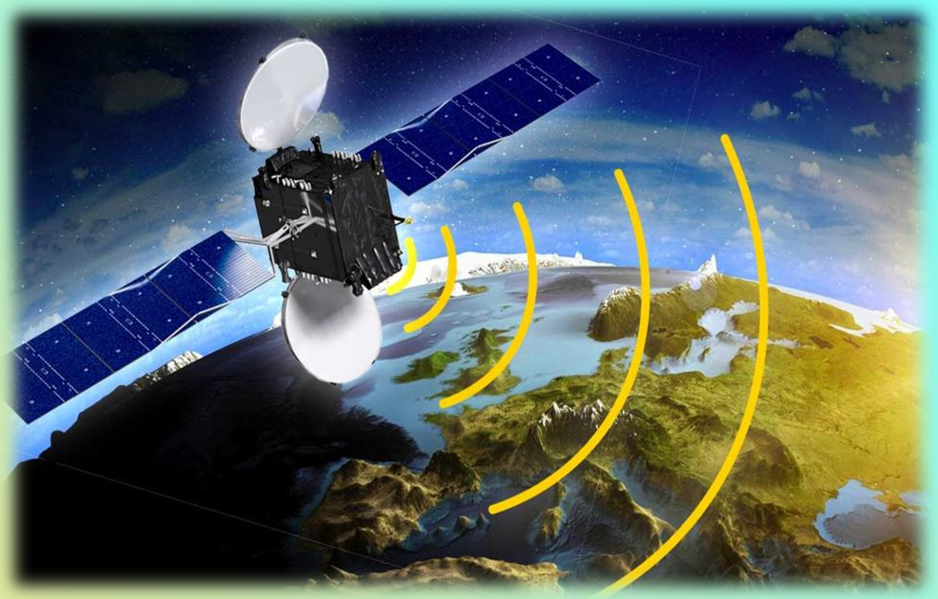
# Low Earth Orbit Satellite Communications



December 05, 2024

Part 1 of 2

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# Low Earth Orbit Satellite Communications

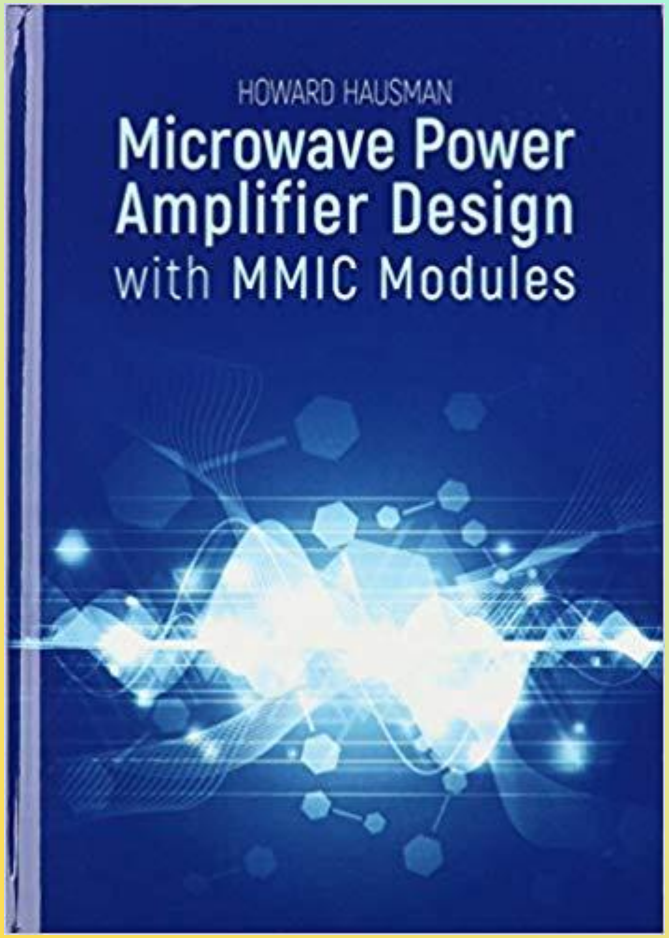
**ABSTRACT:** Satellite Communications can and in some instances does provide ubiquitous internet access to all regions of the world. Traditionally most satellite communication used Geostationary Earth Orbits (GEO) but recently the interest and investments have been in Medium Earth Orbit (MEO) and Low Earth Orbit (LEO) systems. Discussed is the difference between operating in each orbital category with emphasis on the LEO Satellite Systems. The lecture is concept based and therefore informative to attendees working in the engineering field as well as those just interested in learning more about the Low Earth Orbit satellite technology.

# Howard Hausman: Biography

- *NYU/Tandon School of Engineering: BSEE & MSEE degrees*
- *President/CEO of RF Microwave Consulting Services*
- *Adjunct : Professor, Hofstra University & Associate Professor, NYIT*
- *Designed Satellite Communications, Power Amplifiers, Microwave Components and Systems for Space, Radar and Reconnaissance systems*
- *Former President/CEO of MITEQ Inc (Also CTO and VP of Engineering)*
  - *Microwave Engineering Co.: $100 million in sales and 500 employees*
- *Recipient of an NYU Distinguished Alumni Award,*
- *IEEE LI Award ""For outstanding contributions in Satellite Communications and Microwave Theory""*
- *NASA Award for work on the Mars Landing System.*
- *Chairman of the IEEE LI Communications Society*
- *Reviewed research papers for the IEEE MIT Undergraduate Conference.*
- *Patent "Measuring Satellite Linearity from Earth –.".*
- *Authored a textbook "Microwave Power Amplifier Design …"*
- *Many technical papers and lectured around the world on Satellite Communications, Microwave Power Amplifiers and microwave systems.*

# Microwave Power Amplifier Design With MMIC Modules

by Howard Hausman



Pages: 384
ISBN: 9781630813468

Available from Amazon

**Part One: Useful Microwave Design Concepts** -- Lumped Components in RF and Microwave Circuitry. Transmission Lines. S-Parameters. Microstrip Transmission Lines. Circuit Matching and VSWR. Noise in Microwave Circuits. Non-Linear Signal Distortion. System Cascade and Dynamic Range Analysis.

**Part Two: Designing the Power Amplifier** -- Defining the Output Power Requirements for a Communication Link and Other Wireless Systems. Parallel Amplifier Topology Enhancing SSPA Performance. MMIC Amplifier Modules for Use in Parallel Combining Circuits. Measuring and Matching the Impedance of High Power MMIC Amplifier Modules. Power Dividers and Combiners Used in Parallel Amplifier SSPAs. Power Amplifier Chain Analysis.

**Part Three: Designing the Power Amplifier System** -- RF Signal Monitoring Circuits. DC Power Interface with the RF Signal Path. SSPA DC Voltage and Current. Thermal Design and Reliability. Electromagnetic Interference (EMI). Appendices. Index.

Published by Artech House, Boston & London

# Low Earth Orbit Satellite Communications

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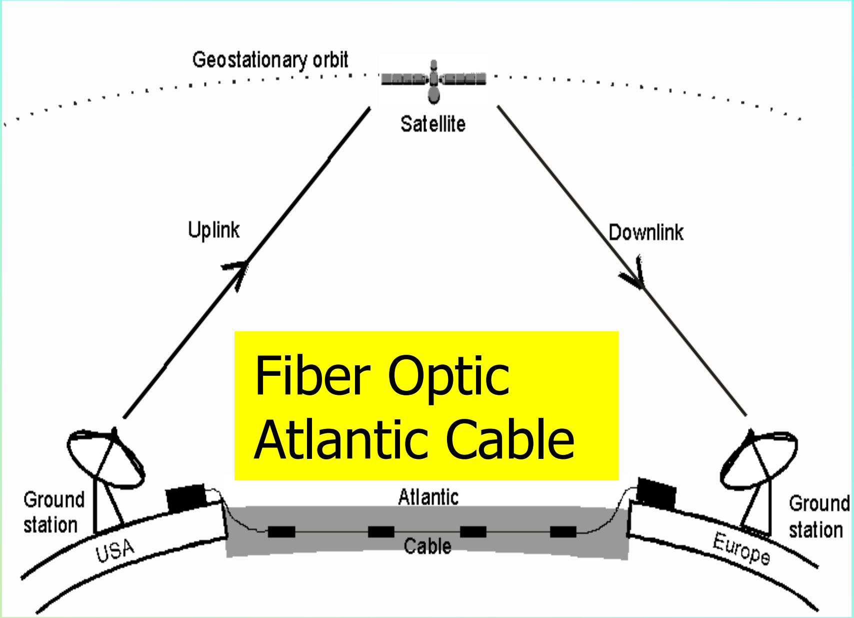
# Decibels

- The Decibel Unit:
  - Standard unit describing transmission gain (loss) and relative power levels
  - Gain: $N(\text{dB}) = 10 \log(P_2/P_1)$
  - Decibels above or below 1W: $N(\text{dBW}) = 10 \log(P_2/1W)$
  - Decibels above or below 1Milliwatt: $N(\text{dBm}) = 10\log(P_2/1mW)$
- Example:
  - P = 1mW => P(dBm) = 0dBm ; P(dBW) = -30dBW
  - P = 10mW => P(dBm) = +10dBm ; P(dBW) = -20dBW

# Satellite Communications Introduction

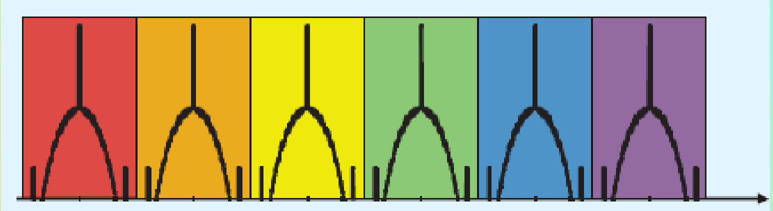
- Are Satellites a Cost-Effective Means of two-way Communications?
  - Answer is NO.
  - Limited Frequency Spectrum
  - Limited Spatial Capacity
    - Orbital Slots
  - High Equipment Cost



Fiber Optic Atlantic Cable

- Fiber Optic Land lines are More Cost Effective
  - Fiber has access to the entire Frequency Spectrum
  - Re-Use the frequency spectrum
    - Optical frequency multiplexing
    - Multi-Fiber Cables
  - One multi-fiber cable can carry as much information as all the satellites in orbit --

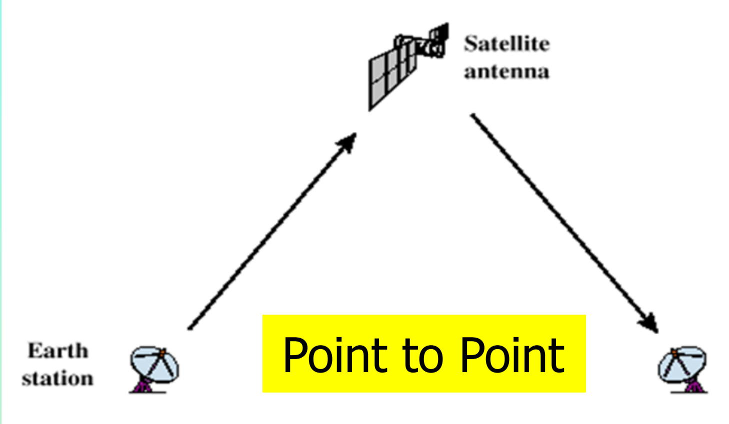
Wavelength Division Multiplexing (WDM)

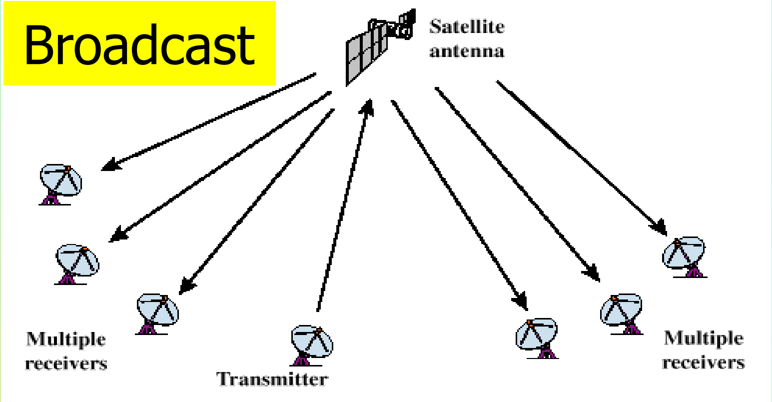


Frequency ➔

# *Satellites Provides Capabilities Not Available with Terrestrial Communication Systems*

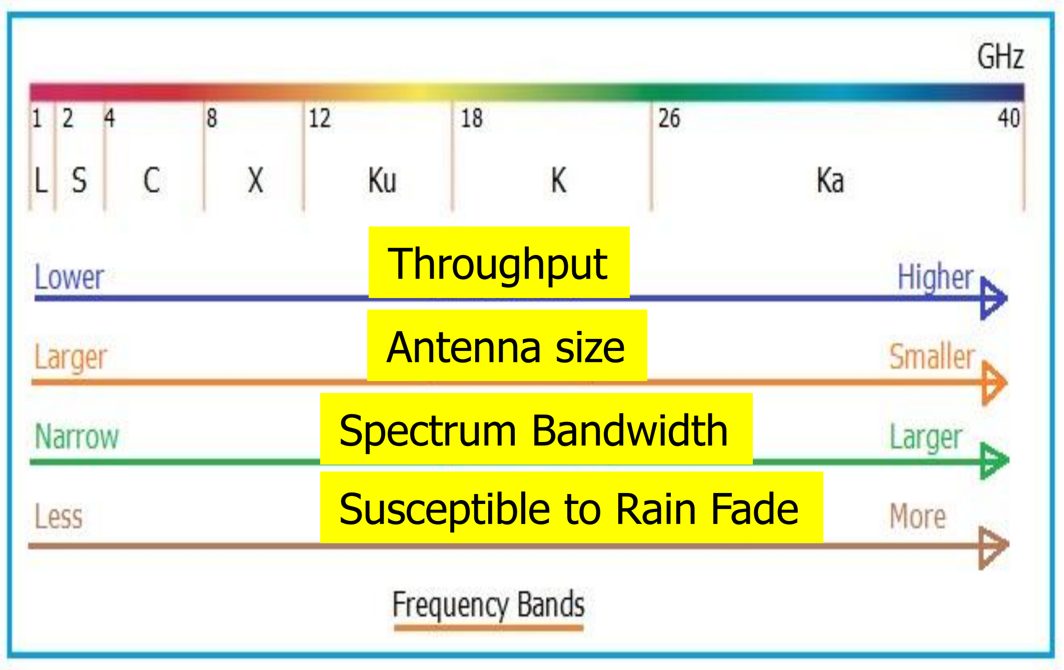
- Adaptability to different customers
- Mobility (No Cell Tower dependence)
- Cost advantage over land lines
  - Sparsely populated areas
- Satellite Broadcasting
  - One satellite signal could cover the USA

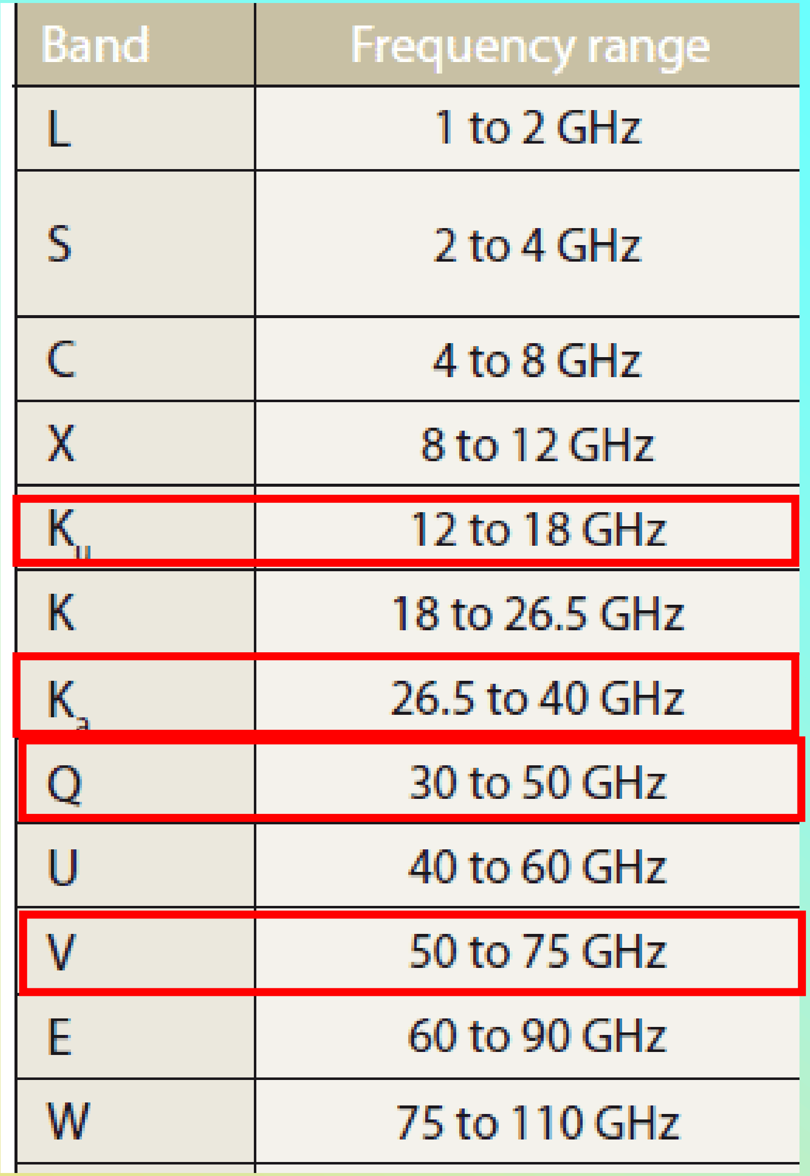




- No geographical obstructions that prohibit landlines
- Quick implementation – e.g. News Gathering, Disaster Relief, etc.
- Alternate routing or redundancy as required
- Cost effective for short term requirements e.g. Sporting Events --

# Microwave Frequency Bands





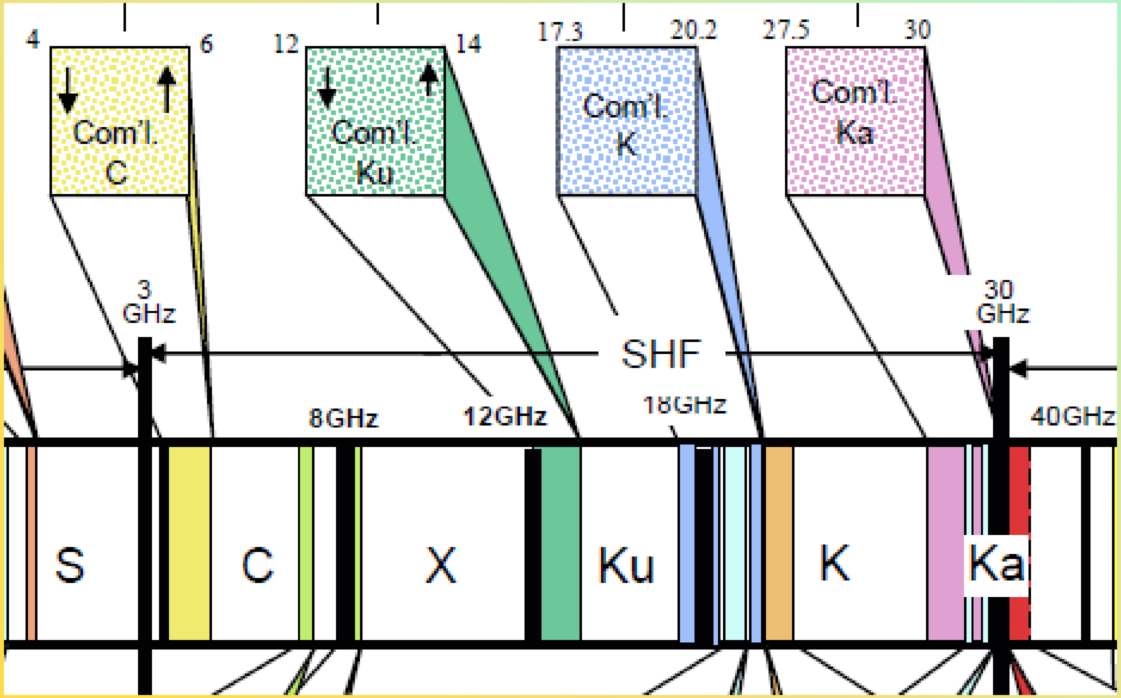
| Band | Frequency range |
|---|---|
| L | 1 to 2 GHz |
| S | 2 to 4 GHz |
| C | 4 to 8 GHz |
| X | 8 to 12 GHz |
| $K_u$ | 12 to 18 GHz |
| K | 18 to 26.5 GHz |
| $K_a$ | 26.5 to 40 GHz |
| Q | 30 to 50 GHz |
| U | 40 to 60 GHz |
| V | 50 to 75 GHz |
| E | 60 to 90 GHz |
| W | 75 to 110 GHz |

Higher frequencies

- Higher signal loss
- Problem penetrating obstructions
- Higher Data Rates

# Primary Commercial SATCOM Frequencies

| BAND | FREQUENCY (GHz) Up Link | FREQUENCY (GHz) Down Link |
|---|---|---|
| C-band | 5.850 to 6.650 | 3.400 to 4.200 |
| Ku-band | 13.750 to 14.500 | 10.950 to 12.750 |
| DBS (Direct Broadcast) | 18 GHz | 12 GHz |
| Commercial Ka-band | 27.500 to 30.000 | 17.700 to 20.200 |



- C-Band
  - Minimum Atmospheric attenuation
- Ku Band
  - GEO Business Apps
  - **LEO & MEO Internet**
- DBS (Direct to Home)
- Ka Band
  - GEO Internet
  - LEO

# Ku Band & Ka Band LEO & MEO Internet

- Ku Band
  - Earth to Satellites Communications
- Ka Band
  - "Ka band LEO satellite intra-satellite‟
  - Link between Low Earth Orbit (LEO) satellites
  - High-throughput data transmission between the satellites within a constellation;
  - Ka-band spectrum: Fast data transfer between satellites •

# Low Earth Orbit Satellite Communications

## 01: Orbital Mechanics

- ☐ How does a Satellite stay in Orbit
- ☐ Orbital Altitude
- ☐ Orbital time
- ☐ Typical Example

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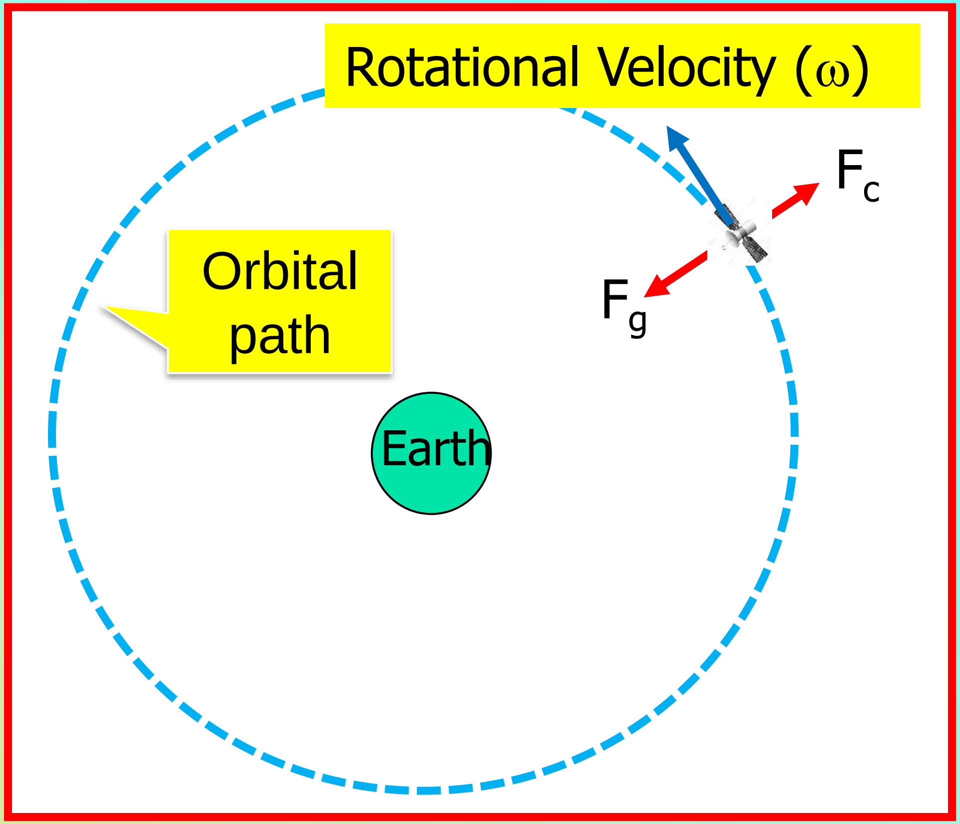
# How does a Satellite stay in Orbit

- Spin an object on a string
  - Faster it spins
  - Greater the force necessary to hold it
- Equalize the satellite velocity with Earth's gravitational force
  - Object will stay in space
- Change the distance from Earth
  - Gravitational force changes
  - Necessary velocity changes
  - Rotational orbit time changes


Rotational Velocity ($\omega$)

Orbital path

Earth

**For each orbital height**

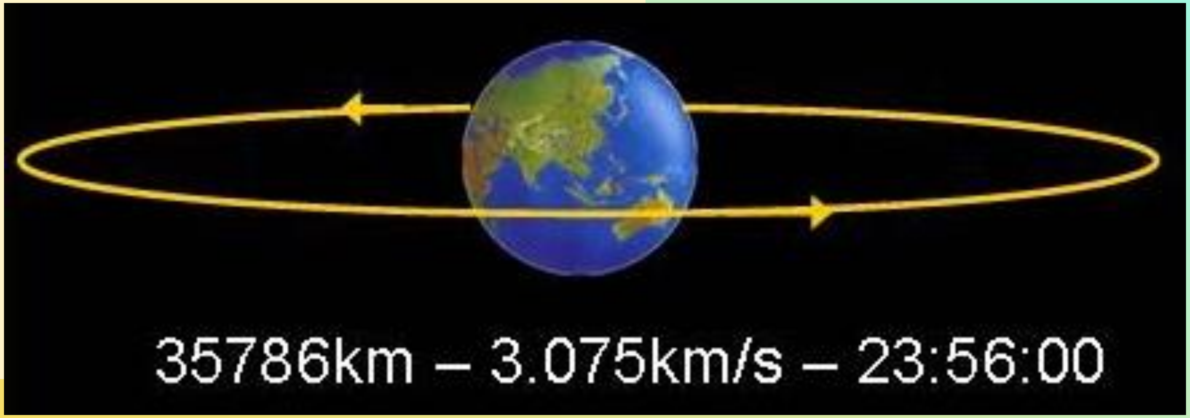
Velocity is set such that: Centrifugal force ($F_c$) = Gravitational force ($F_g$)

**Orbital time is a function of orbital height --**

# Calculation of Circular Orbits

- Gravitational Force ($F_g$)
  - $F_g = m \cdot g \cdot (R_e/r)^2$
  - **r: Orbital distance to the center of the earth**
  - m: mass of the satellite
  - $R_e$ : radius of the earth ($R_e$ = 6,371 km)
  - g: acceleration of gravity (g = 9.807 meters/s²)
  - $R_a = r - R_e$
    - $R_a$ is the distance above the Earth's surface
- Centrifugal force $F_c = m \cdot r \cdot \omega^2$
- $\omega$: angular velocity = $\omega = 2 \cdot \pi \cdot F$,
  - F: rotation frequency
  - T = 1/F
    - T = orbital time
- **Stable orbit**
  - **$F_g = F_c$**

Only variables
For a Stable orbit
1. Orbital time
   F (T=1/F)
2. Orbital height
   r -



# Equations for Calculating Circular Orbits

**Orbital Height Equation (r)**

$$r = \left(\frac{g \cdot R_e^2}{(2 \cdot \pi \cdot F)^2}\right)^{\frac{1}{3}}$$

**Orbital Time (T) Equation**

$$T = \left(\frac{g \cdot R_e^2}{(2 \cdot \pi)^2 \cdot r^3}\right)^{\frac{1}{3}}$$

- $R_e$ : radius of the earth ($R_e$ = 6,371 km)
- **r: Orbital distance to the center of the earth**
  - $R_a = r - R_e$
  - $R_a$ is the distance above the Earth’s surface
- g: acceleration of gravity (g = 9.807 meters/s²)
- F: rotation frequency
- T = orbital time
  - T = 1/F

# Example of Circular Orbital Calculations

Approximate Gravitational Force

$$g = 9.807\,\frac{m}{s^2}$$

Approximate Radius of the Earth

$$Re := 6371\cdot km$$

$$Re = 3958.756\,mi$$

Note: "T" is orbital time

Note:
"r" is the distance to the center of the Earth

Time for Low Earth Orbit (Ra = 150 miles)

$$\boxed{Ra := 150\cdot mi}$$

$$r := Ra + Re$$

$$T := \sqrt{\frac{(2\cdot\pi)^2\cdot r^3}{g\cdot Re^2}}$$

$$\boxed{T = 89.248\,min}$$

Geostationary (24 hours) Orbital Height (Ra is height above Earth's Surface) --

$$\boxed{T := 24\cdot hr}$$

$$F := \frac{1}{T}$$

$$r := \left[g\cdot\frac{Re^2}{(2\cdot\pi\cdot F)^2}\right]^{\frac{1}{3}}$$

$$r = 4.222\times 10^4\,km$$

$$r = 26235.27733\,mi$$

$$Ra := r - Re$$

$$\boxed{Ra = 22276.521\,mi}$$

# Low Earth Orbit Satellite Communications

## 02: Satellite Orbit

- ☐ **Satellite Orbit Characteristics**
  - ☐ **Geostationary Earth Orbits (GEO)**
  - ☐ **Medium Earth Orbits (MEO)**
  - ☐ **Low Earth Orbit (LEO)**
  - ☐ **Highly Elliptical Orbit (HEO)**

- ☐ **Van Allen Radiation Belts**
  - ☐ **Defines Orbital Categories**

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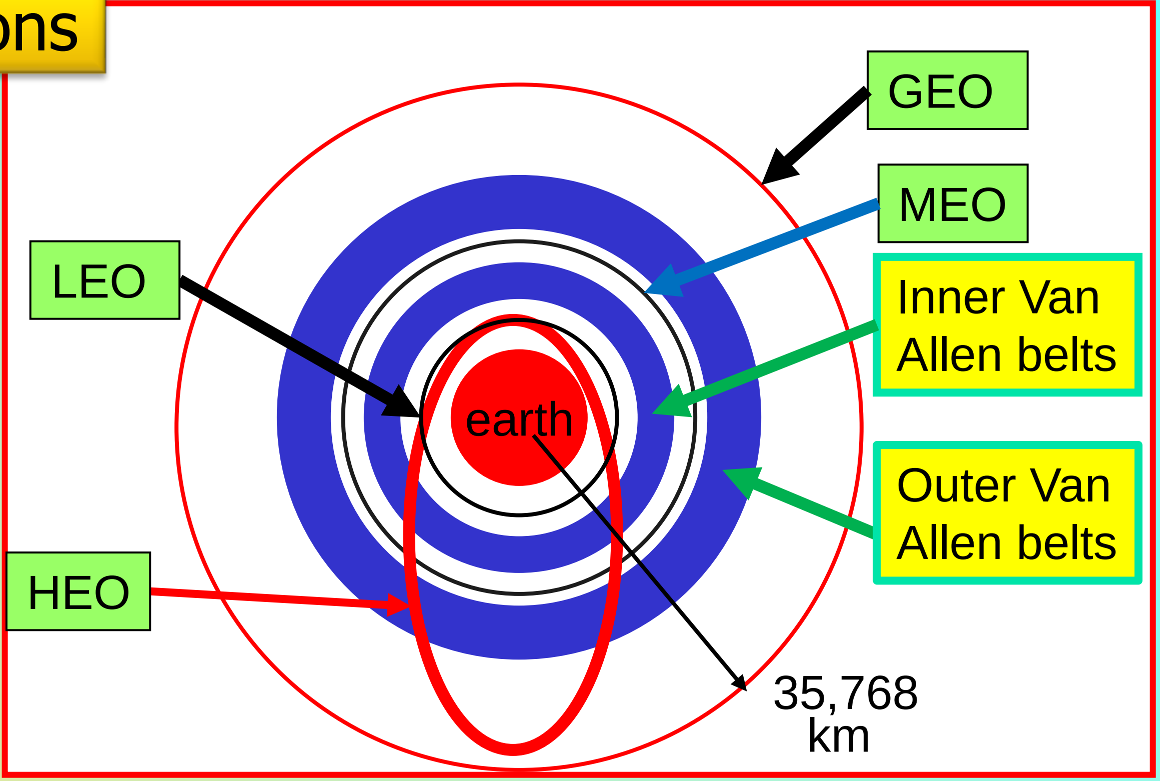
# Satellite Orbital Locations

- ❑ GEO: Geostationary orbit:
  - ❑ 22,236 Miles above earth surface at the equator
  - ❑ 26,199 Miles from the Earth's center
- ❑ LEO (Low Earth Orbit):
  - ❑ 100 to 600 miles
- ❑ MEO (Medium Earth Orbit):
  - ❑ 6,000 to 12,000 miles
- ❑ HEO (Highly Elliptical Orbit)
  - ❑ Quasi Fixed Satellite above the North Pole



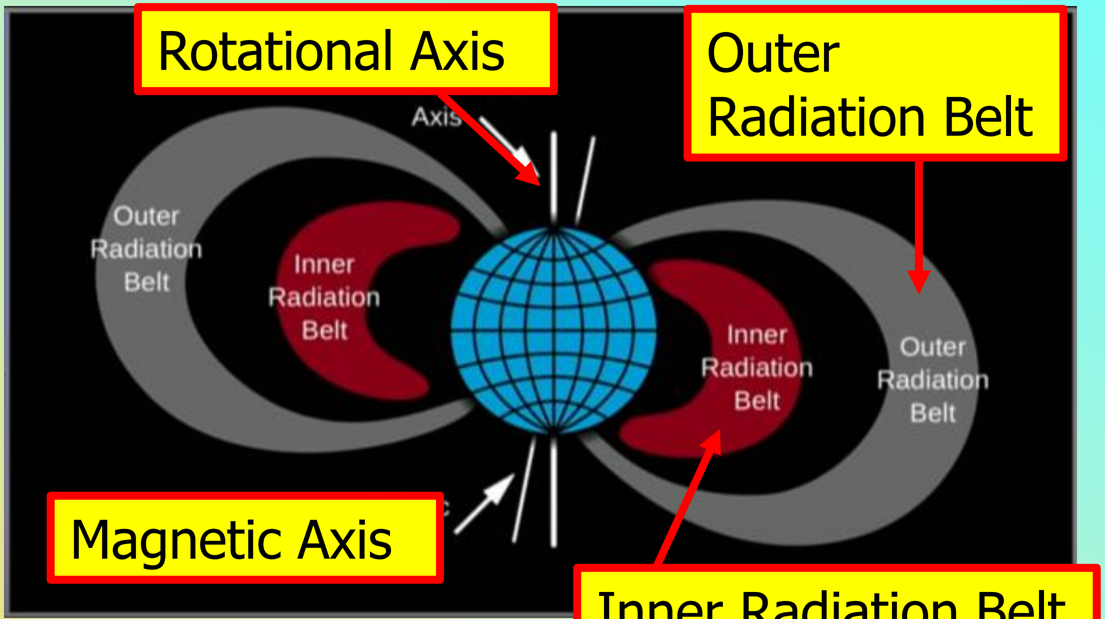
- ➢ LEO Orbits: Below the inner Van Allen Belt
- ➢ MEO orbits: Between the Van Allen Belts •

- ➢ Higher orbits ➔ Larger footprints ➔ Less satellite hand off
- ➢ Lower orbits ➔ Needs less signal from Earth ➔ Smaller footprint •

# Van Allen Radiation Belts

- Evidence for the radiation belts: Reported in 1958 by James Van Allen
  - Discover by cosmic ray detectors
    - First NASA mission: Explorer 1

- Named the Van Allen Belts,
- Regions of charged particles
- Work together with Earth's magnetic field
  - Protect us from the harsh radiation of the Sun
- Belts tend to shrink and swell
  - Respond to solar wind blasted in our direction



Rotational Axis

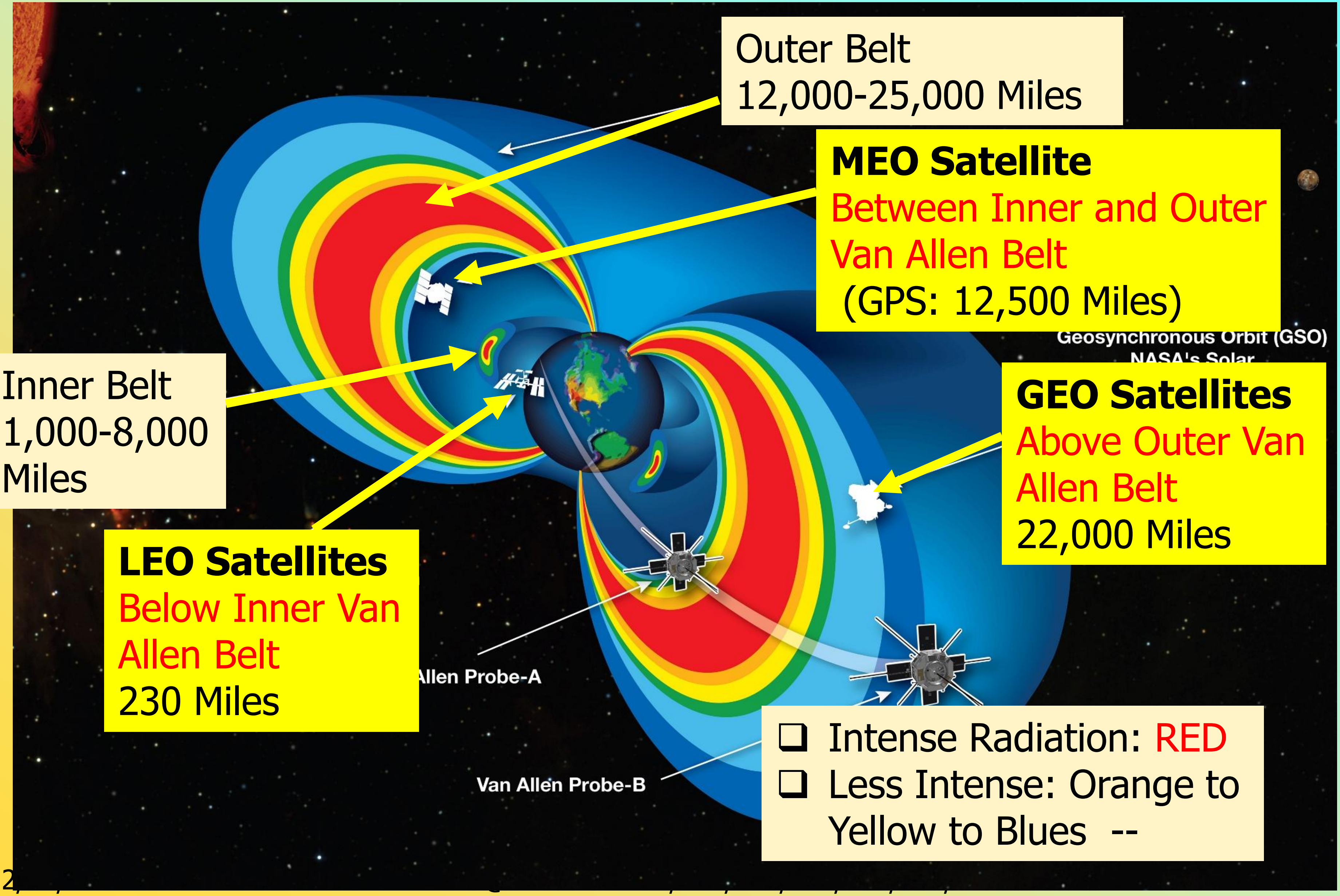
Outer Radiation Belt

Magnetic Axis

Inner Radiation Belt

Radiation Belts are perpendicular to the Magnetic Axis not the Rotational Axis --

- ☐ Magnetically trapped, highly energetic charged particles surround Earth.
- ☐ Giant donut-shaped swaths of particles



Outer Belt
12,000-25,000 Miles

**MEO Satellite**
Between Inner and Outer Van Allen Belt
(GPS: 12,500 Miles)

Inner Belt
1,000-8,000 Miles

**GEO Satellites**
Above Outer Van Allen Belt
22,000 Miles

**LEO Satellites**
Below Inner Van Allen Belt
230 Miles

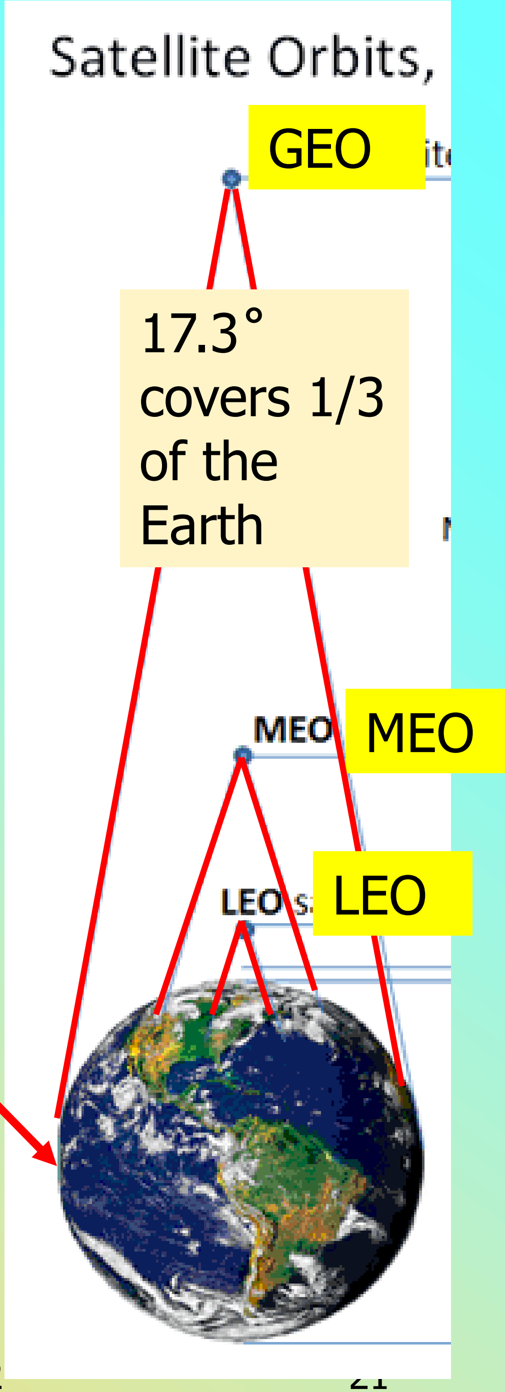
- ☐ Intense Radiation: RED
- ☐ Less Intense: Orange to Yellow to Blues --

# Satellite Orbit Characteristics

## GEO – Geostationary Earth Orbits

### GEO – Geostationary Earth Orbits

- Geosynchronous Orbit above the Equator
- Stationary with respect to the Earths Surface
- 17.3° covers 1/3 of the Earth
    - Does NOT cover the Polar Regions
- Characteristics
    - High signal delay
    - Requires High Earth Station Power --



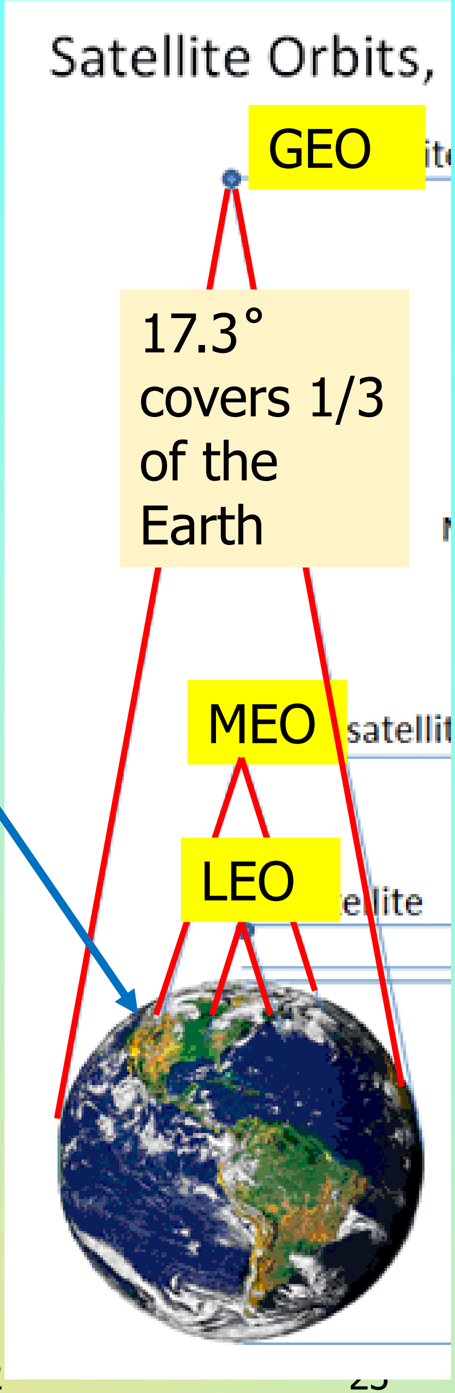
# GEO Satellites

- No handover Satellite to Satellite
- Altitude: ~35.786 km (≈ 23,000 Miles above the Earth Surface)
- One-way propagation delay: 250-280 ms
- 3 to 4 satellites for global coverage
- Mostly used in video broadcasting, Internet Service to Rural areas
- Other applications: Weather forecast, global communications, military applications
- Advantage: well-suited for broadcast services
- Disadvantages: Long delay, high free-space attenuation --

# MEO Characteristics

MEO – Medium Earth Orbits

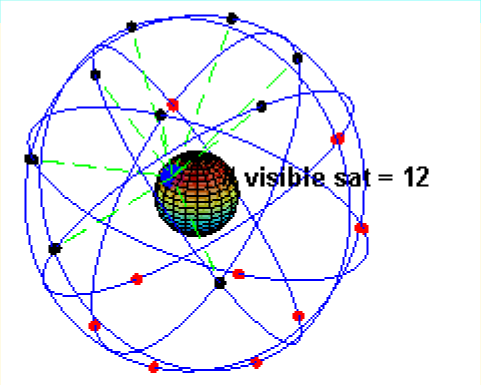
- Requires Higher RF power than LEO’s
- Larger Footprint than LEO Satellites
- Leo Delay < MEO delay < GEO delay --



# MEO Satellites

- Altitude: 10,000 – 15,000 km
- One-way propagation delay: 100 – 130 ms
- 10 to 15 satellites for global coverage
- Infrequent handover
- Orbit period: ~6 Hrs – 12Hrs
- Mostly used in navigation
  - GPS, Galileo, Glonass
- Communications: e.g. Inmarsat --

# MEO Example: GPS

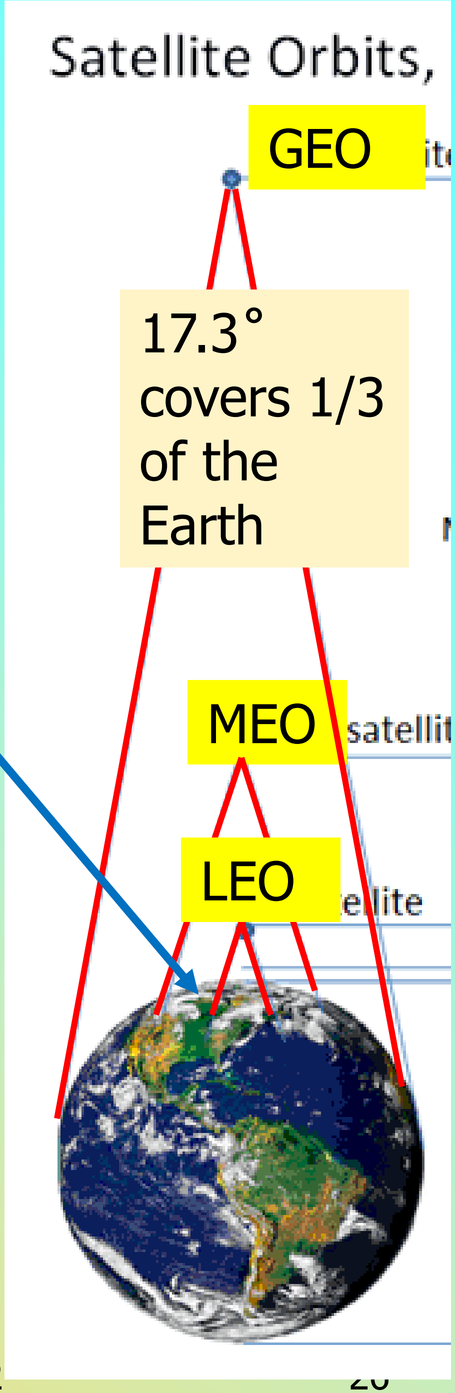


- Global Positioning System
  - Developed by US Dept. Of Defence
  - Became fully operational in 1993
  - Currently 31 satellites at 20,200 km.
- It works based on a geometric principle
  - “Position of a point can be calculated if the distances between this point and three objects with known positions can be measured”
- Four satellites are needed to calculate the position
  - Fourth satellite is needed to correct the receiver’s timing clock.
- Selective Availability
- Glonass (Russian): 24 satellites, 19,100 km
- Galileo (EU): 30 satellites, 23,222 km
- Beidou (China): Currently limited coverage --

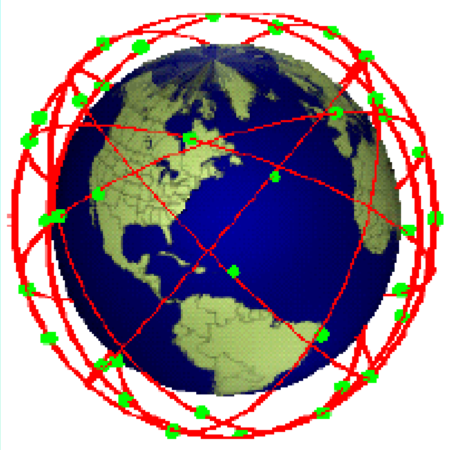
# LEO Characteristics

LEO – Low Earth Orbits

- Requires Low RF power
- Low delay
- Small Earth Footprint
- Requires Many Satellites for complete Earth coverage
- Complete Polar coverage --



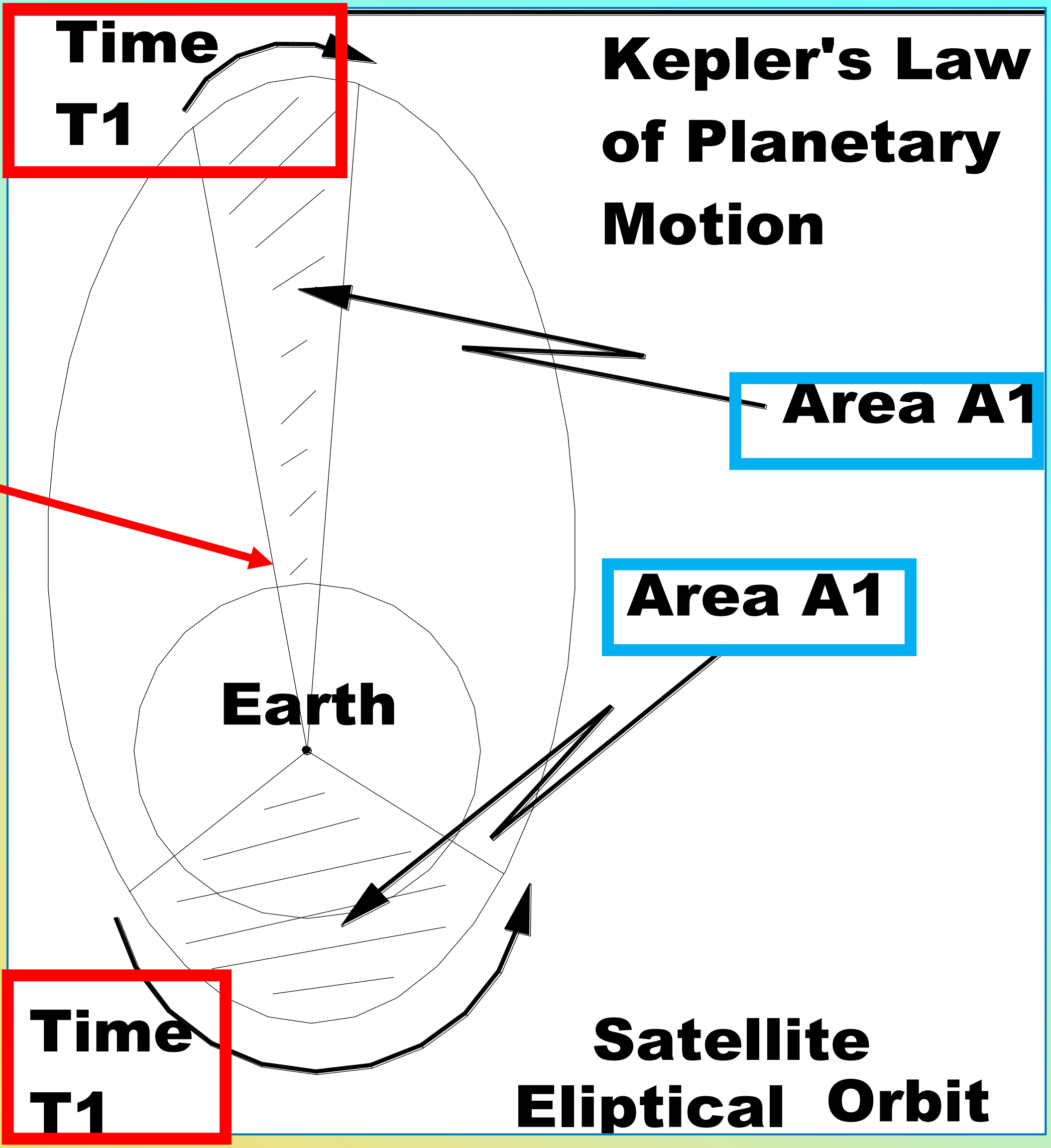
# Low Earth Orbit (LEO) Satellites



- Low Earth Orbits (LEO)
  - Visibility of a satellite:
    - 10 - 40 minutes
  - latency (Delay 5 - 10 ms)
- System must cope with large Doppler shifts
  - Fast moving satellites:
    - Frequency shift relative to a ground station
  - Requires Doppler compensation
- Satellite footprints are small
- Requires a large number of satellites for continuous coverage
- Better signal strength --

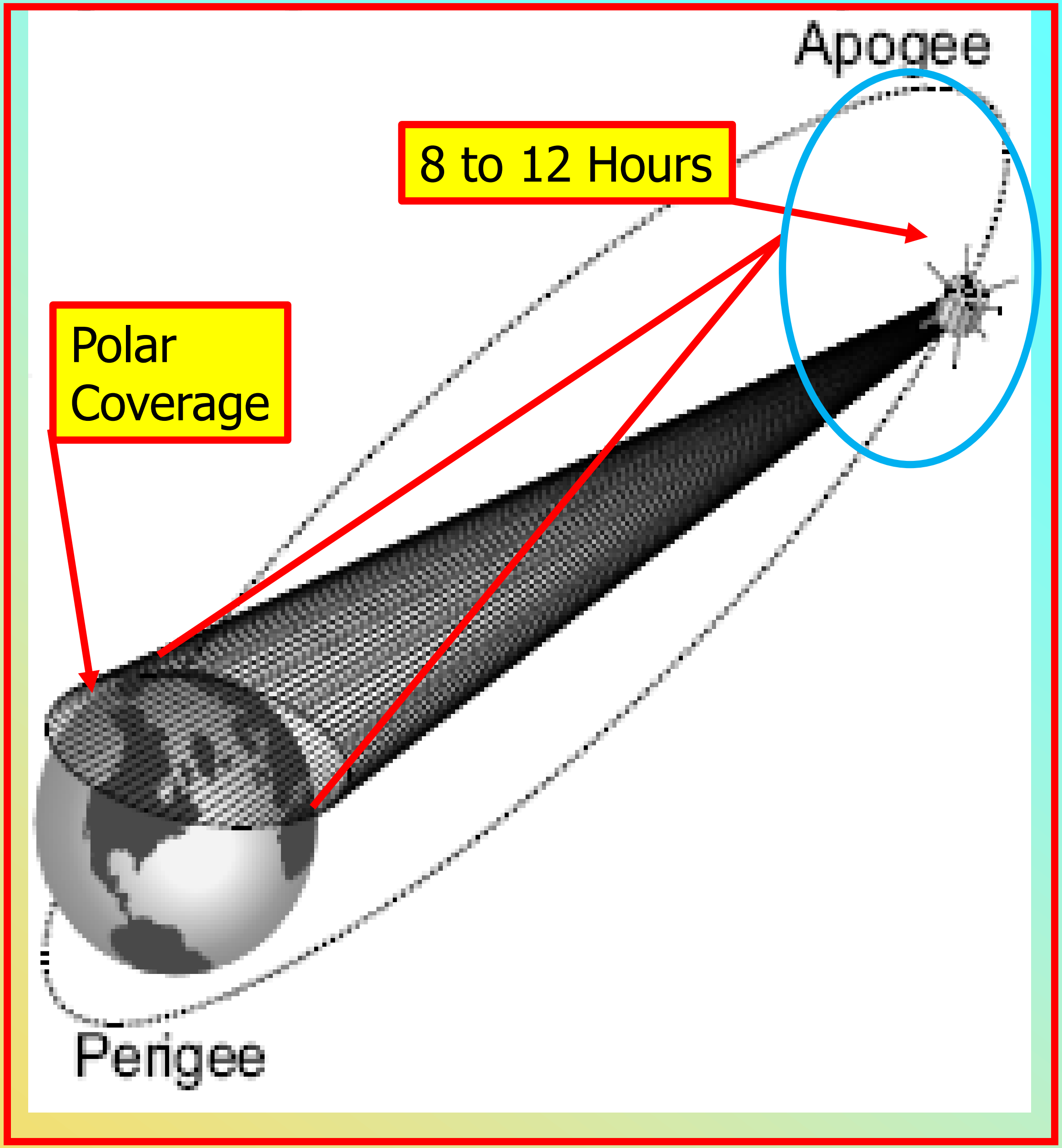
# HEO (Highly Elliptical Orbit) Satellite Systems

- Kepler Law of Planetary Motion
- Equal Time (T1) Over Equal Areas (A1)
- Polar Region



- Satellite Loiter over the North Pole
- 2 or 3 satellites are sufficient for continuous coverage
- Molniya Satellites (Russia)
  - Coverage for Polar Regions --

# HEO (Highly Elliptical Orbit) Satellite Systems



# 03: Antenna Gain and Beamwidth

- ☐ **Antenna Gain**
- ☐ **Antenna Beam-Width**
- ☐ **Side Lobe Radiation Problem**
- ☐ **Estimating Antenna Gain**
- ☐ **Example: Antenna Gain & Beam-Width**

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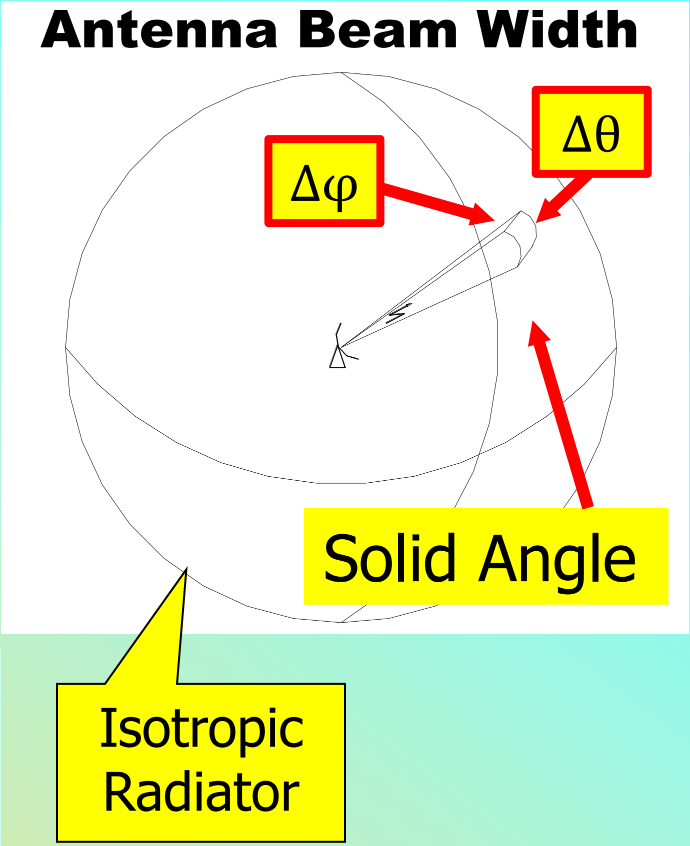
# Antenna Gain

### Isotropic Radiator

- Isotropic antenna is (theoretical) point in space
  - Radiates in all directions equally
  - Gives spherical radiation pattern

### Actual Antenna beam pattern

- Solid angle radiating in a focused direction



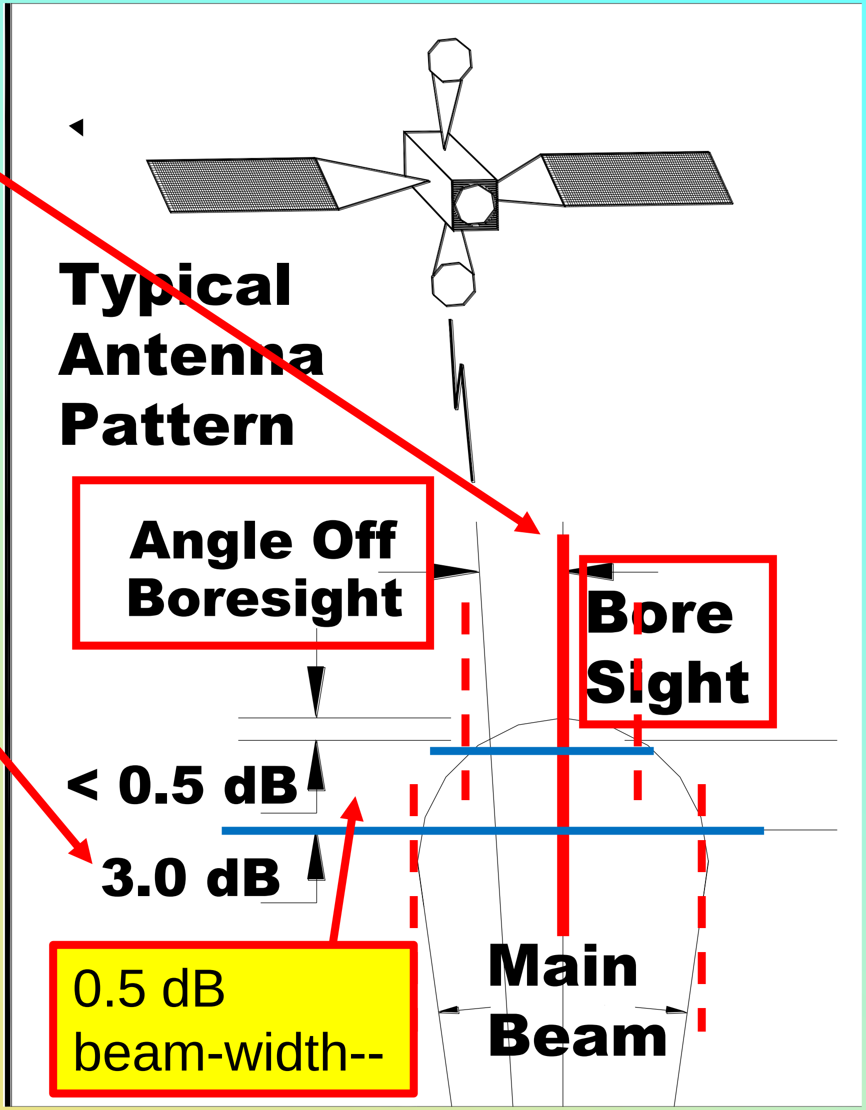
**Antenna Beam Width**

### Antenna Gain (Gp)

- Ratio of the Directional radiated power to the radiated power of an isotropic antenna
- Gain of an antenna:
  - Ability to focus its beam
- Antenna Gain is usually measured in decibels (dB or dBi)
- An isotropic antenna has a gain of 0 dBi --

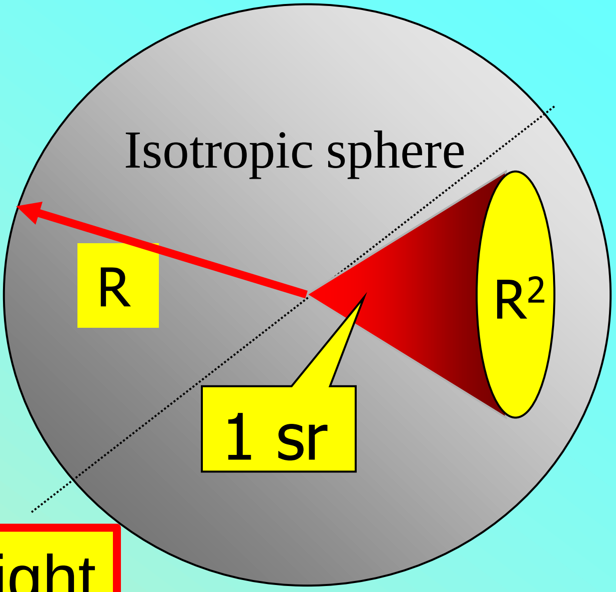
# Antenna Beam-Width

- Boresight
  - Center of the Beam
  - Peak Power
- Signal Offset from boresight:
  - Signal Loss
- Beamwidth:
  - Angle where antenna power is within 3 dB (1/2 Power) of the peak
- Beam width (BW) (degrees)
  - BW ≈ 21 / (F*D)
  - F = Frequency in GHz
  - D = diameter of the dish (Parabolic dish) in Meters
- Satellite GEO Ground Based Antennas require 0.5dB accuracy



# Solid Angle

- Surface area of a sphere is $4 \cdot \pi \cdot R^2$
- Area = radius ($R^2$): one steradian (sr)
  - $4 \cdot \pi$ steradians on a sphere



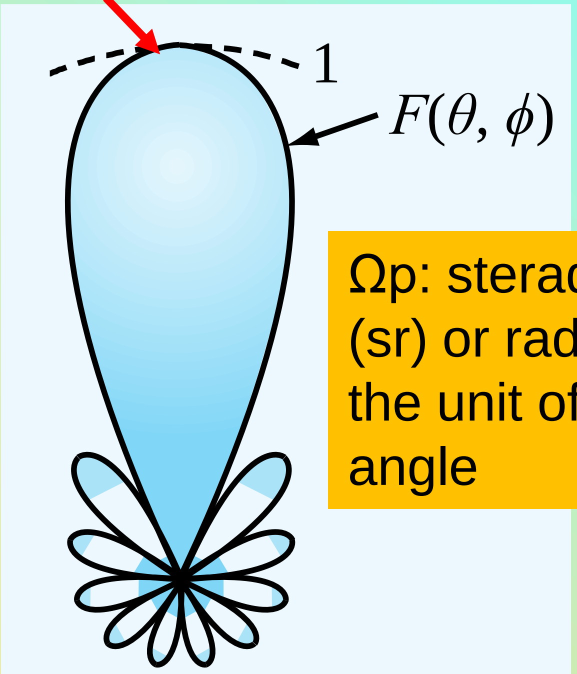
Sphere's Differential solid angle=dΩ (sr)

$$d\Omega = \sin(\theta)\, d\theta d\varphi$$

- θ is the elevation angle
- φ is the azimuth angle
- For sphere, the solid angle is dΩ

$$\Omega p = \int_{\varphi=0}^{\phi} \int_{\theta=0}^{\theta} \sin\theta \, d\theta d\varphi$$

- Integral of Sine ➔ Cosine
- Small Angle Cosine ➔ 1
  - $\Omega_p \approx \Delta\theta \times \Delta\varphi$ (radian²) --

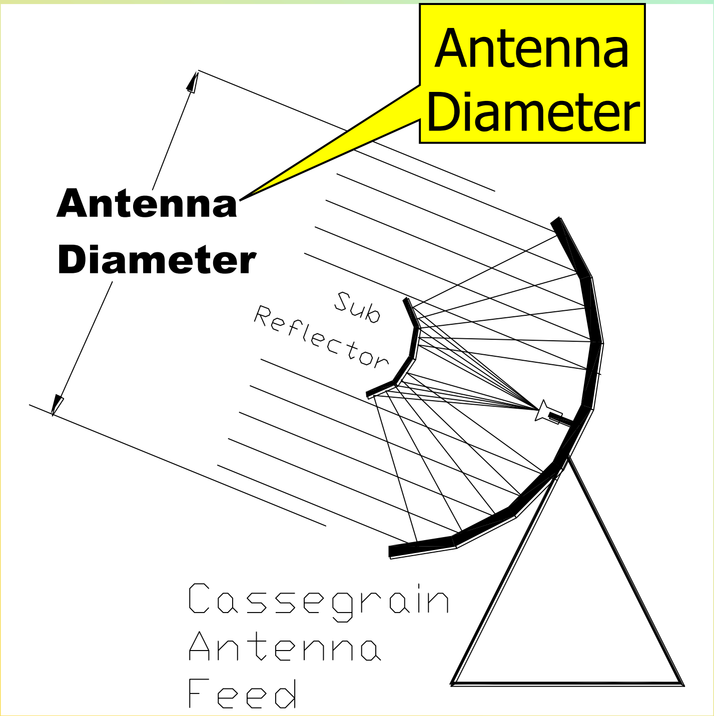


Ωp: steradian (sr) or radian² is the unit of solid angle

# Antenna Gain – Parabolic Dish

**Antenna Gain is a Function of frequency and dish diameter.**

Gain (dB) = 10 · $\text{Log}_{10}$ ($60 \cdot F^2 \cdot D^2$)
F = Frequency in GHz
D = diameter of the dish (Parabolic dish) in Meters



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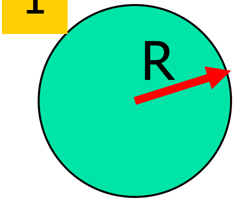


$$Area = \pi \cdot R^2$$

$$Area = \pi \cdot (D/2)^2$$

$$Area = \pi \cdot (D^2/4)$$

2

$$Gain = \eta \cdot \frac{4 \cdot \pi \cdot Area}{\lambda^2} = \eta \cdot \frac{4 \cdot \pi \cdot \pi \cdot (D^2/4)}{\lambda^2})$$

$$Gain = \eta \cdot \left(\frac{\pi \cdot D}{\lambda}\right)^2$$

$$Number\ of\ wavlengths = \frac{D}{\lambda}$$

- λ(Lambda) = The wavelength
- D = The Diameter of the Dish
- η = The Efficiency of the Antenna
  - Side lobes & other Losses
  - Typically, < 0.8 ➔ < 2 dB --

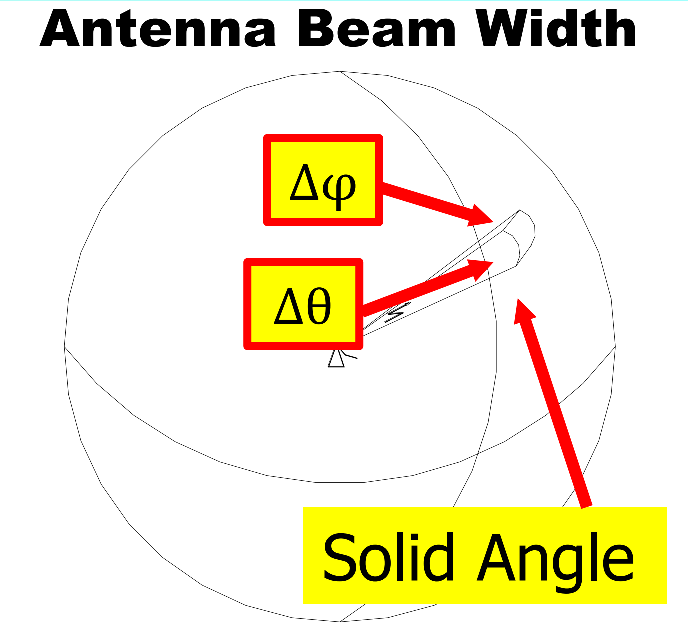
# Estimating Antenna Gain

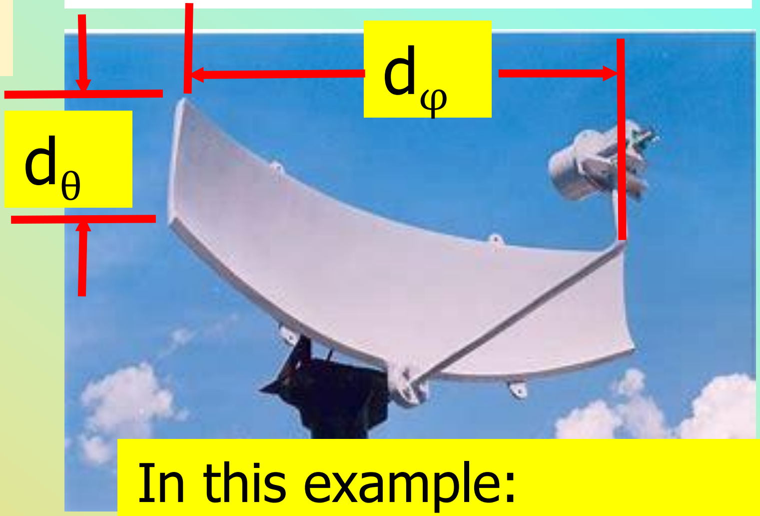
- Estimating antenna gain ($G_p$)
  - $\Delta\theta \approx (\lambda/d_\theta)$ (radians)
    - $d_\theta$ is the antenna dimension along the angle "θ" axis
    - Large antenna means small $\Delta\theta$
  - $\Delta\varphi \approx (\lambda/d_\varphi)$ (radians)
    - $d_\varphi$ is the antenna dimension along the angle "φ" axis

$$\Delta\theta \approx \frac{\lambda}{d_\theta} = \frac{1}{d_\theta/\lambda} = \frac{1}{n_\theta}\ (Radians)$$

$$n_\theta = d_\theta/\lambda\ (number\ of\ wavelengths)$$

$$Gmax = \frac{4\pi}{\Omega p} \approx \frac{4\pi}{\Delta\theta\ \Delta\varphi} = 4\cdot\pi\cdot n_\theta\cdot n_\varphi$$


Antenna Beam Width



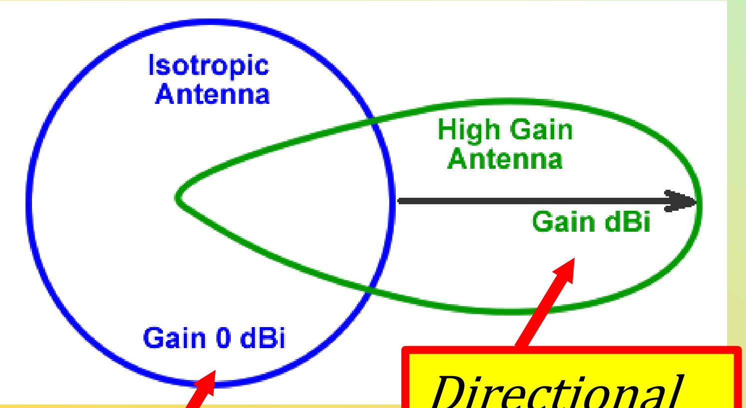
In this example:
Horizontal angle is smaller than the Vertical angle--

# Example: Antenna Gain & Beam-Width

Many times, antennas are classified by the diameter in wave lengths (λ) -

$$\Delta\theta \approx \frac{\lambda}{d_\theta} = \frac{1}{d_\theta/_\lambda} = \frac{1}{n}\ (Radians)$$

$$Gmax = \frac{4\pi}{\Omega p} \approx \frac{4\pi}{\Delta\theta\,\Delta\varphi} = 4 \cdot \pi \cdot n_\theta \cdot n_\varphi \text{ --}$$



*Isotropic Antenna* $(Gain:\ 0dBi)$

*Directional Antenna* $(Gain\ \ dBi)$

### Example: Parabolic Antenna Gain & Beam width

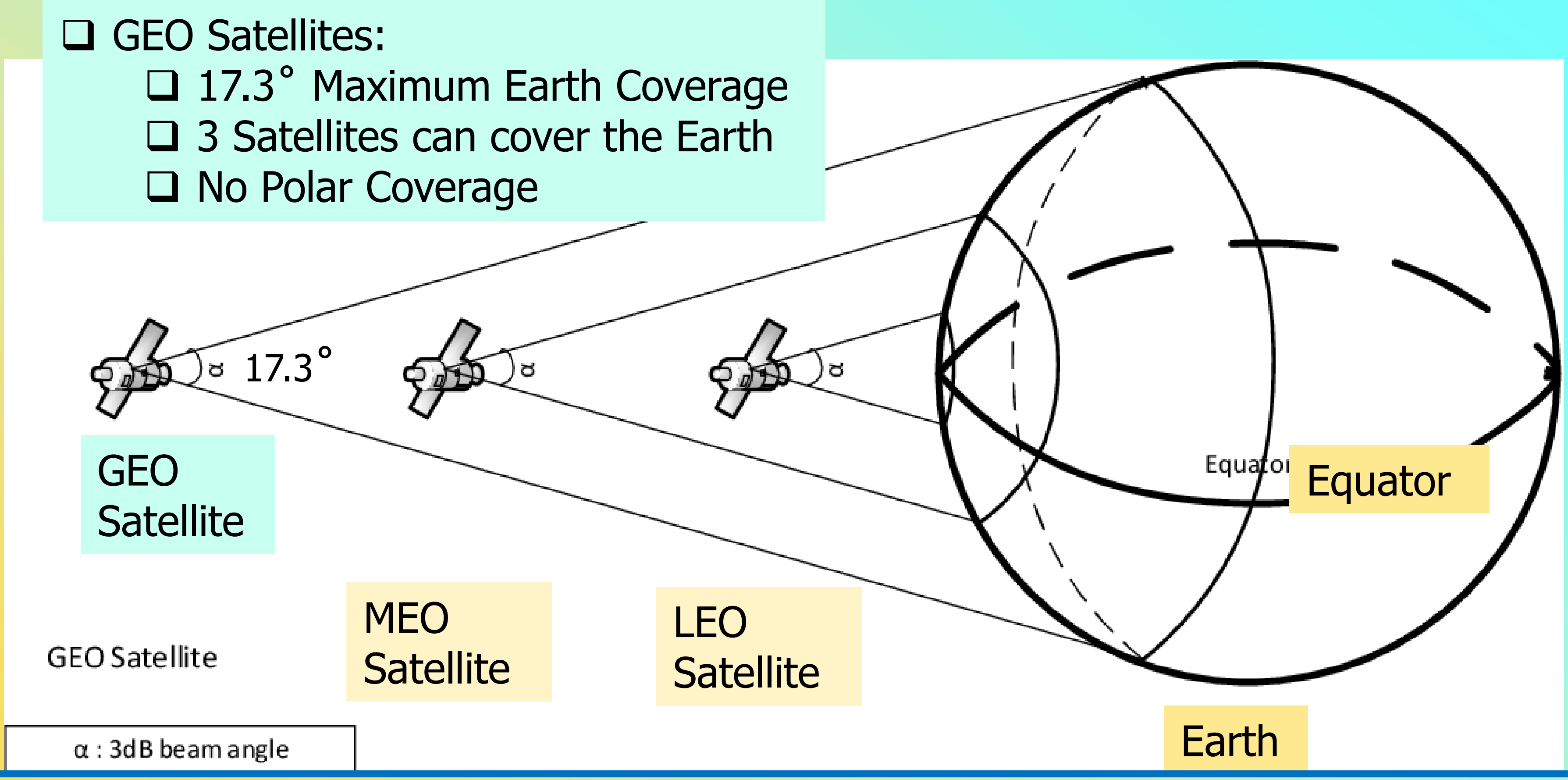
**Gain & Beam width** --

| | | | | |
|---|---|---|---|---|
| Diameter | 3 | Meters | 1.071 | Meters |
| Frequency | 14 | GHz | 14 | GHz |
| Lambda (λ) | 0.0214 | Meters | 0.0214 | Meters |
| N Lambda | 140 | | 50 | |
| Ideal Gain | 50.25 | dBi | 41.30 | dBi |
| Ant Effic. | 2 | dB | 2 | dB |
| Ant Gain | 48.25 | dBi | 39.30 | dBi |
| Beam Width | 0.5 | Degrees | 1.4 | Degrees |

# 04: Satellite Footprint on Earth

- ☐ **Relative Satellite Footprints vs. Orbital Height**
- ☐ **Antenna Coverage on Earth**
- ☐ **LEO Satellites: Smaller Footprints**
- ☐ **Earth Tracking Fast moving Satellites**
  - ☐ **LEO/MEO: Doppler Shift Issues**

# Relative Satellite Footprints vs. Orbital Height



- GEO Satellites:
  - 17.3˚ Maximum Earth Coverage
  - 3 Satellites can cover the Earth
  - No Polar Coverage

GEO Satellite

MEO Satellite

LEO Satellite

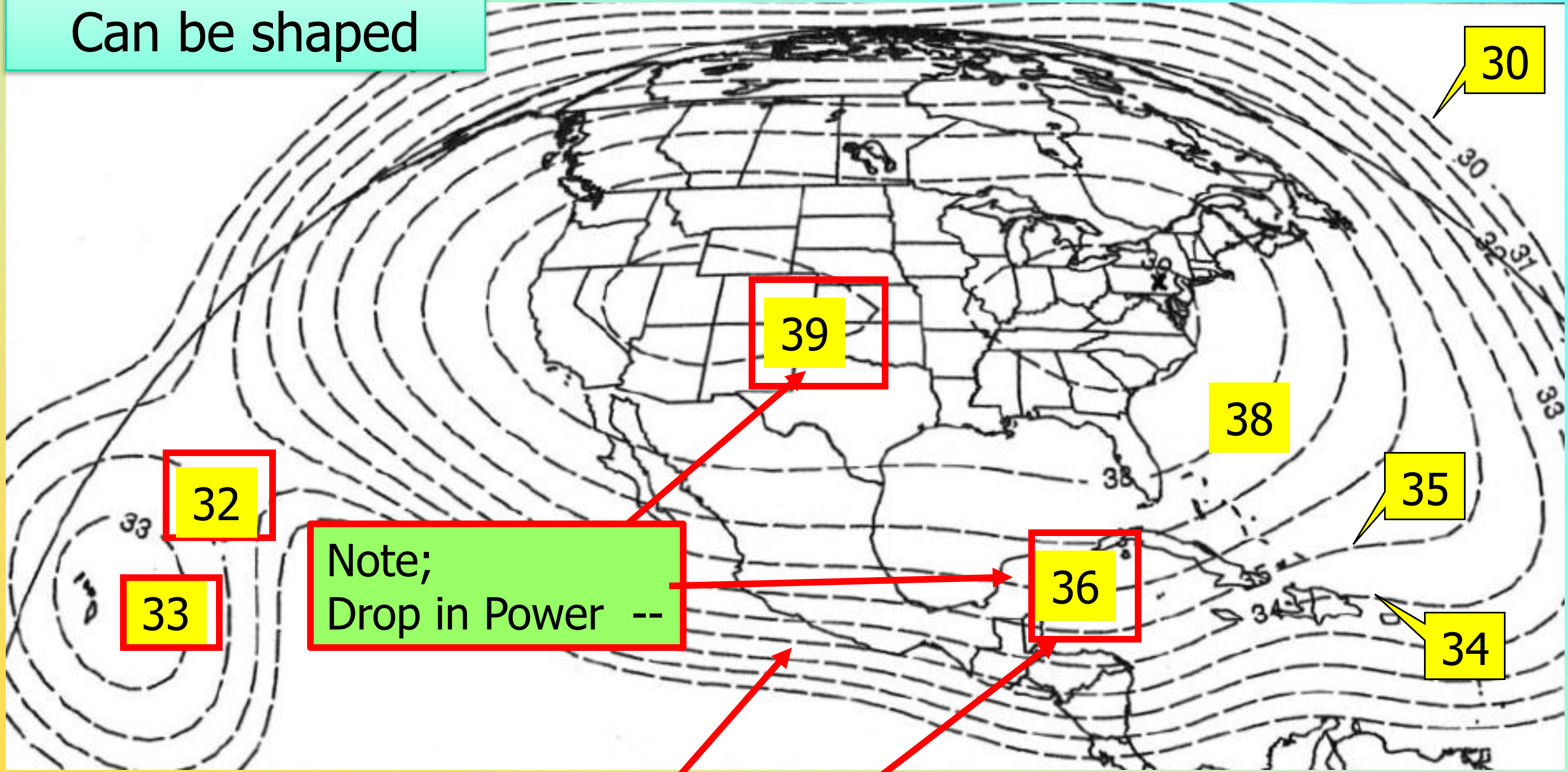
Equator

Earth

- Higher Orbits ➔ Larger Footprint
- Continuous coverage: At least one satellite is always in line of sight
  - LEO systems require a large number of satellites --

# **Antenna Coverage on Earth:** GEO Satellite Antenna Footprint

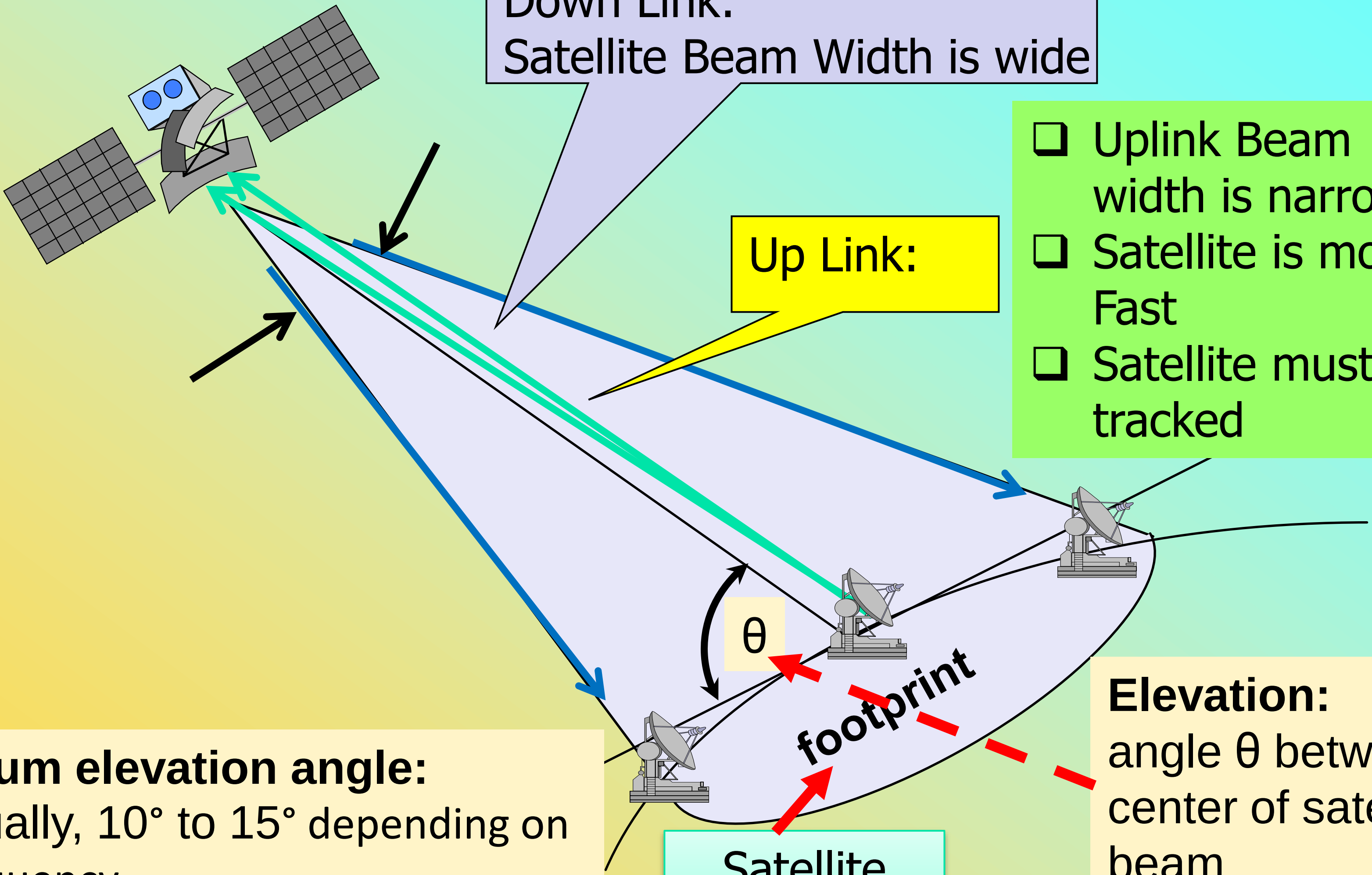
Antenna Footprint:
Can be shaped



Note;
Drop in Power --

- Contours are Radiated Power from the satellite
- Number is in decibels referred to 1Watt (dBW)
- Antenna Boresight power 39 dBW

# LEO Satellites:  Smaller Footprints



Down Link:
Satellite Beam Width is wide

Up Link:

- Uplink Beam width is narrow
- Satellite is moving Fast
- Satellite must be tracked

**Minimum elevation angle:**

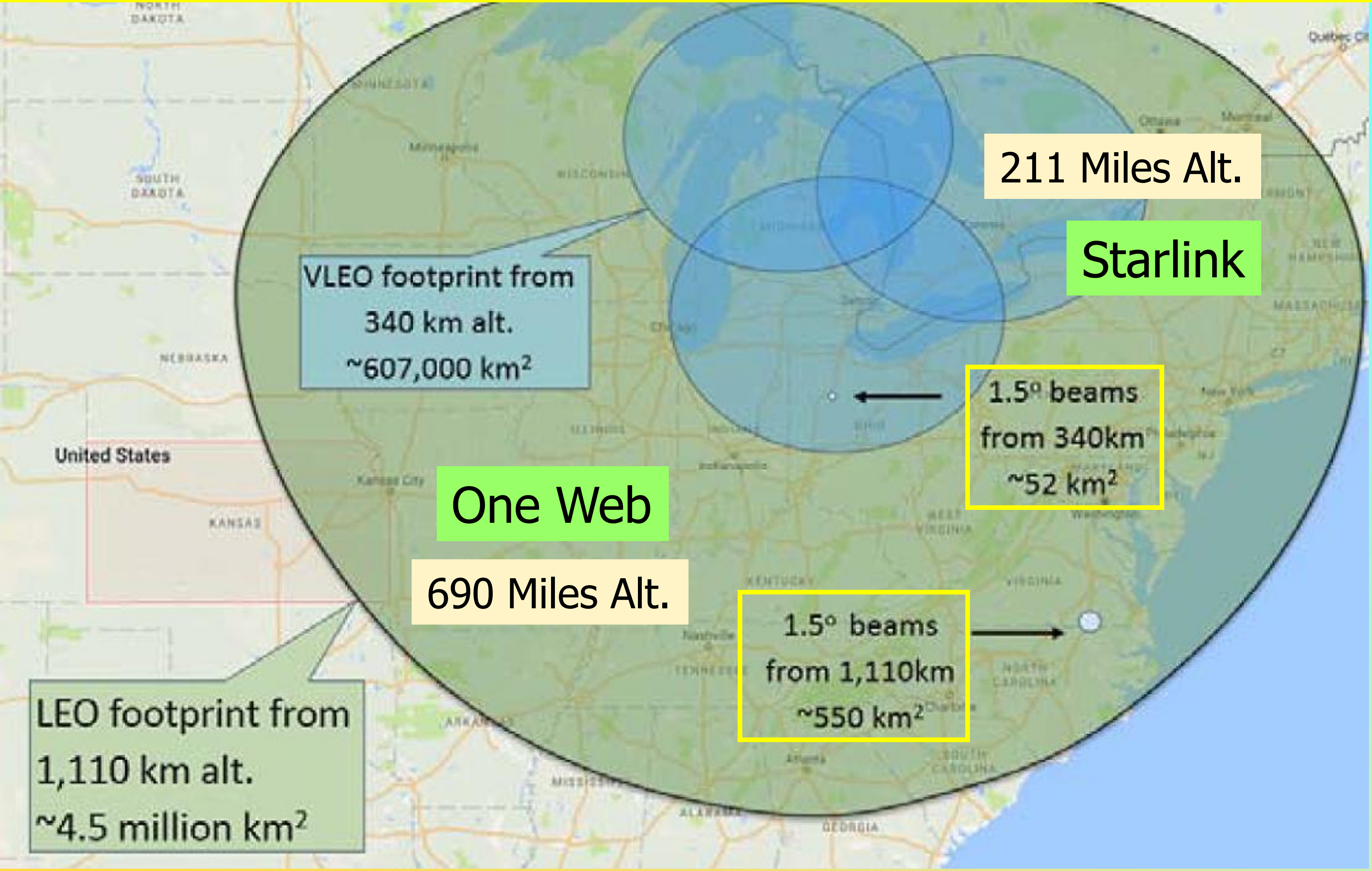
- Usually, 10° to 15° depending on
- Frequency
- Terrain

Satellite Footprint

**Elevation:**
angle θ between center of satellite beam
and surface

# LEO Satellite Footprints vs. Orbital Height

- Starlink requires more satellites than One Web for Earth Coverage
- One Web in this example requires 9 times the transmit power for = C/N --



211 Miles Alt.

**Starlink**

VLEO footprint from 340 km alt. ~607,000 km²

1.5° beams from 340km ~52 km²

**One Web**

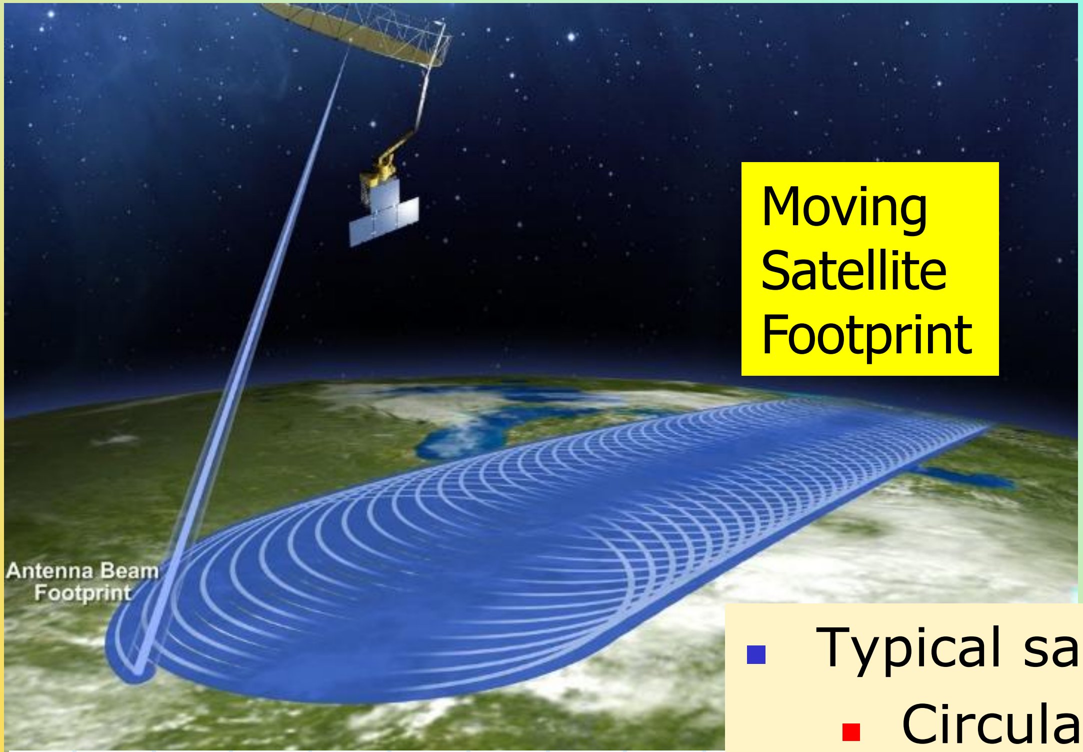
690 Miles Alt.

1.5° beams from 1,110km ~550 km²

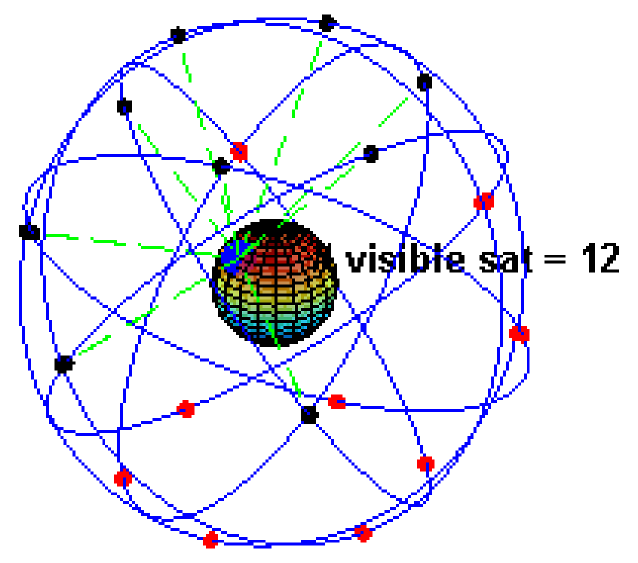
LEO footprint from 1,110 km alt. ~4.5 million km²

# Low Earth Orbit (LEO) Satellite Systems

## Global coverage: Requires a large number of satellites



Moving Satellite Footprint

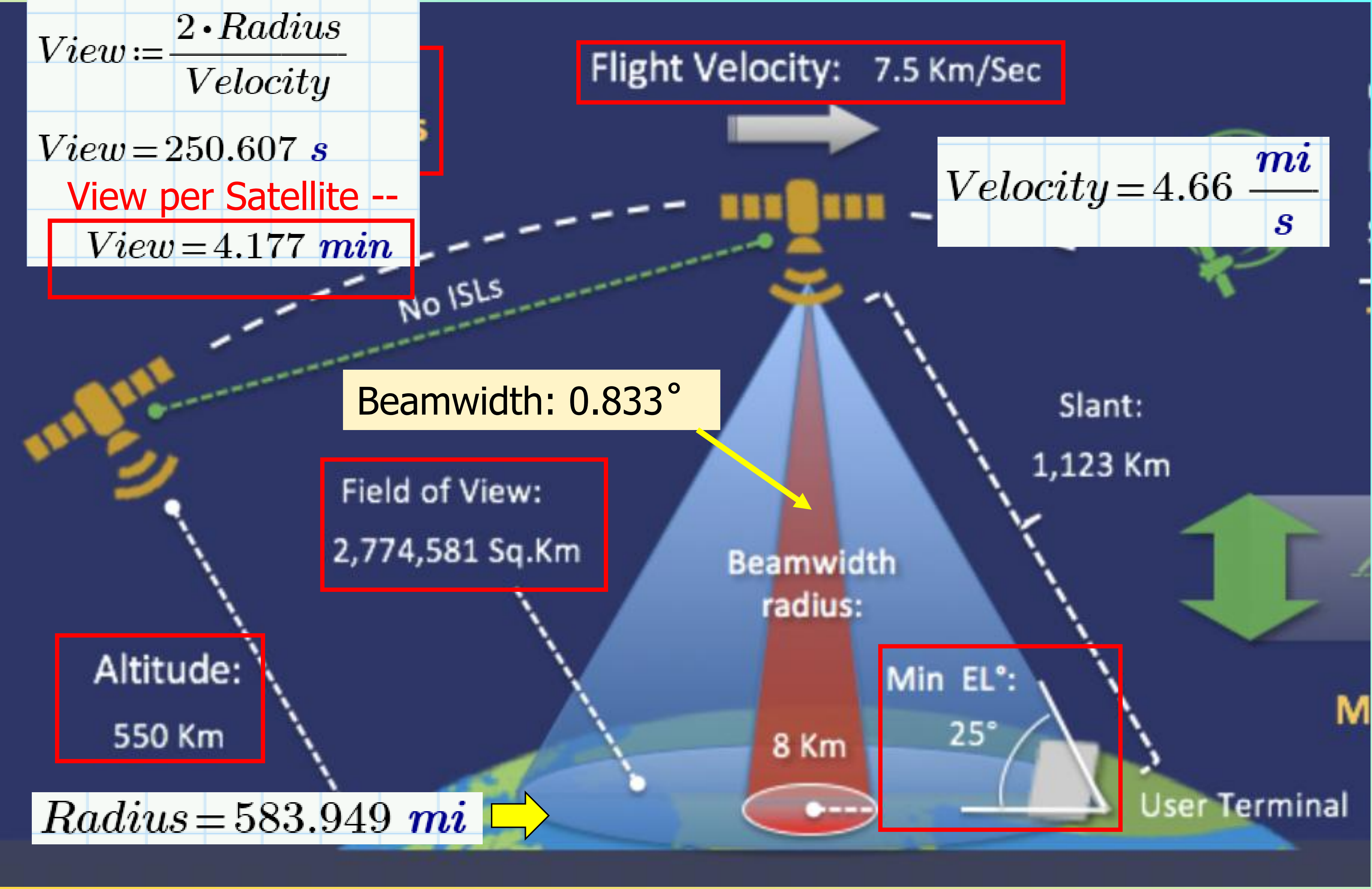


$$Velocity = 16777.022\ \frac{mi}{hr}$$

$$Velocity = 4.66\ \frac{mi}{s}$$

- Typical satellite positions
  - Circular orbit
  - Altitude: 150 to 500 Miles
- LEO’s travel faster than GEO’s
  - A typical 17,000 MPH
  - Revolution takes ≈ 90 minutes --

# Starlink LEO Earth Footprint: Time Satellite in View



$Radius = 583.949\ mi$

$$View := \frac{2 \cdot Radius}{Velocity}$$

$View = 250.607\ s$

View per Satellite --

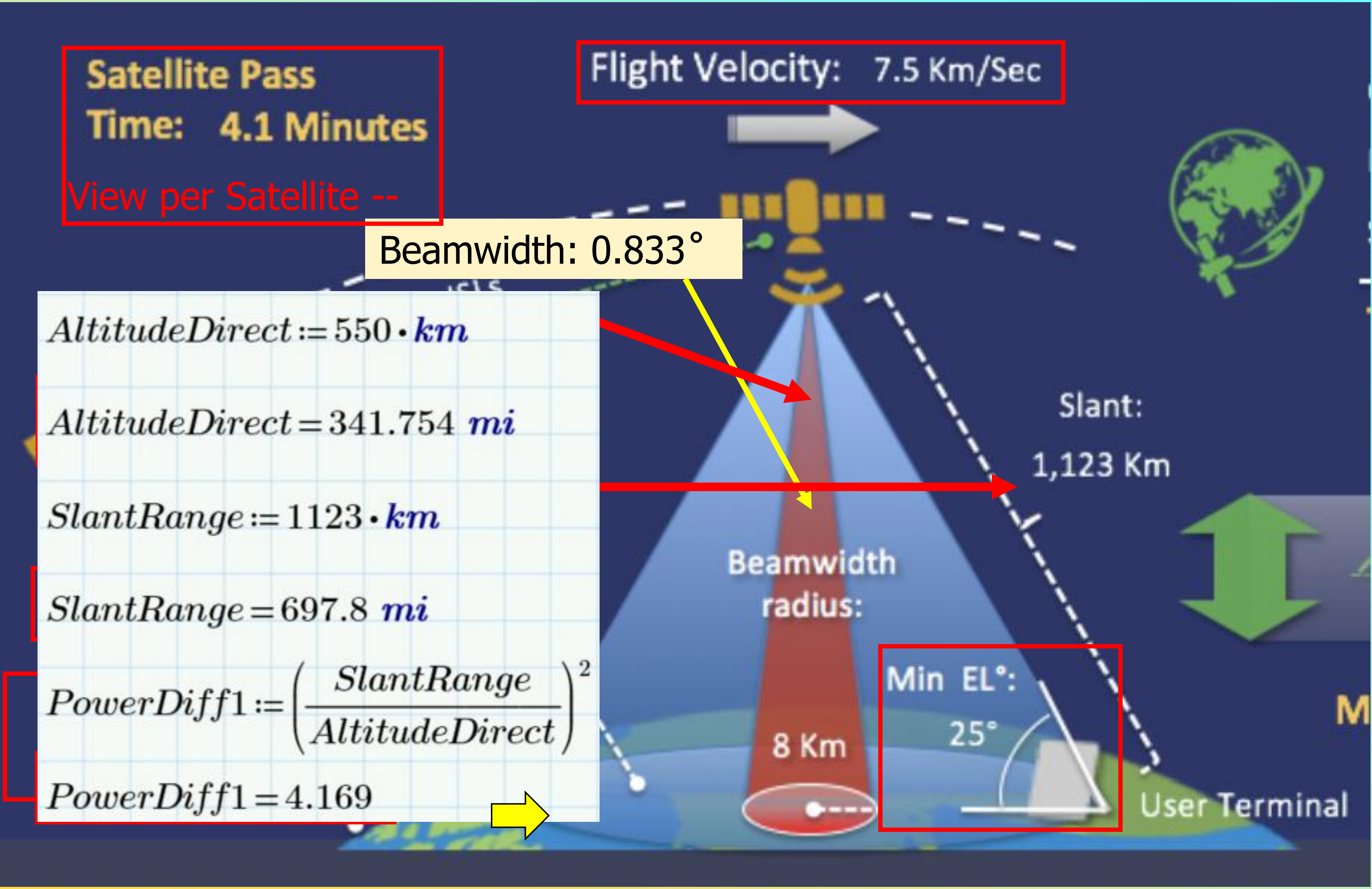
$View = 4.177\ min$

$$Velocity = 4.66\ \frac{mi}{s}$$

Beamwidth: 0.833°

$Radius = 583.949\ mi$

# Starlink LEO Earth Footprint: Relative Path Loss



View per Satellite --

Beamwidth: 0.833°

$$AltitudeDirect := 550 \cdot km$$

$$AltitudeDirect = 341.754\ mi$$

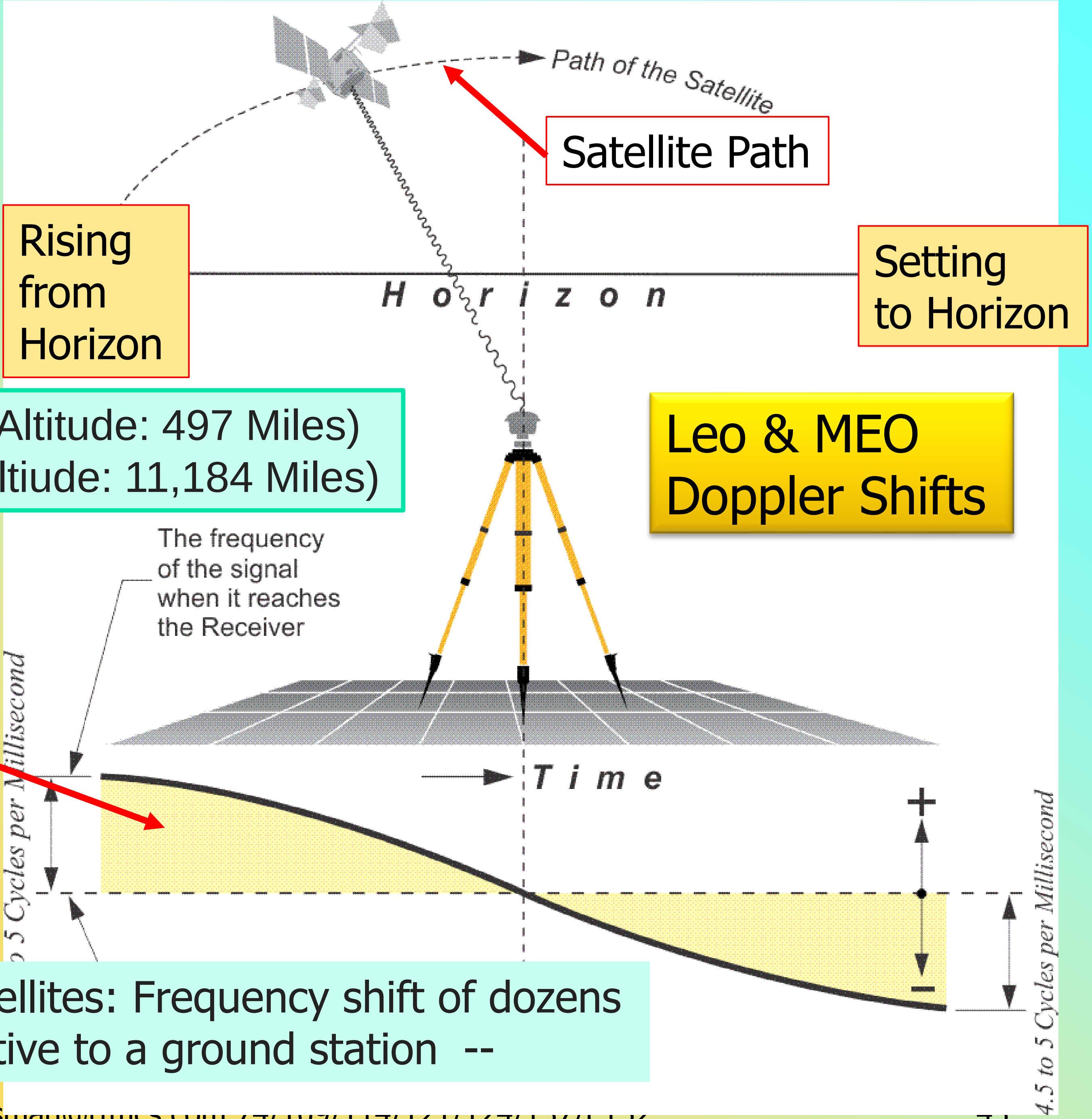
$$SlantRange := 1123 \cdot km$$

$$SlantRange = 697.8\ mi$$

$$PowerDiff1 := \left(\frac{SlantRange}{AltitudeDirect}\right)^2$$

$$PowerDiff1 = 4.169$$

Lower Earth Orbits ➔Faster Traveling of Satellites ➔ Larger Frequency Changes



Satellite Path

Rising from Horizon

Setting to Horizon

$V_{LEO}$: 16,665 MPH (Altitude: 497 Miles)
$V_{MEO}$: 8,694 MPH (Altiude: 11,184 Miles)

Leo & MEO Doppler Shifts

ΔFrequency of the signal at the Receiver

Fast moving satellites: Frequency shift of dozens of kilohertz relative to a ground station --

# 05: Satellite Communication Link

- ☐ **Satellite Link**
- ☐ **Effective Isotropic Radiated Power (EIRP)**
- ☐ **Path Loss (PL)**
- ☐ **Thermal Noise**
- ☐ **Receiver Gain/Noise Temperature (G/T)**
- ☐ **Carrier to Noise Ratio (C/N)**
- ☐ **Bit Error Rate (BER)**
- ☐ **Error Detection**

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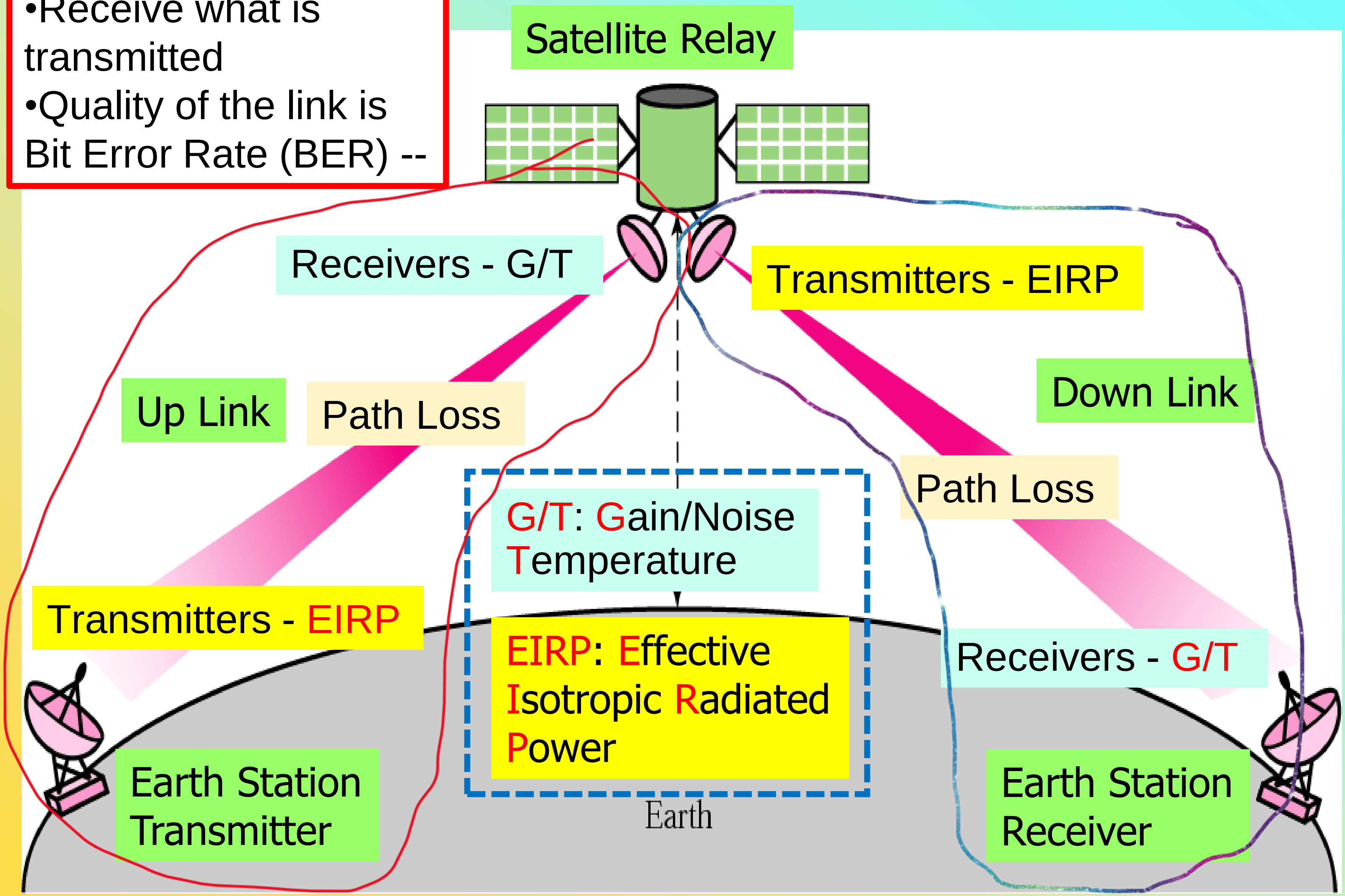
# Satellite Link

- Receive what is transmitted
- Quality of the link is Bit Error Rate (BER) --



Satellite Relay

Receivers - G/T

Transmitters - EIRP

Up Link

Path Loss

Down Link

Path Loss

G/T: Gain/Noise Temperature

Transmitters - EIRP

EIRP: Effective Isotropic Radiated Power

Receivers - G/T

Earth Station Transmitter

Earth Station Receiver

Earth

# Typical Satellite Link Block Diagram: Ku Band

Ground Transmitted Frequency Greater than Satellite Transmit Frequency --

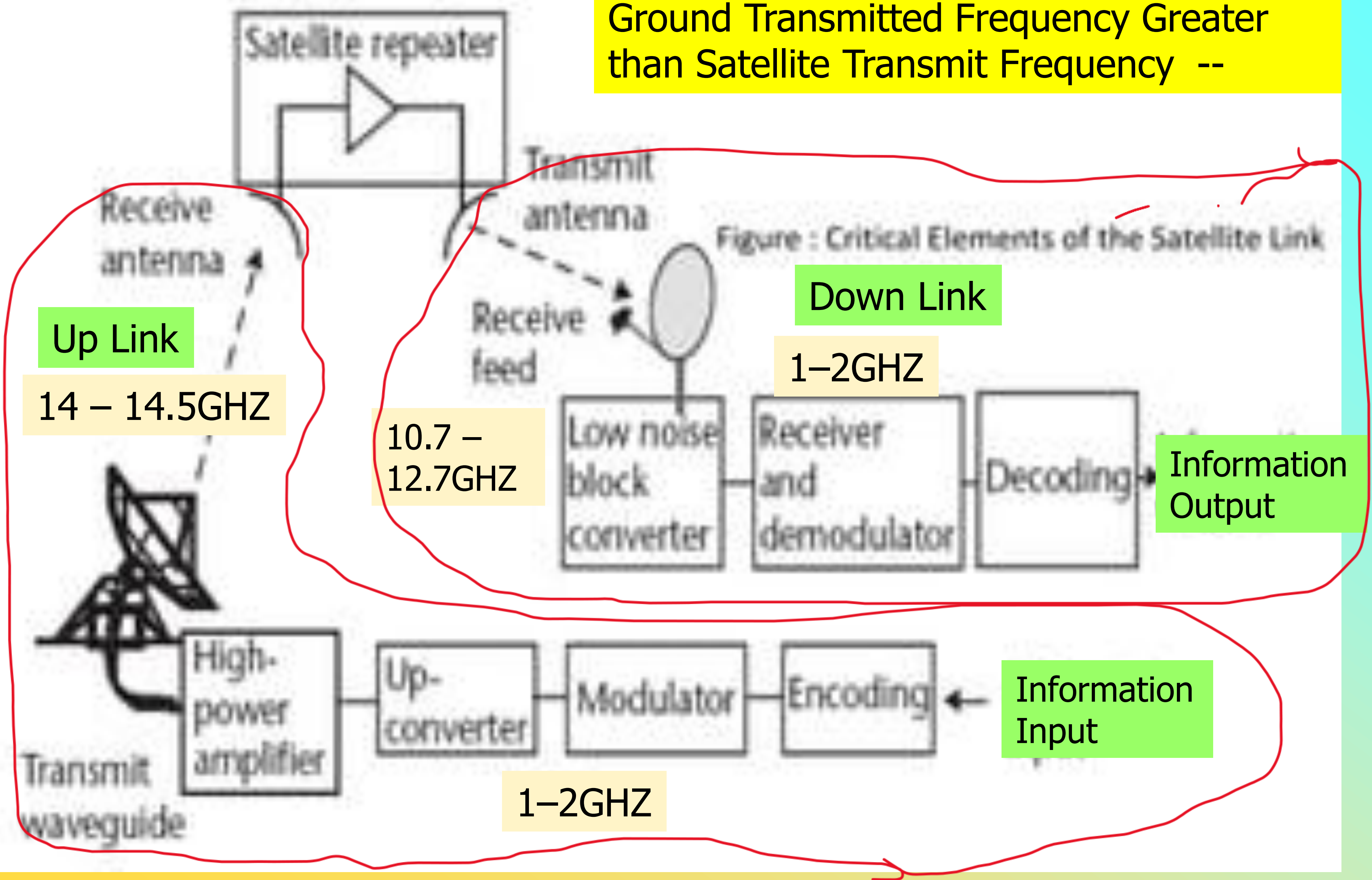


Figure : Critical Elements of the Satellite Link

Up Link

14 – 14.5GHZ

Down Link

1–2GHZ

10.7 – 12.7GHZ

Information Output

Information Input

1–2GHZ

# Design Factors to Consider in a Communications Link

Goal is $C/N_0$ → Bit Error Rates, (BER)

- EIRP
  - Effective Isotropic Radiated Power
  - Antenna Gain x Output Power
- Path Loss
  - Distance to Satellite
  - 150 Miles to ≈ 23,000 miles
  - Weather effects
- G/T
  - Antenna Gain divided by Noise Temperature
- Using Minimum Bandwidth (B)
  - Bandwidth is costly
- Signal Tracking
  - LEO Satellites are fast moving --

☐ *K:* Boltzmann constant
☐ *T: Temperature (°K)*
☐ *B: Bandwidth (Hz)*

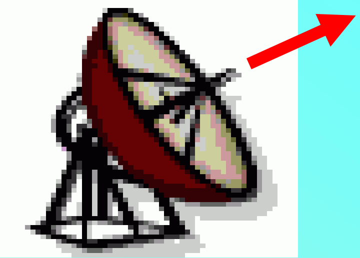
--

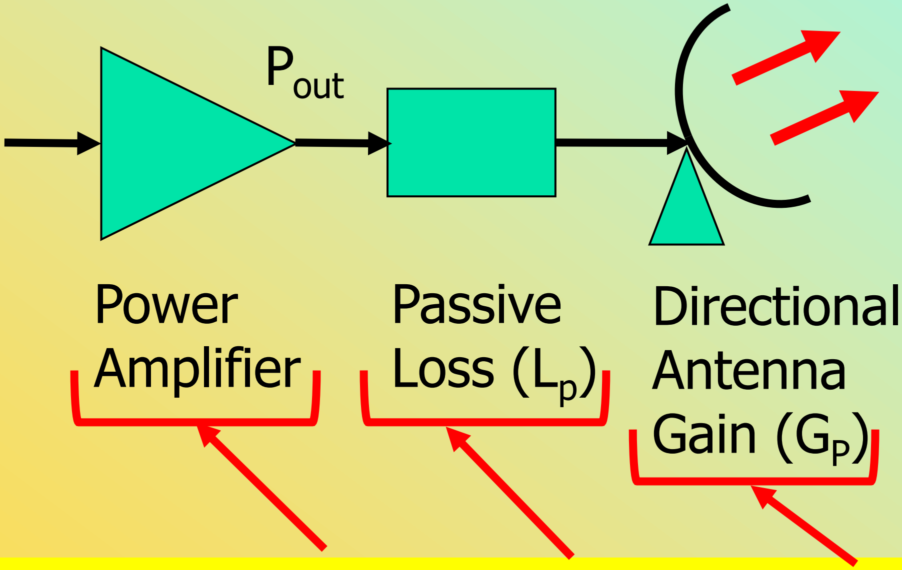
$$C/N[dB] = EIRP\ [dBm] - (Path\ Loss[dB]) + G/T[dB] - 10 \cdot Log(k \cdot T \cdot B)\ [dBm]$$

# Signal Transmission – EIRP

**EIRP: Effective Isotropic Radiated Power**

Power emitted from an antenna assuming the power is the same in all directions





$P_{out}$

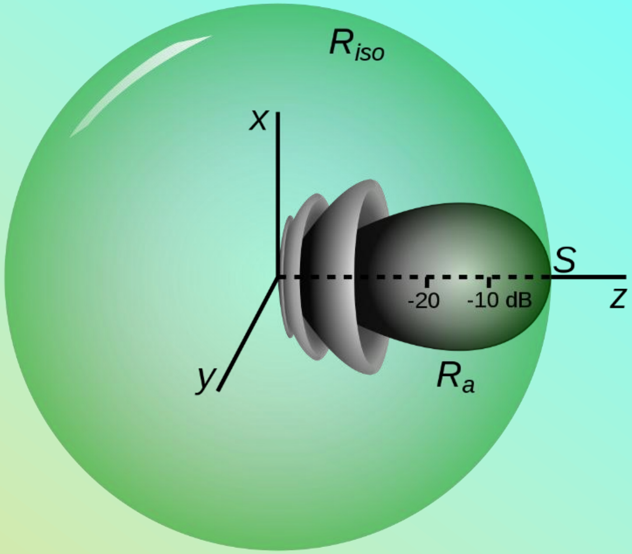
Power Amplifier

Passive Loss ($L_p$)

Directional Antenna Gain ($G_P$)

$$\text{EIRP (dBW)} = P_{out}\text{(dBW)} - L_p\text{(dB)} + G_p\text{(dB)}$$

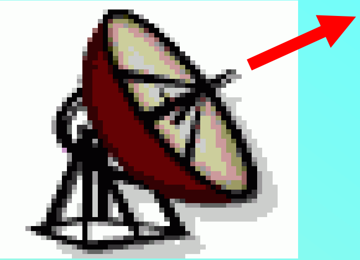
--

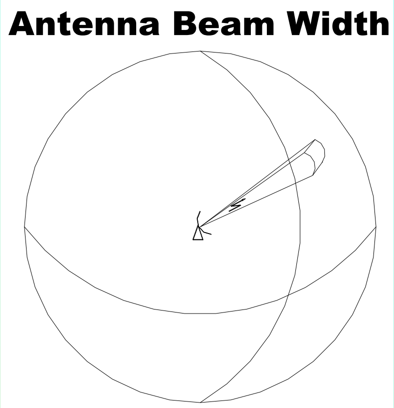


Isotropic Radiator

# Signal Transmission – EIRP

- Once the EIRP is known, no additional information about the transmitter is required
  - Assumes the antenna boresight is pointed at the receiver
- Output power is concentrated in a small solid angle
- EIRP includes the effects of:
  - Antenna Gain
  - Antenna Efficiencies
  - Transmitter Output Power
  - Coupling and Wave Guide Losses, Etc. --



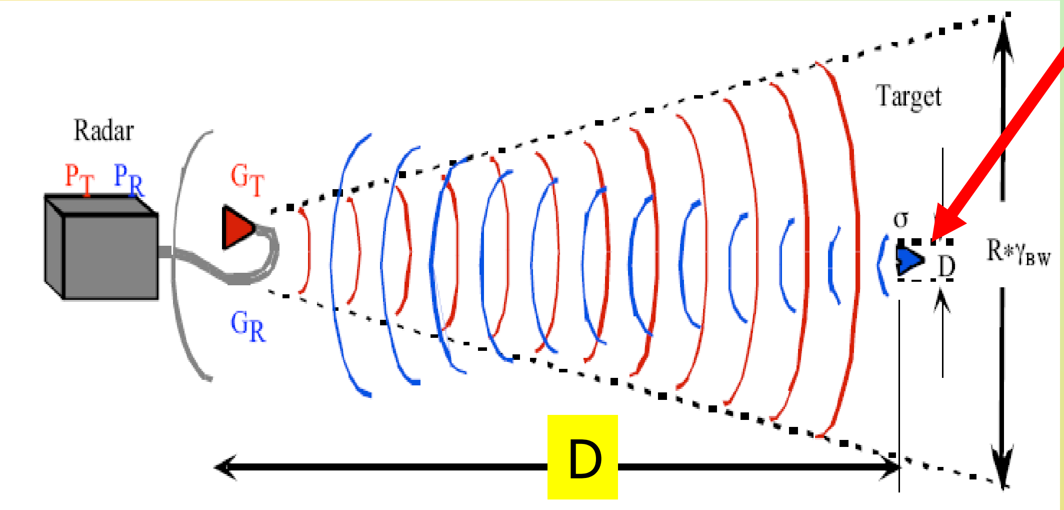


Isotropic Radiator

# Calculating Path Loss (PL)

## Path Loss ($P_L$) to the Satellite

- Signal radiates out from a point source
- Electromagnetic Field (Flux) Density is less at receiving antenna as the distance increases
- Path Loss is actually a dispersion of the transmitted signal



Receiving antenna sees less of the wave front as the distance increases

$$\text{Path Loss "}P_L\text{"} = \left(\frac{4\pi D}{\lambda}\right)^2$$

"λ" is the wavelength
"D" is the Distance Traveled

Path Loss in dB = $10 \cdot \mathrm{Log}(P_L)$ --

# Free Space Loss

- Free space loss

$$\frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2} \Rightarrow L_{dB} = 10\log\frac{P_t}{P_r} = 20\log\left(\frac{4\pi d}{\lambda}\right)$$

- $P_t$ = signal power at transmitting antenna
- $P_r$ = signal power at input to receiving antenna
- $\lambda$ = carrier wavelength
- $d$ = propagation distance between antennas
- $c$ = speed of light ($\approx 3 \cdot 10^8$ m/s)
- Note: $d$ and $\lambda$ are in the same units (e.g., meters)

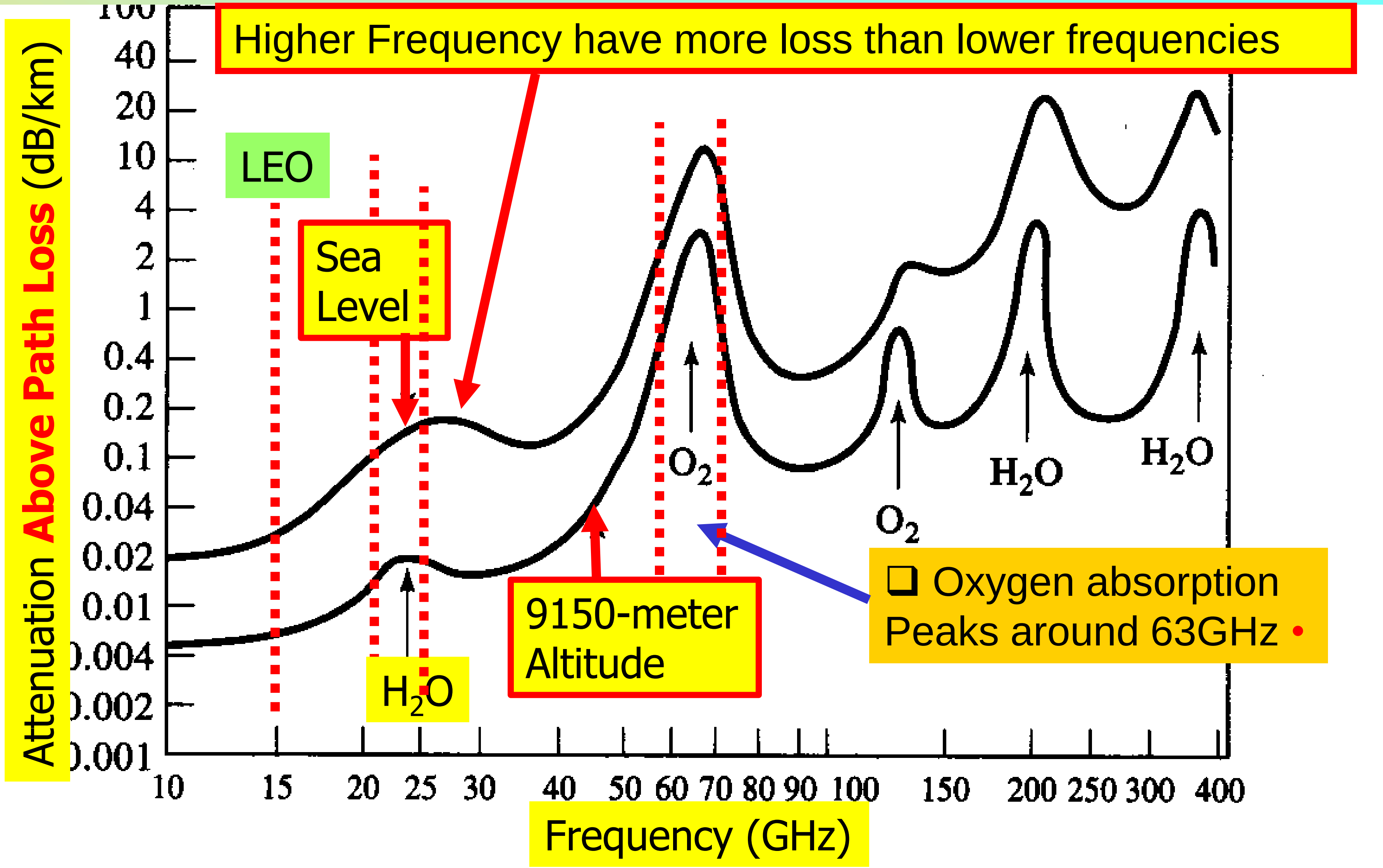
# Free Space Loss Including Antenna Gain

- Free space loss accounting for antenna gain

$$\frac{P_t}{P_r} = \frac{(4\cdot\pi)^2(d)^2}{G_r\cdot G_t\cdot\lambda^2} = \frac{(\lambda\cdot d)^2}{A_r\cdot A_t} = \frac{(c\cdot d)^2}{f^2\cdot A_r\cdot A_t}$$

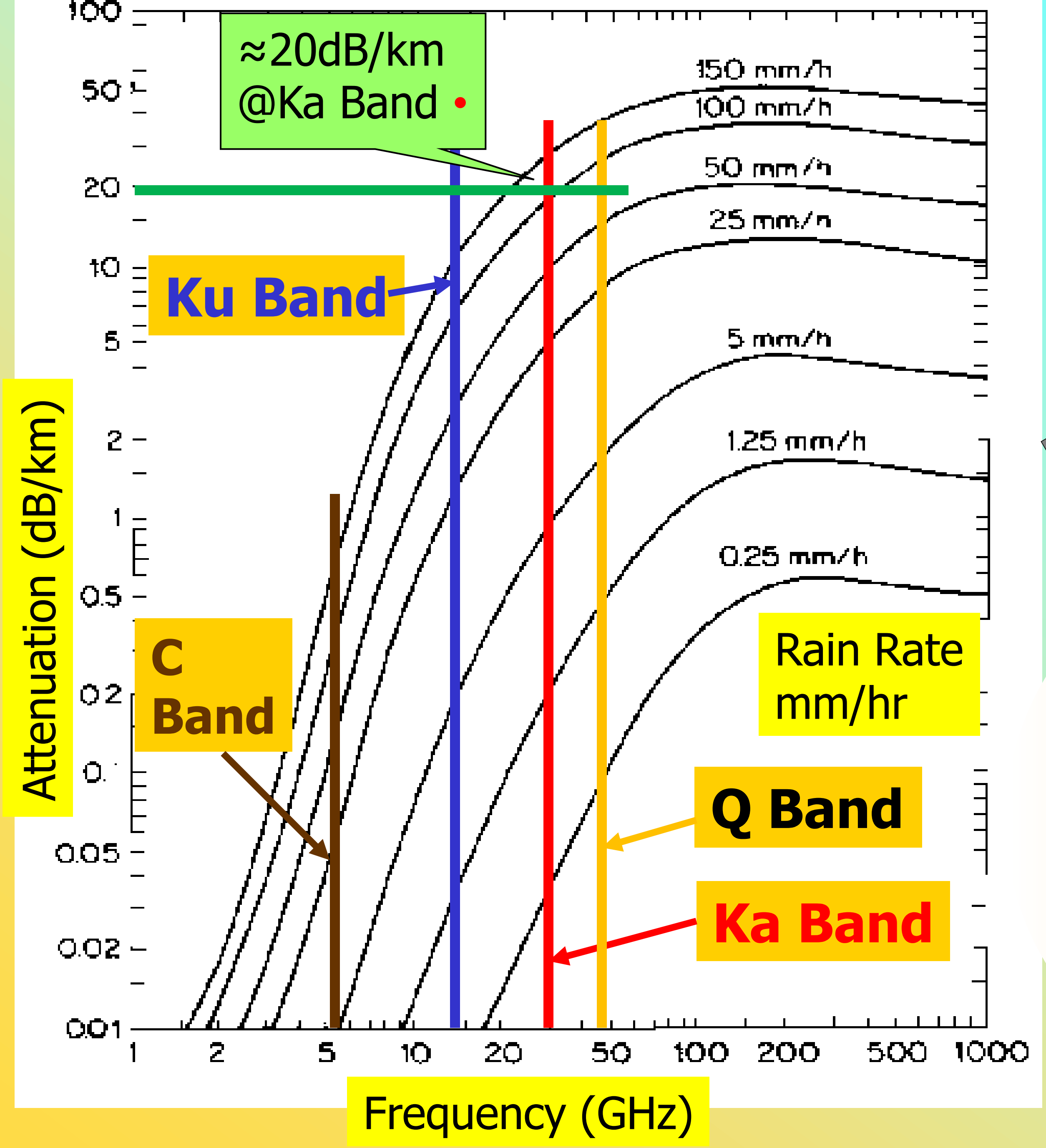
  - $G_t$ = gain of transmitting antenna
  - $G_r$ = gain of receiving antenna
  - $A_t$ = effective area of transmitting antenna
  - $A_r$ = effective area of receiving antenna
  - $d$ = propagation distance between antennas
  - $c$ = speed of light ($\approx 3\cdot10^8$ m/s)
  - $\lambda$ = carrier wavelength

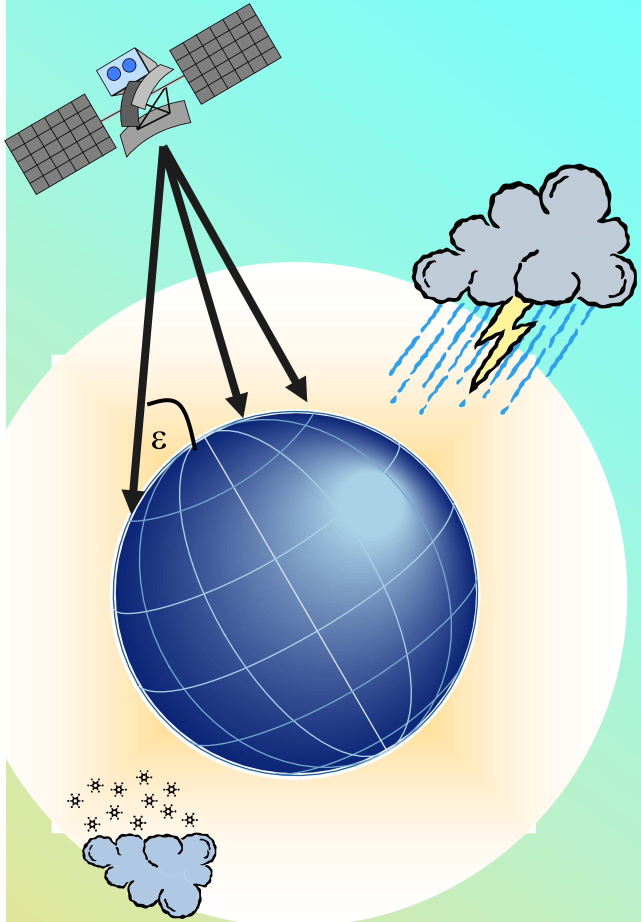
# Atmospheric Attenuation vs. Frequency (Horizontal Polarization): Clear Sky



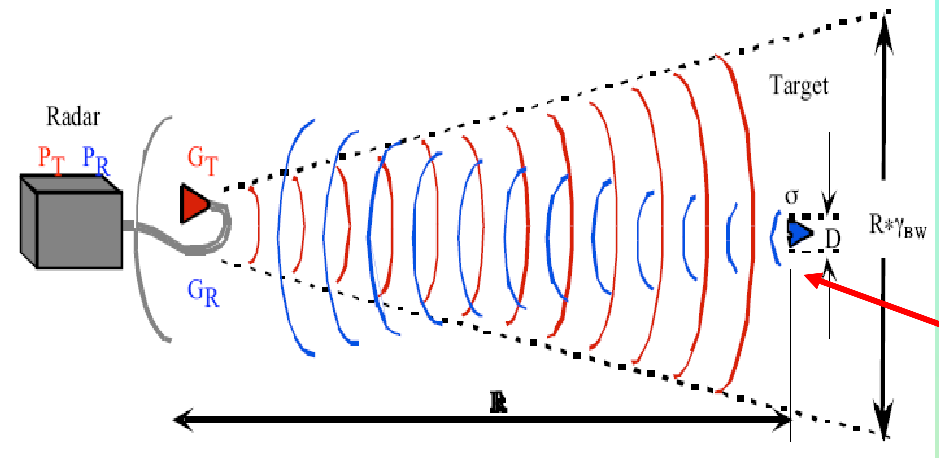
hhausman@rfmcs.com 74/109/114/121/124/137/E152

# Rain Attenuation





# Signal Reception - G/T and C/N



Receive Antenna Gain (G): Larger the receive antenna the more signal captured --

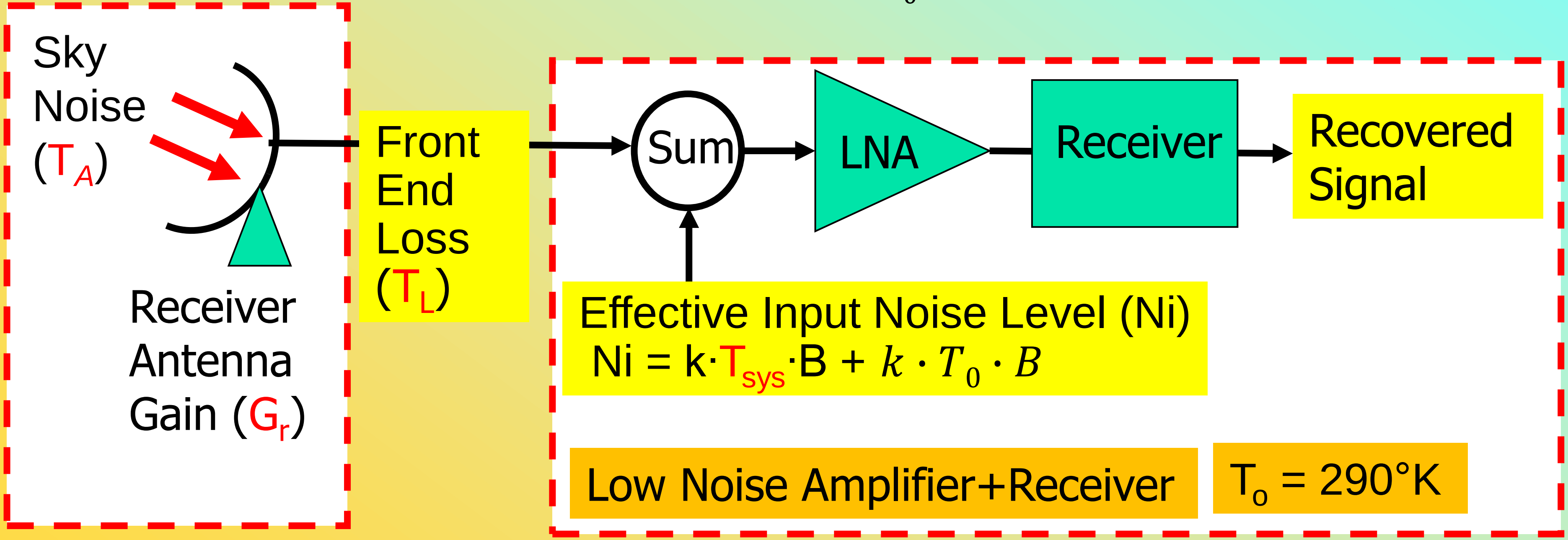
- C/N is key to determining Bit Error Rates (BER)
- C/N can be found at the Receiving antenna knowing:
  - Signal level at the receive antenna [EIRP(dBm) –Path Loss (dB)]
  - G/T of the receiver
    - G/T includes System Noise Figure
  - No other information is necessary
- Signal into the antenna is increased by G/T (dB)
- $C/N\ (\mathrm{dB}) = \mathrm{EIRP(dBm)} - \mathrm{Path\ Loss\ (dB)} + \underbrace{G/T\ (\mathrm{dB})}_{\text{Includes NF}} + \underbrace{k\cdot T\cdot B\ (\mathrm{dBm})}_{\text{Thermal Noise}}$

# Signal Reception - G/T

- G/T ➔ $G_r/T_{sys}$ ➔ Receiver Antenna Gain (Gr) divided by Effective Noise temperature (*T*sys) of the receiving system (Linear units)
- Gr/*T*sys (dB) = Antenna Gain (dB) – Noise Temperature (dB)
  - Gr/*T*sys (dB) = Antenna Gain (dB) – 10·Log(*T*sys/1°K) --

$$Noise\ Factor\ of\ the\ Amplifier = Famp = \frac{k \cdot T_{sys} \cdot B + k \cdot T_0 \cdot B}{k \cdot T_0 \cdot B}$$

$$\text{Total Noise Factor } (F) = 1 + \frac{T_{sys}}{T_0} \Rightarrow T_{sys} = (F-1) \cdot T_o \text{ --}$$



Sky Noise ($T_A$)

Receiver Antenna Gain ($G_r$)

Front End Loss ($T_L$)

Sum

LNA

Receiver

Recovered Signal

Effective Input Noise Level (Ni)

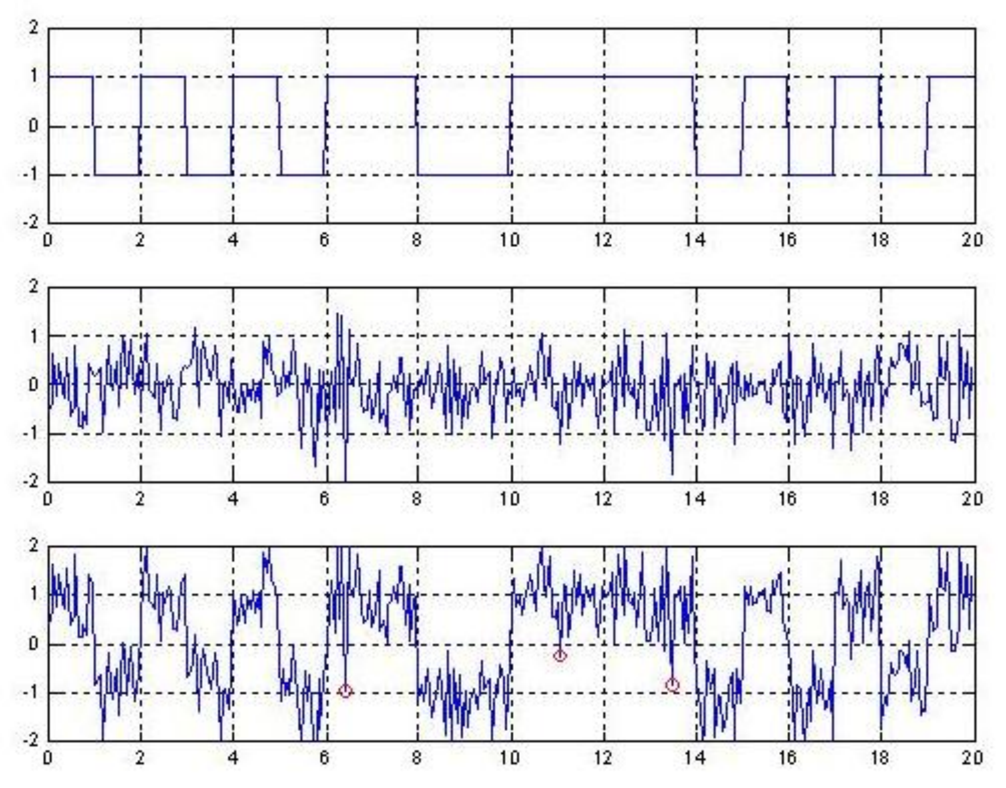
$Ni = k \cdot T_{sys} \cdot B + k \cdot T_0 \cdot B$

Low Noise Amplifier+Receiver

$T_o$ = 290°K

# Thermal Noise

- Thermal Noise also called Johnson Noise
- Noise is a random voltage fluctuation ($V_{RMS}$)
  - Produced by the thermal agitation of electrons
- Thermal noise accumulates in every communications link function



Binary Signal

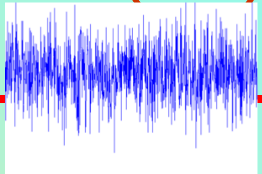
Thermal Noise

Signal + Noise

Original binary signal must be recovered from the received signal + noise --

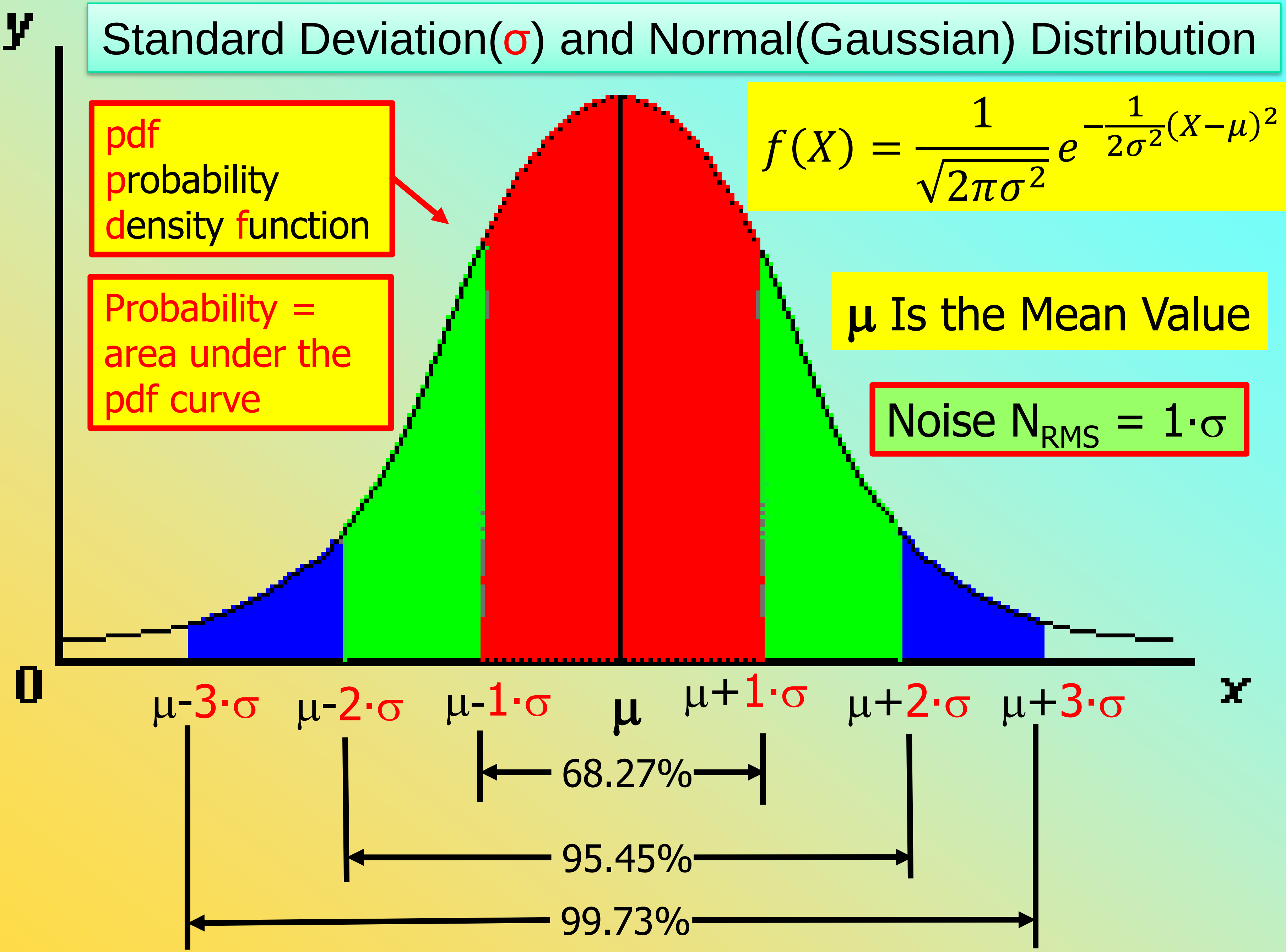
# Thermal Noise Power

- Noise level completely unknown at any instant of time
- Average is precisely known over any time period >> 1/B
  - bandwidth = B
- Noise Voltage is a Gaussian Probability Density Function (pdf)
  - Noise Voltage ($N_{RMS}$ ) is a one standard deviation ($1 \cdot \sigma$) of the Gaussian probability function



- At Room temperature 25°C ≈ 298°K
  - $k \cdot T = 4.11 \times 10^{-18}$ milliWatts in a 1 Hertz Bandwidth
    - $k \cdot T \approx -173.859$ dBm/Hz (≈ -174dBm/Hz)
    - Noise Power is -174dBm in a normalized 1 Hz Band (B=1Hz) --

# Standard Deviation(σ) and Normal(Gaussian) Distribution



pdf
probability
density function

Probability =
area under the
pdf curve

$$f(X) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2\sigma^2}(X-\mu)^2}$$

**μ** Is the Mean Value

Noise $N_{RMS}$ = 1·σ

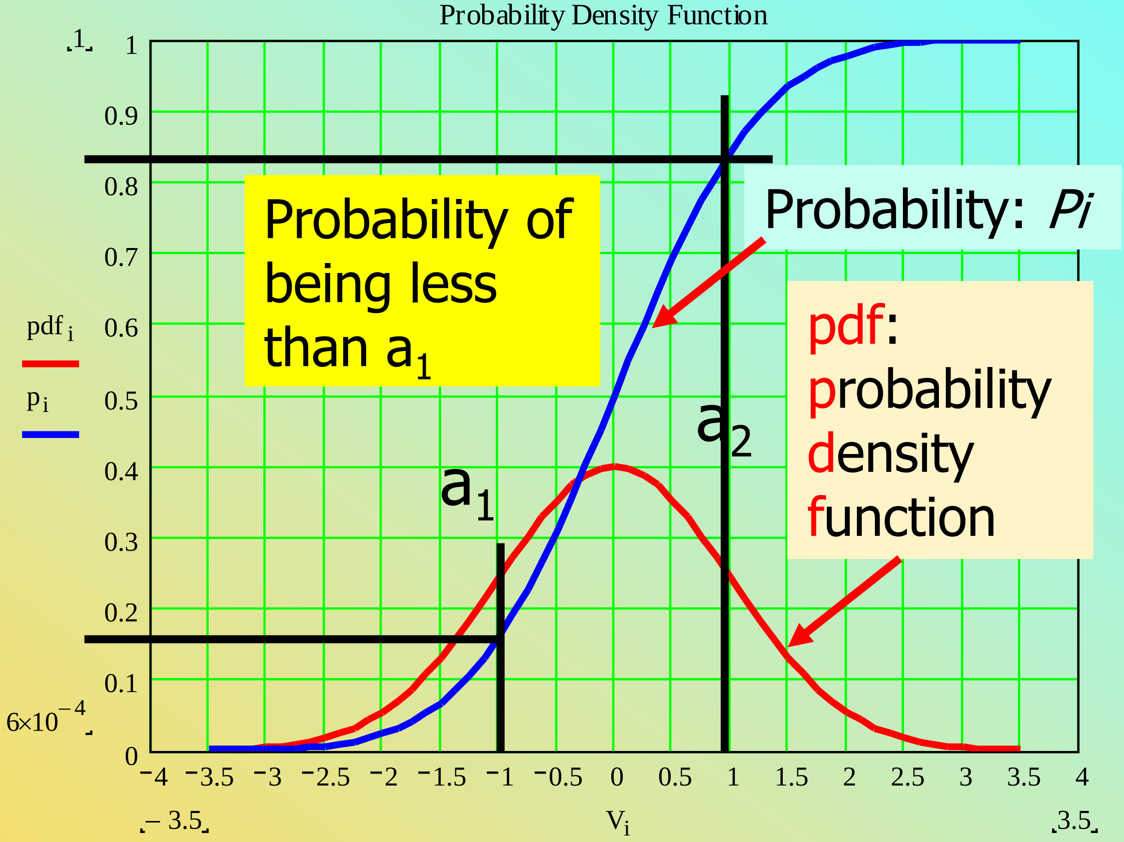
# Probability, Standard Deviation & RMS Noise

- Probability of being less than $a_1$
- Area of pdf curve from -∞ to $a_1$
- Probability of being between a1 & a2
    - P(a2) –P(a1)
- $V_i$ = 0 (Mean), probability = .5

$$P_i = \frac{1}{\sqrt{2\pi\sigma^2}} \int_{-\infty}^{a_i} e^{-\frac{(V_i-\mu)^2}{2\sigma^2}} dV_i$$

- ❑ μ is Average (Mean)
- ❑ σ=standard deviation (Relates to the function spreading)

- $P(V_i < -1\sigma) = .159$
- $P(V_i > 1\sigma) = 1 - .841 = .159$
- $P(V_i < -1\sigma \,\&\, V > +1\sigma) = .682$
- $P(>|1\sigma|) = .318$
- $P(>|2\sigma|) = .046$
- $P(>|3\sigma|) = 2.7\text{x}10^{-3}$
- $P(>|4\sigma|) = 6.3\text{x}10^{-5}$
- $P(>|5\sigma|) = 5.7\text{x}10^{-7}$ --



Probability of being less than $a_1$

Probability: *Pi*

pdf: probability density function

# Table of Noise Temperature vs. Noise Figure

| To | 290 | Deg K |
|---|---|---|
| **Te** | **F** | **NF** |
| **Deg K** | | **dB** |
| **10** | 1.034 | 0.147 |
| **20** | 1.069 | 0.290 |
| **40** | 1.138 | 0.561 |
| **70** | 1.241 | 0.939 |
| **100** | 1.345 | 1.287 |
| **150** | 1.517 | 1.811 |
| **200** | 1.690 | 2.278 |
| **250** | 1.862 | 2.700 |
| **300** | 2.034 | 3.085 |
| **400** | 2.379 | 3.765 |
| **500** | 2.724 | 4.352 |
| **700** | 3.414 | 5.332 |

| To | 290 | Deg K |
|---|---|---|
| **NF** | **F** | **Te** |
| **dB** | | **Deg K** |
| **0.100** | 1.023 | 6.755 |
| **0.200** | 1.047 | 13.667 |
| **0.300** | 1.072 | 20.741 |
| **0.400** | 1.096 | 27.979 |
| **0.500** | 1.122 | 35.385 |
| **0.600** | 1.148 | 42.965 |
| **0.700** | 1.175 | 50.720 |
| **0.800** | 1.202 | 58.657 |
| **0.900** | 1.230 | 66.778 |
| **1.000** | 1.259 | 75.088 |
| **1.100** | 1.288 | 83.592 |
| **1.200** | 1.318 | 92.294 |

$$NF = 10 \cdot \mathrm{Log}_{10} \left[1 + \frac{T_e}{T_0}\right]$$

Standard Temperature = To=290°K -

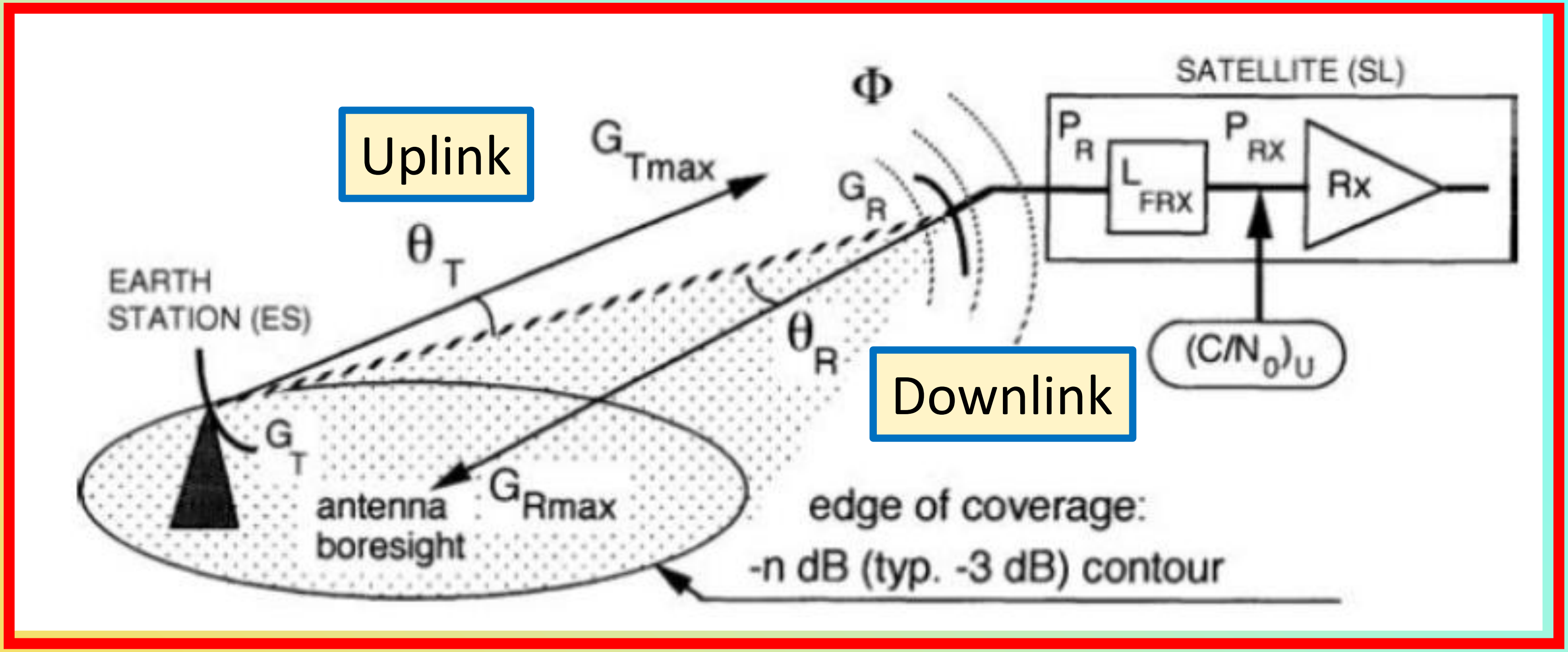
# Carrier to Noise: C/N

- C/N is key to determining Bit Error Rates (BER)

- C/N can be found at the Receiving antenna knowing:
  - Signal level into the receive antenna
  - G/T of the receiver
  - No other information is necessary
- Signal into the antenna is increased by G/T (dB)
- C/N (dB) = Signal (Carrier) Level (dBm) + G/T (dB) with respect to Thermal Noise (k·T·B in dBm)

$$C/N\ (\text{dB}) = \overbrace{\text{Carrier [dBm]}}^{\text{Carrier Level into antenna}} + \overbrace{G/T[\text{dB}]}^{\text{Receiver } G/T} - \overbrace{10\cdot \text{Log}(k\cdot T\cdot B)\ [\text{dBm}]}^{\text{Thermal Noise}} \quad \text{--}$$

# C/N: Carrier to Noise Ratio at Receiver Input



$C/N_0$=(EIRP)(1/L)·(G/T)· (1/k) / Hz

Atmosphere Loss: $L_A$

Free space Loss: $L_{FS}$

- Effective Isotropic Radiated Power: (EIRP = $P_T \cdot G_T$)
- Path loss: $L = L_A \cdot L_{FS}$
- Gain/Noise Temperature: G/T
  - Noise : $k \cdot T = N_0$ /Hz
  - *k* is the Boltzmann constant --

# Ultimate Link Goal: Bit Error Rate (BER)

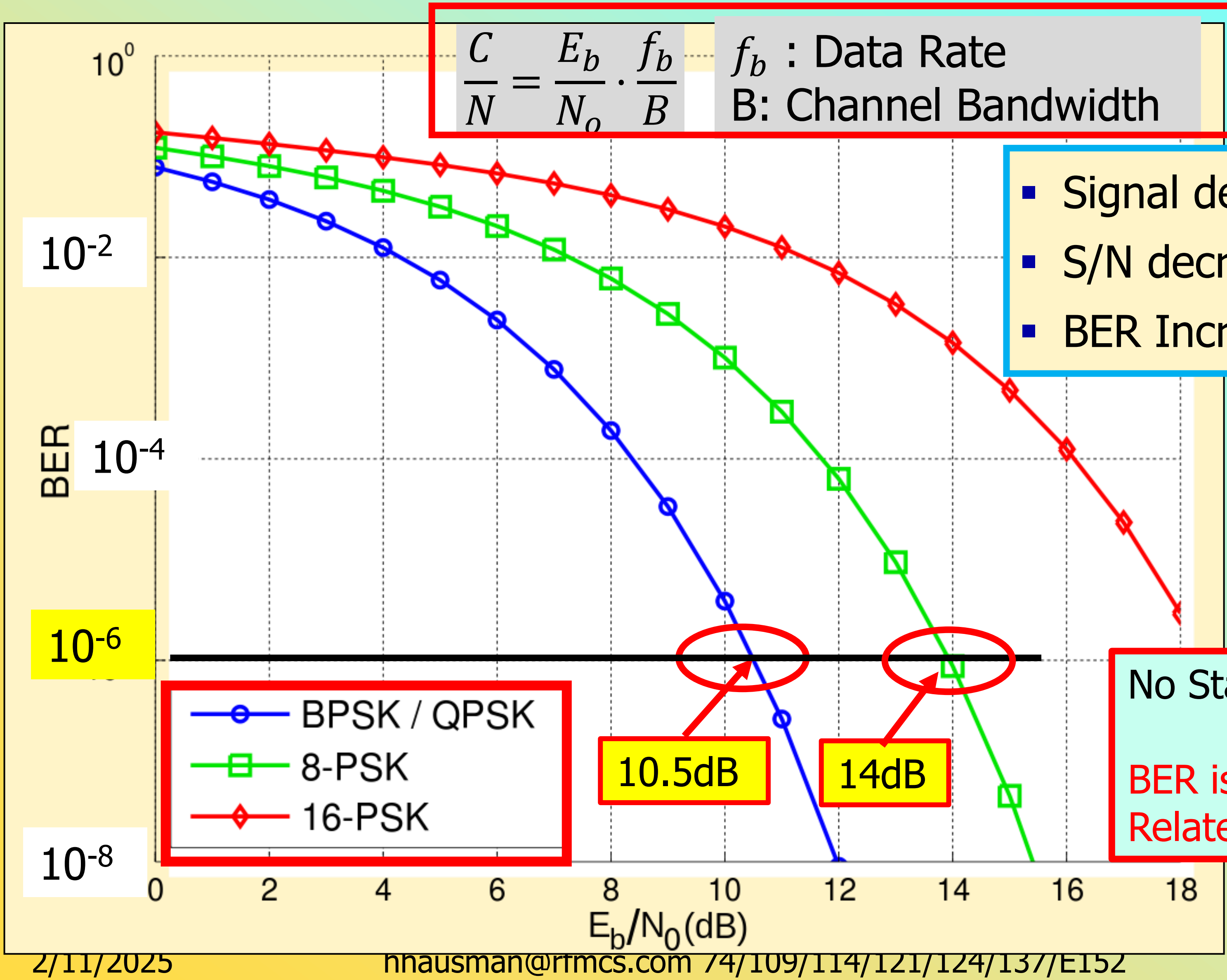
Bit Error Rate ➔ Carrier to Noise Ratio (C/N) ➔ $E_b/N_o$

$$\frac{C}{N} = \frac{E_b}{N_o} \cdot \frac{f_b}{B}$$

$f_b$ : Data Rate
B: Channel Bandwidth

$$f_b \geq B$$

- Signal decreases ⇩
- S/N decreases ⇩
- BER Increases ⇧



10.5dB

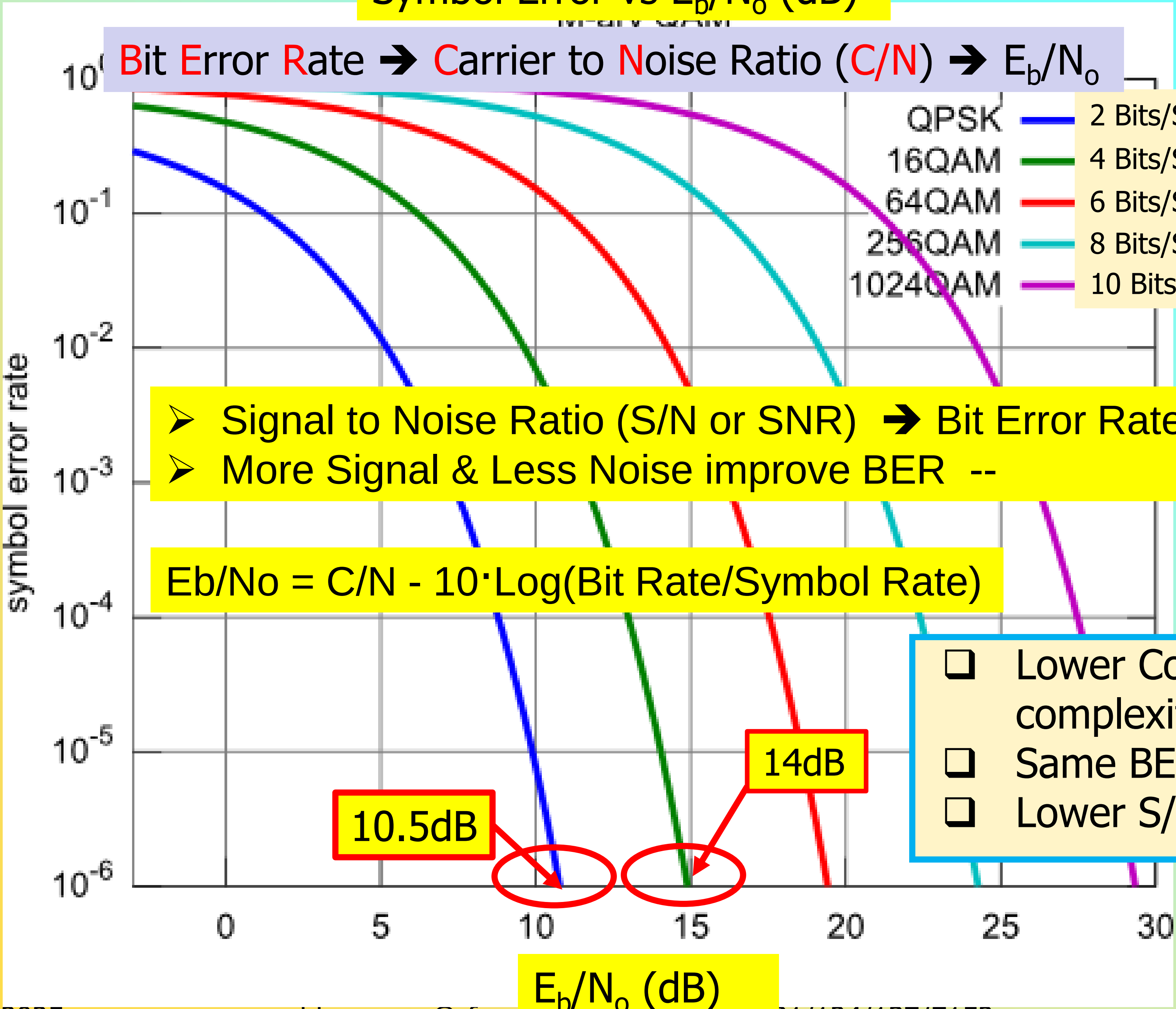
14dB

No Standard for BER

BER is Application Related --

# Symbol Error vs $E_b/N_o$ (dB)

## Bit Error Rate ➔ Carrier to Noise Ratio (C/N) ➔ $E_b/N_o$



| | |
|---|---|
| QPSK | 2 Bits/Symbol |
| 16QAM | 4 Bits/Symbol |
| 64QAM | 6 Bits/Symbol |
| 256QAM | 8 Bits/Symbol |
| 1024QAM | 10 Bits/Symbol |

- ➢ Signal to Noise Ratio (S/N or SNR) ➔ Bit Error Rates (BER)
- ➢ More Signal & Less Noise improve BER --

Eb/No = C/N - 10·Log(Bit Rate/Symbol Rate)

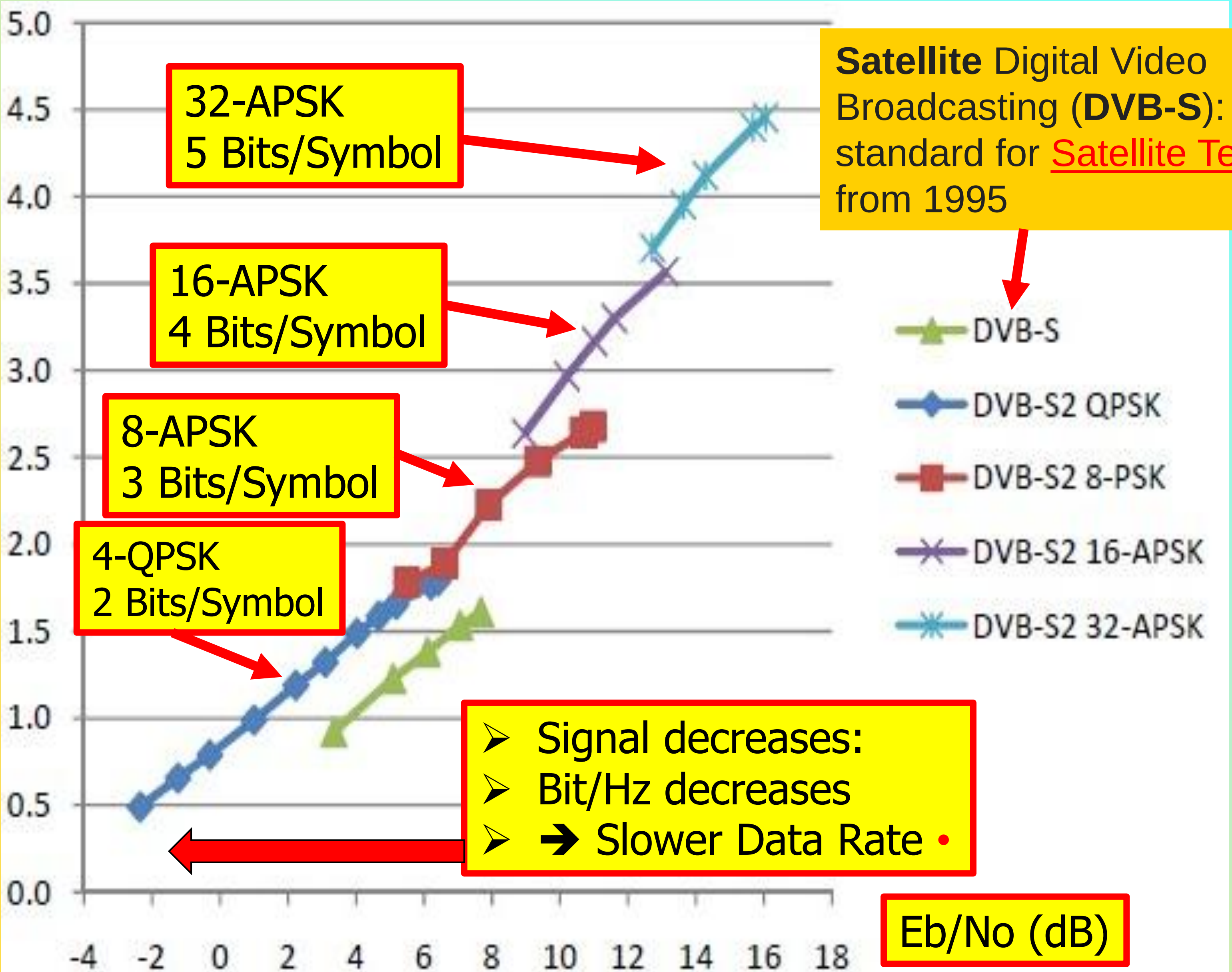
10.5dB

14dB

- ☐ Lower Constellatio complexity
- ☐ Same BER
- ☐ Lower S/N ⬇

$E_b/N_o$ (dB)

# HTS System Design: Modulation Efficiency



Spectral Efficiency (bits/Hz)

Eb/No (dB)

32-APSK
5 Bits/Symbol

16-APSK
4 Bits/Symbol

8-APSK
3 Bits/Symbol

4-QPSK
2 Bits/Symbol

**Satellite** Digital Video Broadcasting (**DVB-S**): Original standard for Satellite Television from 1995

- Signal decreases:
- Bit/Hz decreases
- ➔ Slower Data Rate •

# Error Detection

BER of 1 in $10^6$ is Great

**Simplest Form of Error detection codes uses Parity Checks**

- Parity bit added to a block of data
- Parity Words added to the end of a block of words
- Even parity
  - Added a bit ensures an even number of 1's
- Odd parity
  - Added a bit ensures an odd number of 1's
- Example, 7-bits of data [1110001] & 8-bit code
  - Even parity [11100010]
  - Odd parity [11100011]

Parity bit

# Two-Dimensional Parity

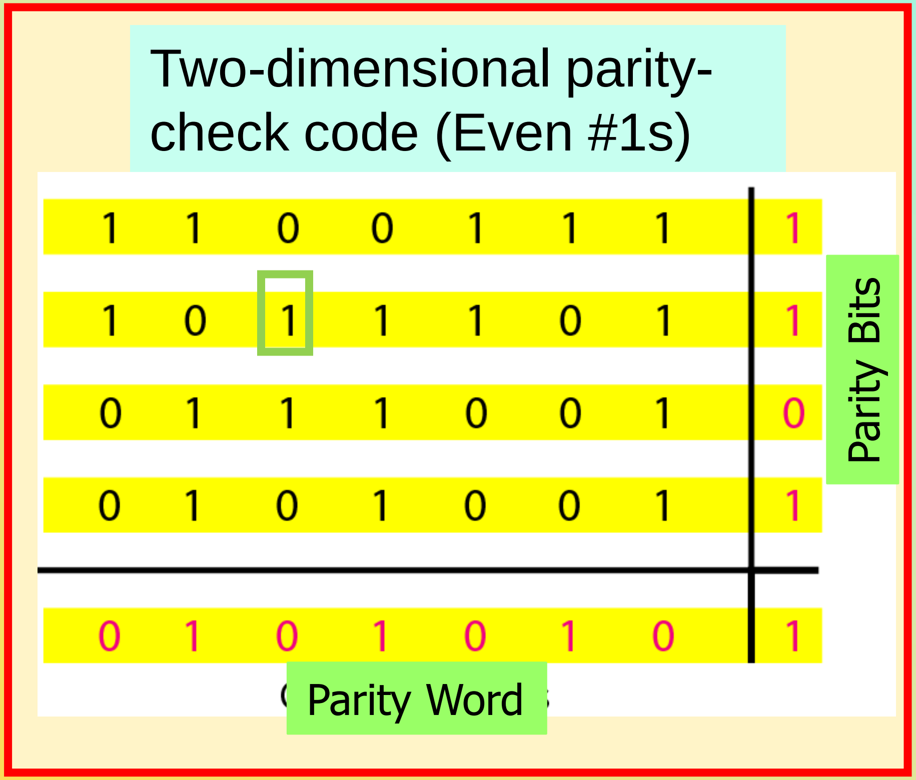
| Data | Even Parity Bits |
|---|---|
| 0101001 | 1 |
| 1101001 | 0 |
| 1011110 | 1 |
| 0001110 | 1 |
| 0110100 | 1 |
| 1011111 | 0 |
| 1111011 | 0 |

Even Parity Byte

- 1st dimensional parity
  - Add a Parity Bit
  - Add one bit to every byte (word)
    - Ensure an even/odd number of 1’s
- 2nd dimensional parity
  - Add a Parity word
  - Add an extra byte (word) to every block
  - Bits in the Parity word
  - Ensure even/odd number of 1’s in the respective column --

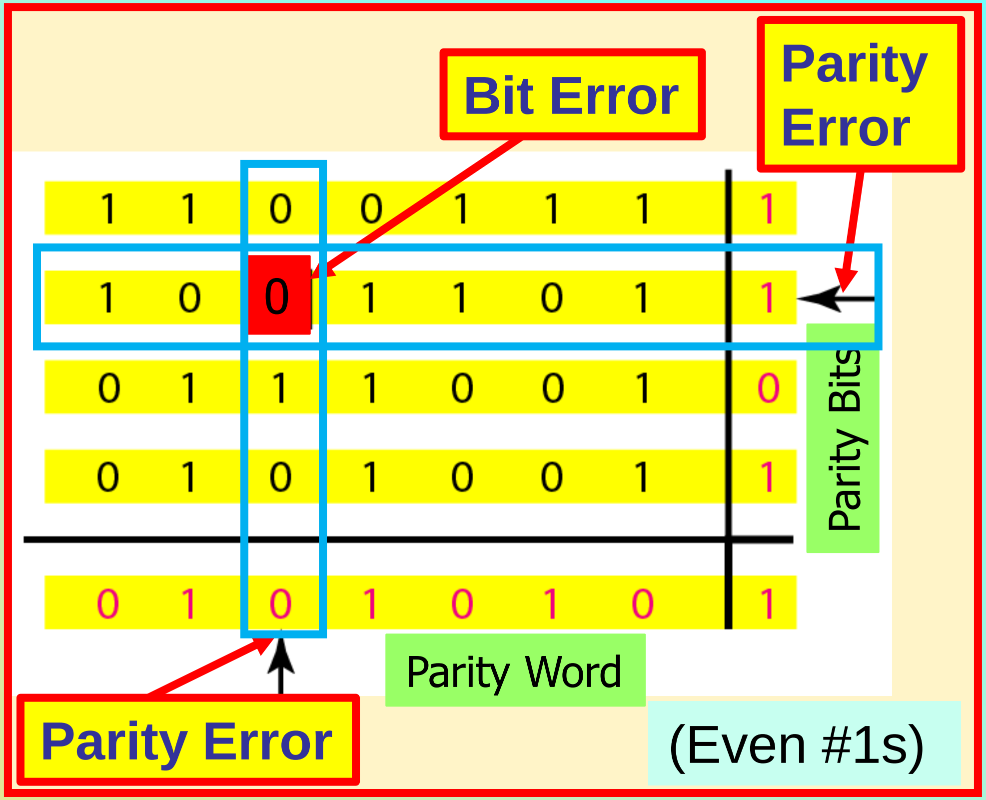
# Forward Error Correction (FEC)

- Simplest Form of two-dimensional parity checks



Two-dimensional parity-check code (Even #1s)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 |
| 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 |
| 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 |
| 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 |
| 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 |

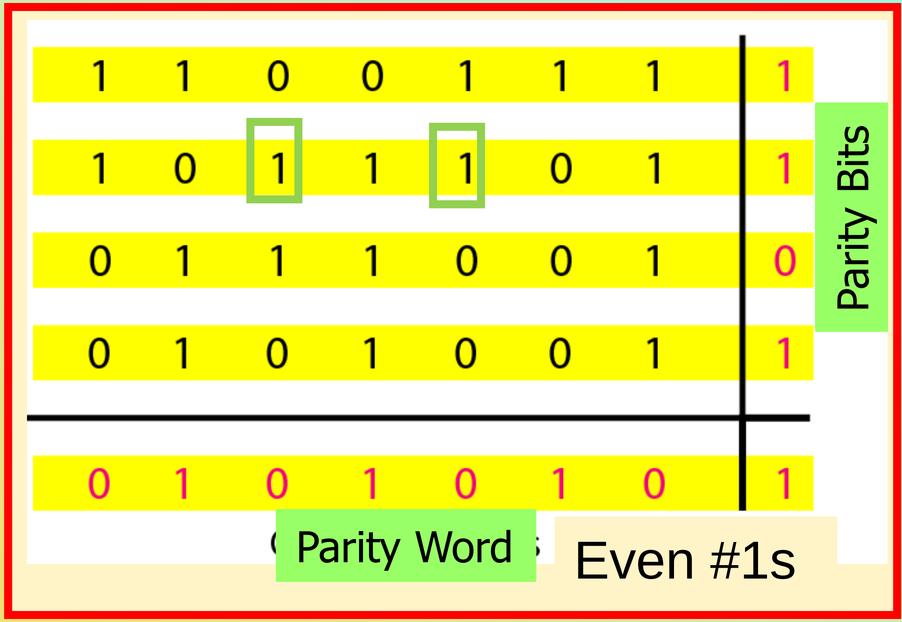


| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 |
| 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 |
| 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 |
| 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 |
| 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 |

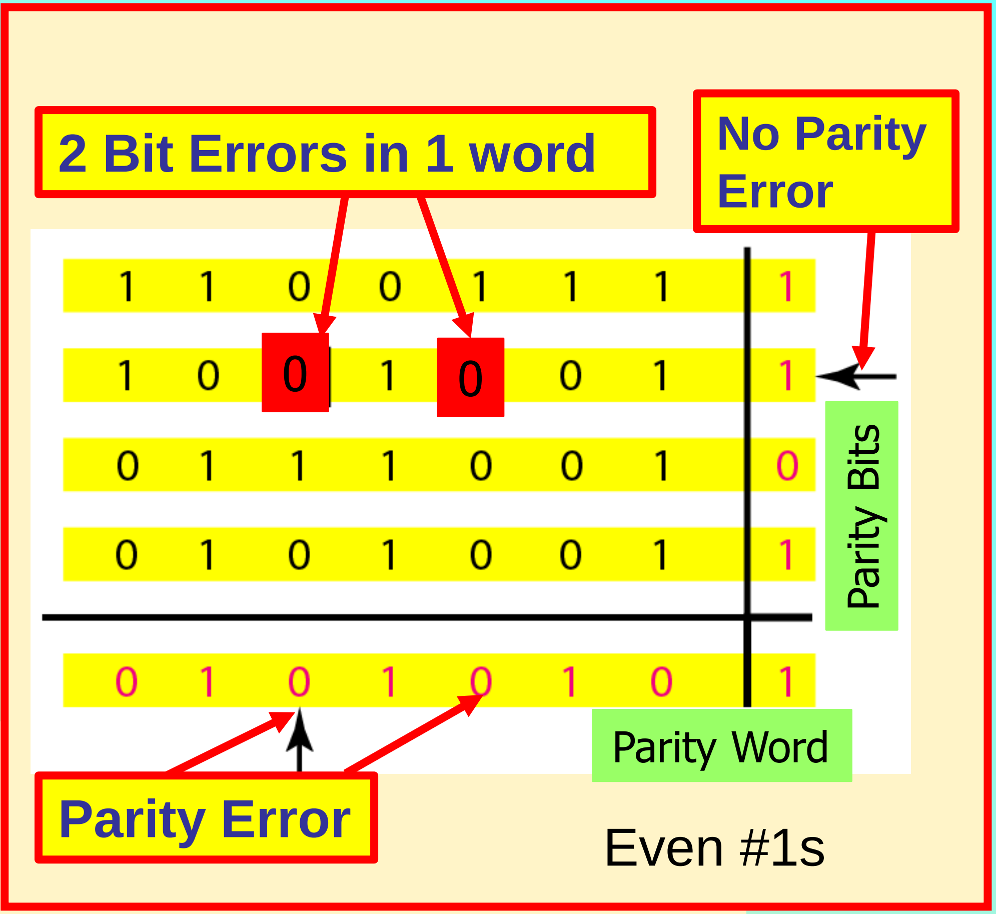
(Even #1s)

- **Horizontal & Vertical Parity Finds & Corrects a single error --**

# Forward Error Correction



| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 |
| 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 |
| 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 |
| 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 |
| 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 |



| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 |
| 1 | 0 | 0 | 1 | 0 | 0 | 1 | 1 |
| 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 |
| 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 |
| 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 |

- Multiple errors in one word
  - Not found in the word parity
  - Found in the Block Parity Word
  - Error is detected but not corrected (Can’t find the Error Word)
- Pr(1 error) = $10^{-6}$ (1 Errors in 1 Million Bits)
- Pr(2 errors) = $10^{-12}$ (1 Errors in 1 Trillion Bits)
- Two errors in 1 block: Error is known but can’t be corrected
  - Request data sent again --

# Questions and Comments

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