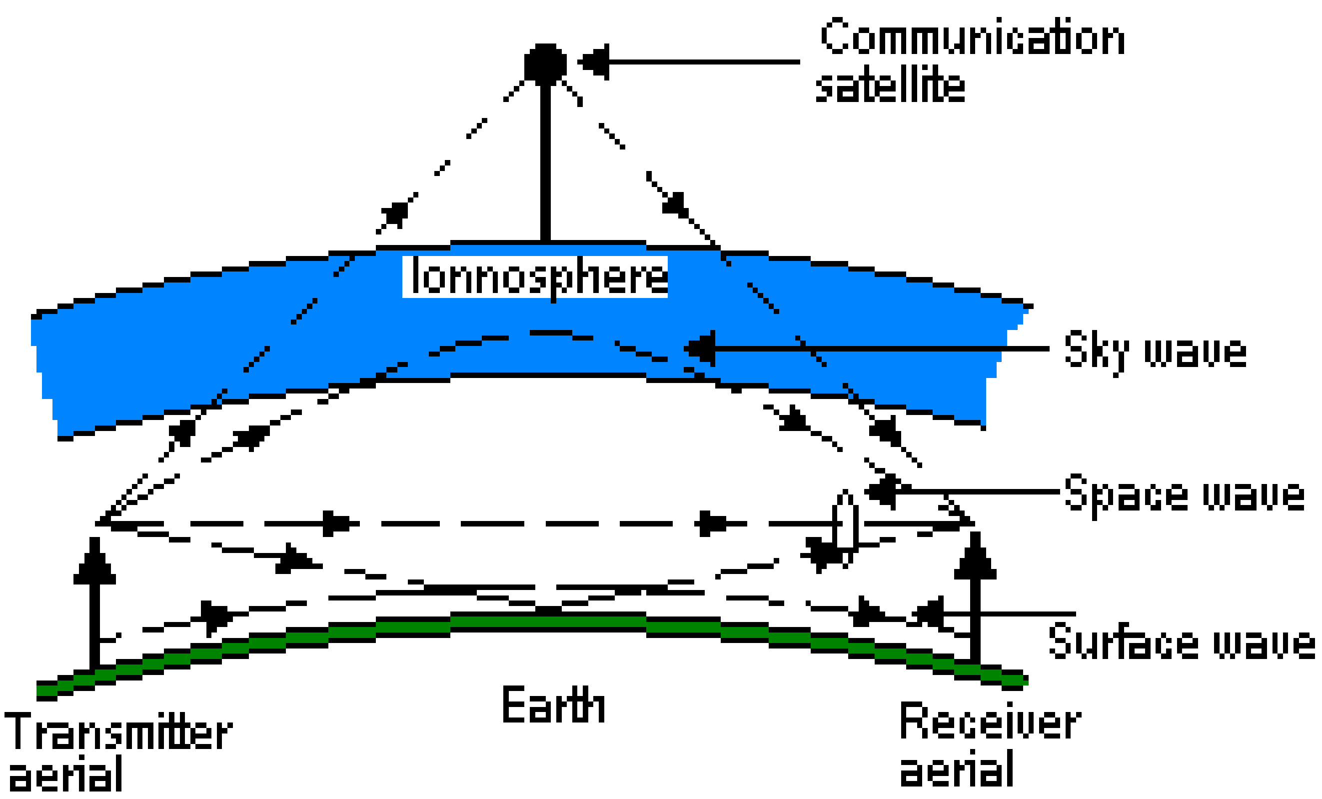
Satellite Frequency Bands:

SATELLITE FREQUENCIES (GHz)		
BAND	**DOWNLINK**	**UPLINK**
C	3.700 -4.200	5.925 - 6.425
X (Military)	7.250 - 7.745	7.900 - 8.395
Ku (Europe)	FSS : 10.7 - 11.7	FSS : 14.0 -14.8
	DBS : 11.7 -12.5	DBS : 17.3 -18.1
	Telecom : 12.5 -12.7	Telecom : 14.0 -14.8
KU (America)	FSS : 11.7 - 12.2	FSS : 14.0 -14.5
	DBS : 12.2 -12.7	DBS : 17.3 - 17.8
Ka	~ 18 - ~ 31	
V	36 - 51.4	





SUMMARY



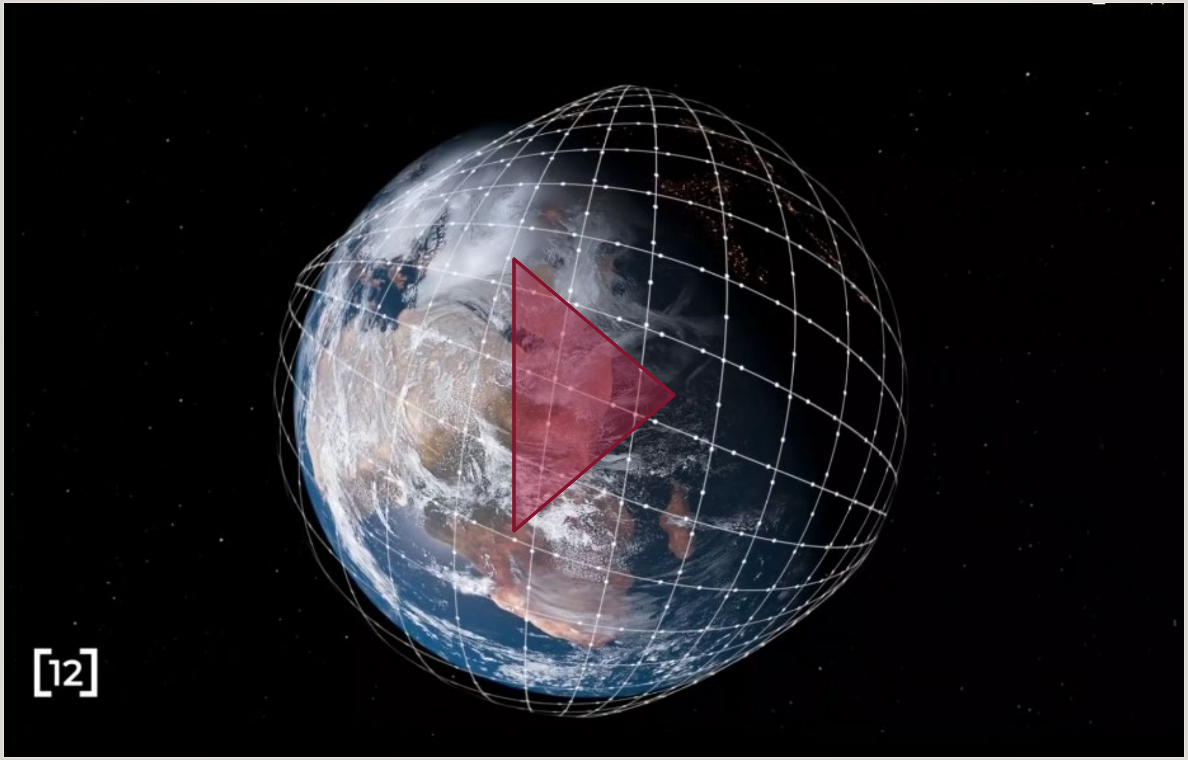
Communication satellite
Ionnosphere
Sky wave
Space wave
Surface wave
Earth
Transmitter aerial
Receiver aerial

SUMMARY

- **Ground Wave**: Low-frequency waves propagate along the Earth's surface, suitable for long-range communication.
- **Sky Wave**: Higher frequencies reflect off the ionosphere, enabling long-distance communication over the horizon.
- **Space Wave**: Direct line-of-sight transmission at higher frequencies, limited by Earth's curvature and obstacles.
- **Satcom**: Satcom: Satellites enable global communication using higher frequency EM waves (usually in GHz), penetrating the ionosphere.
  - Geostationary: Continuous coverage over a specific region.
  - LEO/MEO: Global coverage with lower latencies.

Considerations: Frequency, distance, terrain, and atmospheric conditions impact wave propagation characteristics.

STARLINK PROJECT (SPACEX)



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HOMEWORK

Please work on your course project!