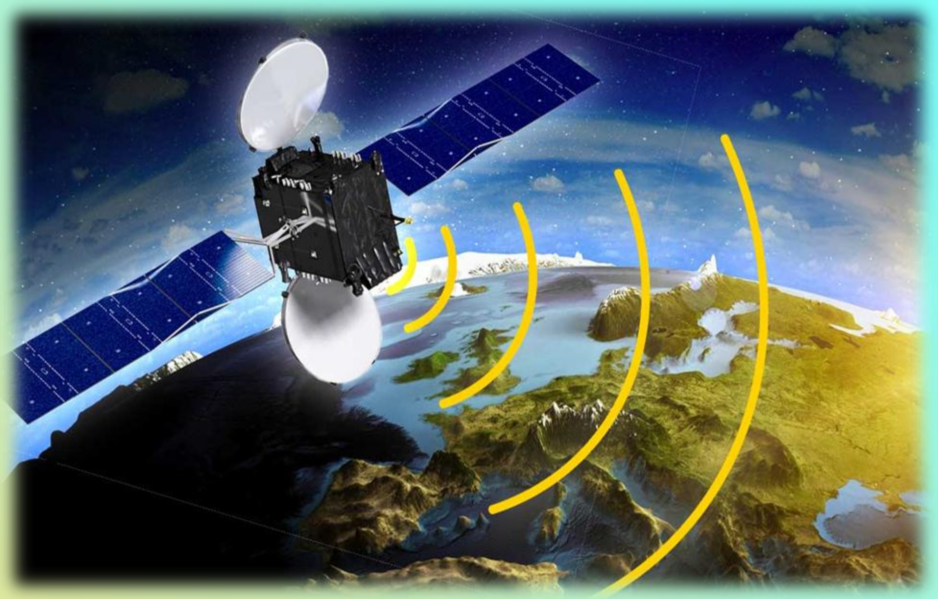
# Low Earth Orbit (LEO) Satellite Communications
# Part 2 of 2

IEEE Consultants Network of Long Island (LICN)

**Feb. 6, 2025**




**Howard Hausman, President/CEO**

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# Low Earth Orbit Satellite Communications

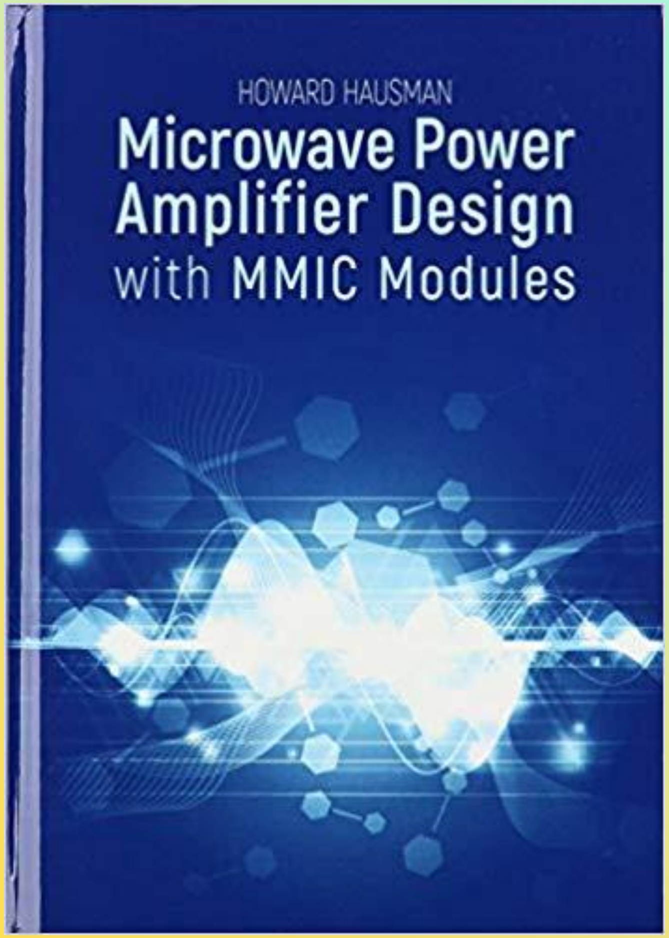
**ABSTRACT:** Low Earth Orbit Satellite Communications Part 1 discussed Satellite orbits, orbital mechanics, satellite coverage footprints on Earth and the analysis of the communications link between the Satellite and the Ground station. Part 2 continues this topic working out some examples of communications link analysis, discussing vector modulation, a technique that maximizes data rates and minimizes Bit Error Rates (BER), a discussion of current LEO satellite Systems, future LEO Satellite systems and cell phone communication directly with LEO satellites. Also discuss will be the trade-offs of currently proposed higher frequency LEO Satellite constellations

# 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




**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.

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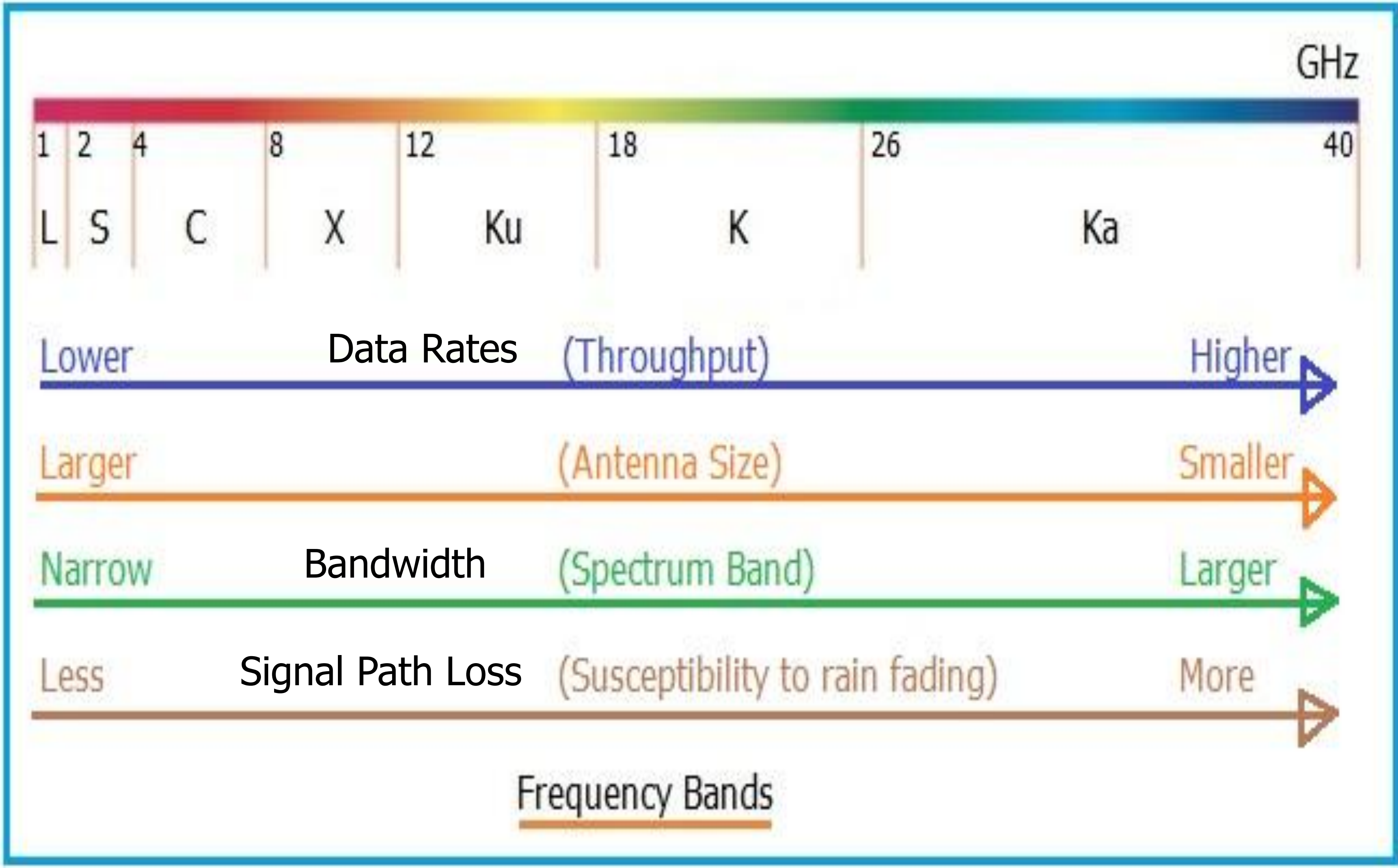
# Decibel Notation

- The Decibel Unit:
  - Standard method:
    - Describing transmission gain (loss)
    - Relative power levels
  - Gain: N(dB) = 10 log($P_2/P_1$)
  - Decibels with respect to 1W: $N$(dBW) = 10 log($P_2/1W$)
  - Decibels with respect to 1Milliwatt:
    - N(dBm) = 10log($P_2$/1mW)
- Example:
  - P = 1mW => P(dBm) = 0dBm ; P(dBW) = -30dBW
  - P = 10mW => P(dBm) = +10dBm ; P(dBW) = -20dBW

# Frequency Bands & Characteristics



# Microwave Frequency Bands of Interest

**Higher Frequencies Issues**

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

| 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 |

# P2-01: LEO Satellite Systems

A. LEO Satellites: Advantages & Disadvantages
B. Space X-Starlink (LEO) Satellites
C. One Web Satellite LEO System
D. Amazon: Project Kuiper
E. IRIDIUM
F. GLOBALSTAR SATELLITES: LEO System

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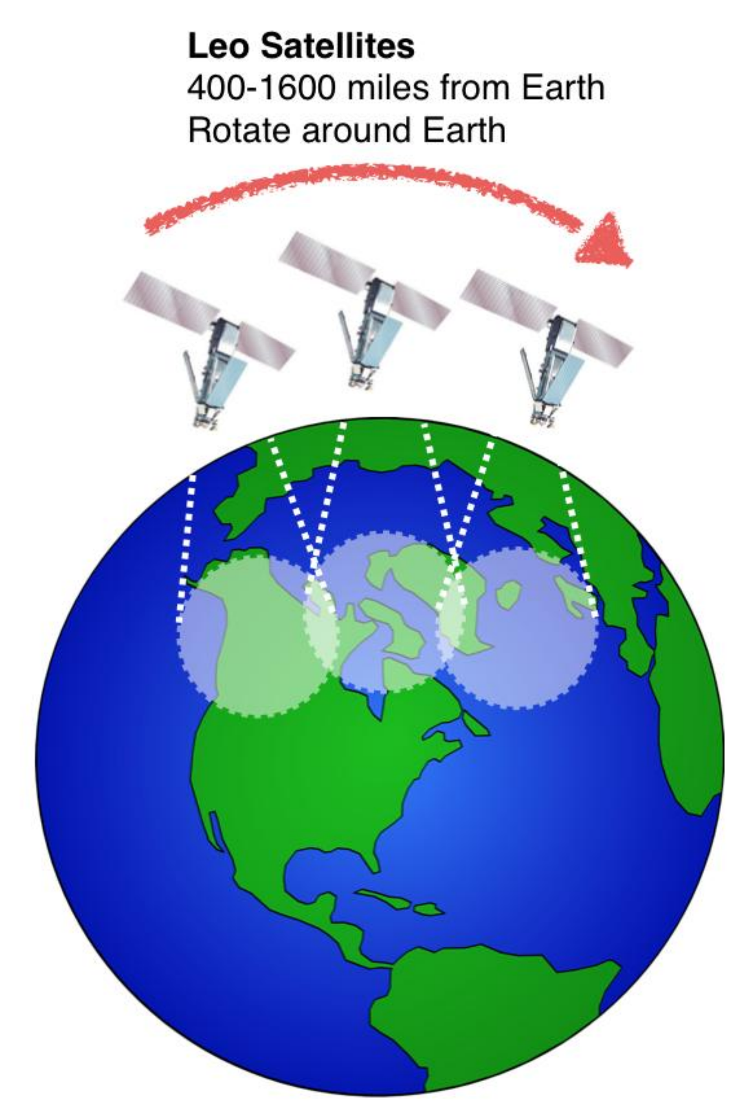
# Low Earth Orbits Satellite Systems: Advantages

## Advantages

- Small User Earth Stations
  - Smaller Antennas
- Lower Signal Path Loss
- Lower Earth Station Transmit Power
  - 5 Watt Internet
  - 0.1 Watts Cell Phone

## Disadvantages

- Requires Many Satellites
  - USA: 11,655 satellites in orbit
- Satellites Travel very Fast
  - Requires Doppler Shift Compensation
- Needs unobstructive Line of Sight --

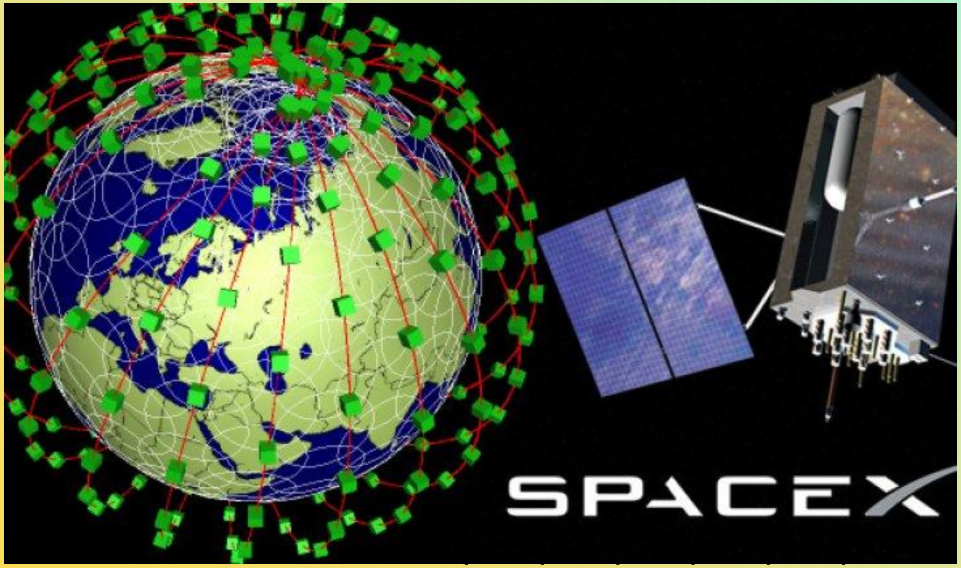


# Starlink: Satellite Internet Constellation

- Operated by **Starlink Services, LLC**
- Wholly owned subsidiary of SpaceX
- Provides Internet coverage to over 100 countries and territories --

# Space X-Starlink: Version 2 (V2) & End of Service

- Began launching Starlink, Version 2 (V2): February 27, 2023
  - V2 has direct to smart cell phone capabilities
- Current V2 Starlink satellite version weighs ≈ 1,760 lbs
  - ≈ 3 times heavier than the older V1 (573 lbs)
- End of their service
  - Old satellites are steered into Earth's atmosphere
  - Expected to burn up.
- Plans to refresh the constellation every five years --

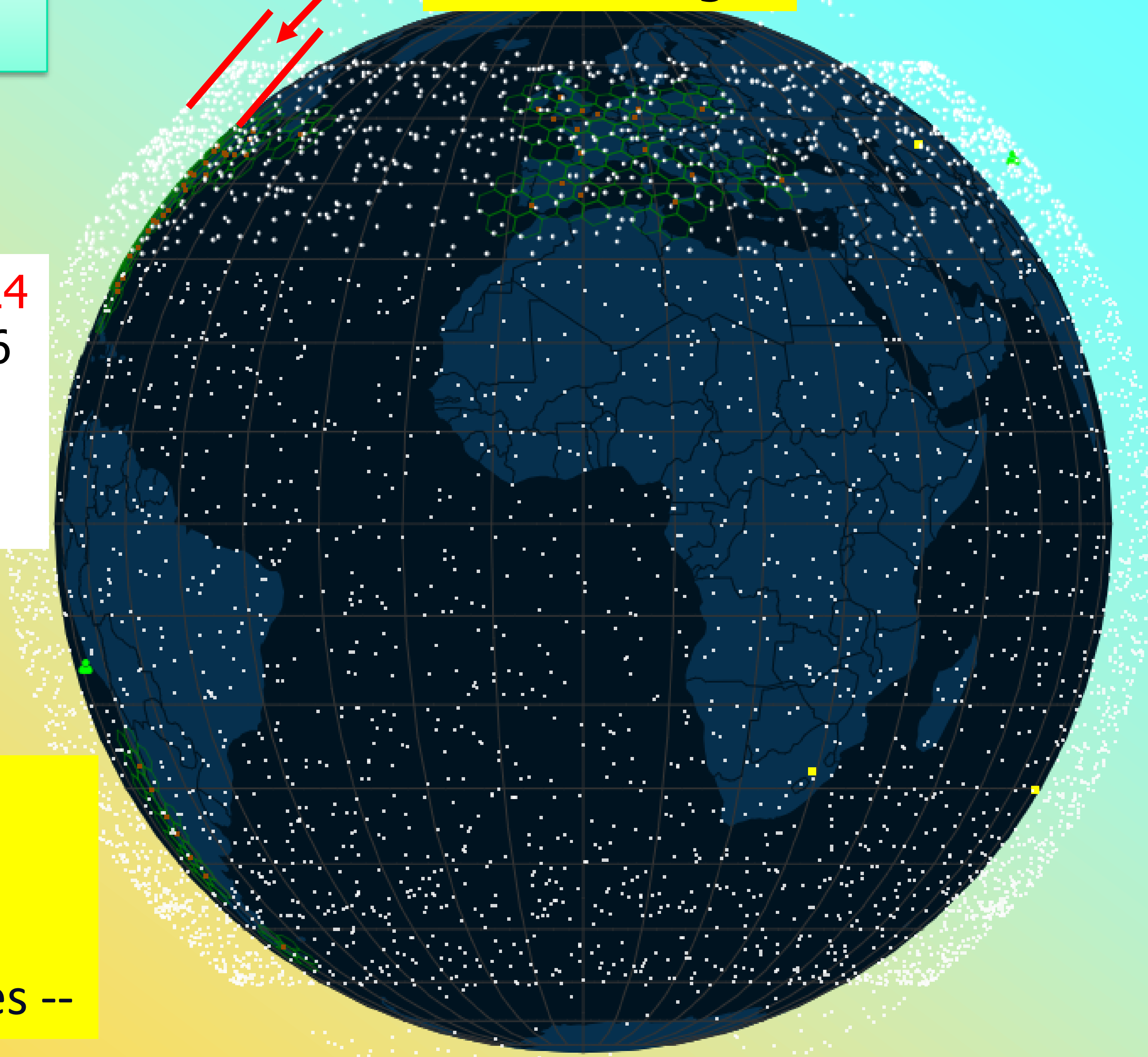


# Space X-Starlink (LEO) Satellites

- Orbit altitude ≈342 miles (550 km)
- Beta tests show data speeds over 100 Mbps (Megabits/Second)
- Latency (signal delay) < 40-50 millisec round trip --

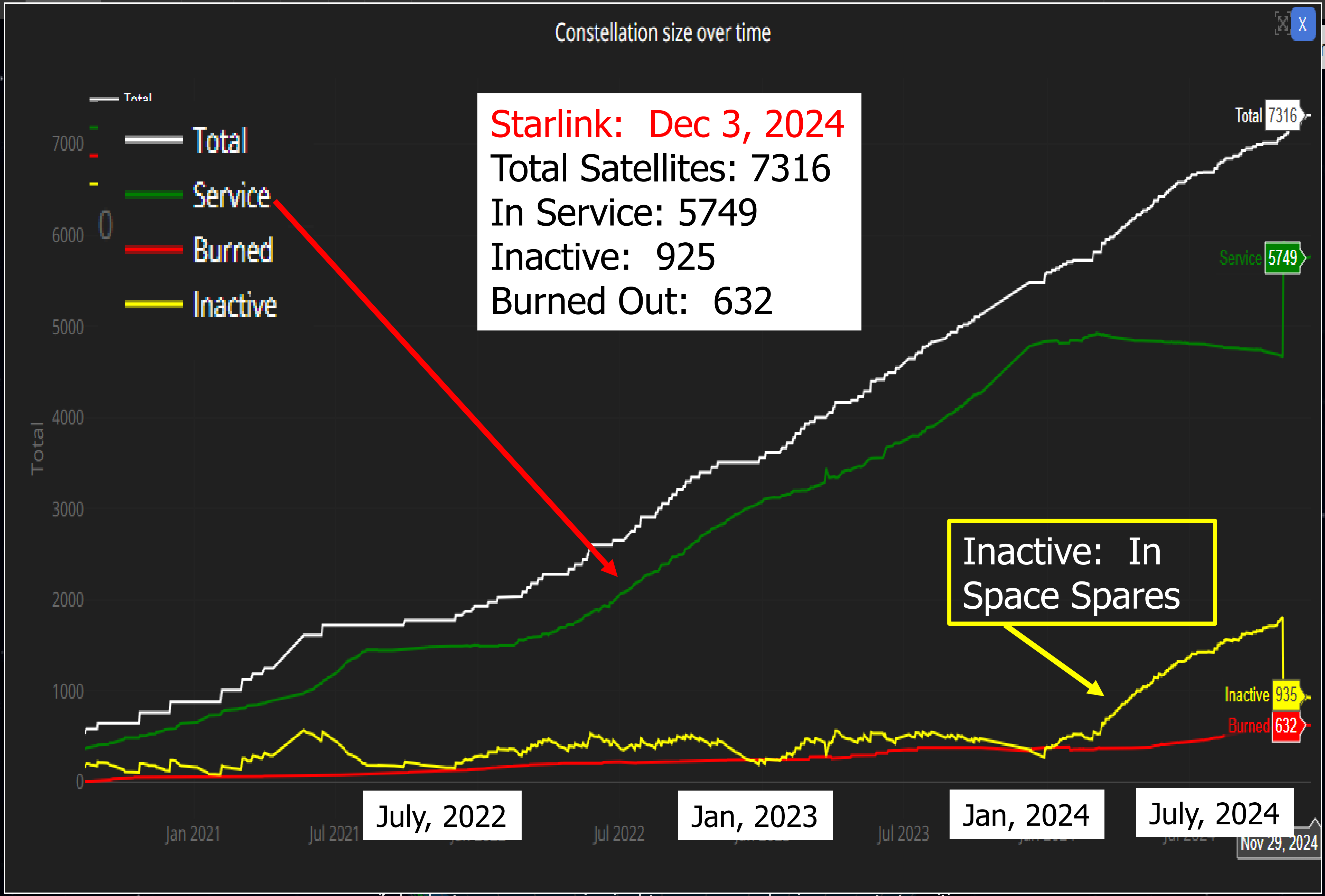
# Starlink Current Coverage Maps

Orbital Height



Starlink: Dec 3, 2024
Total Satellites: 7316
In Service: 5767
Inactive: 925
Burned Out: 630

User Earth Station Switches between satellites
≈ every 4.1 minutes --

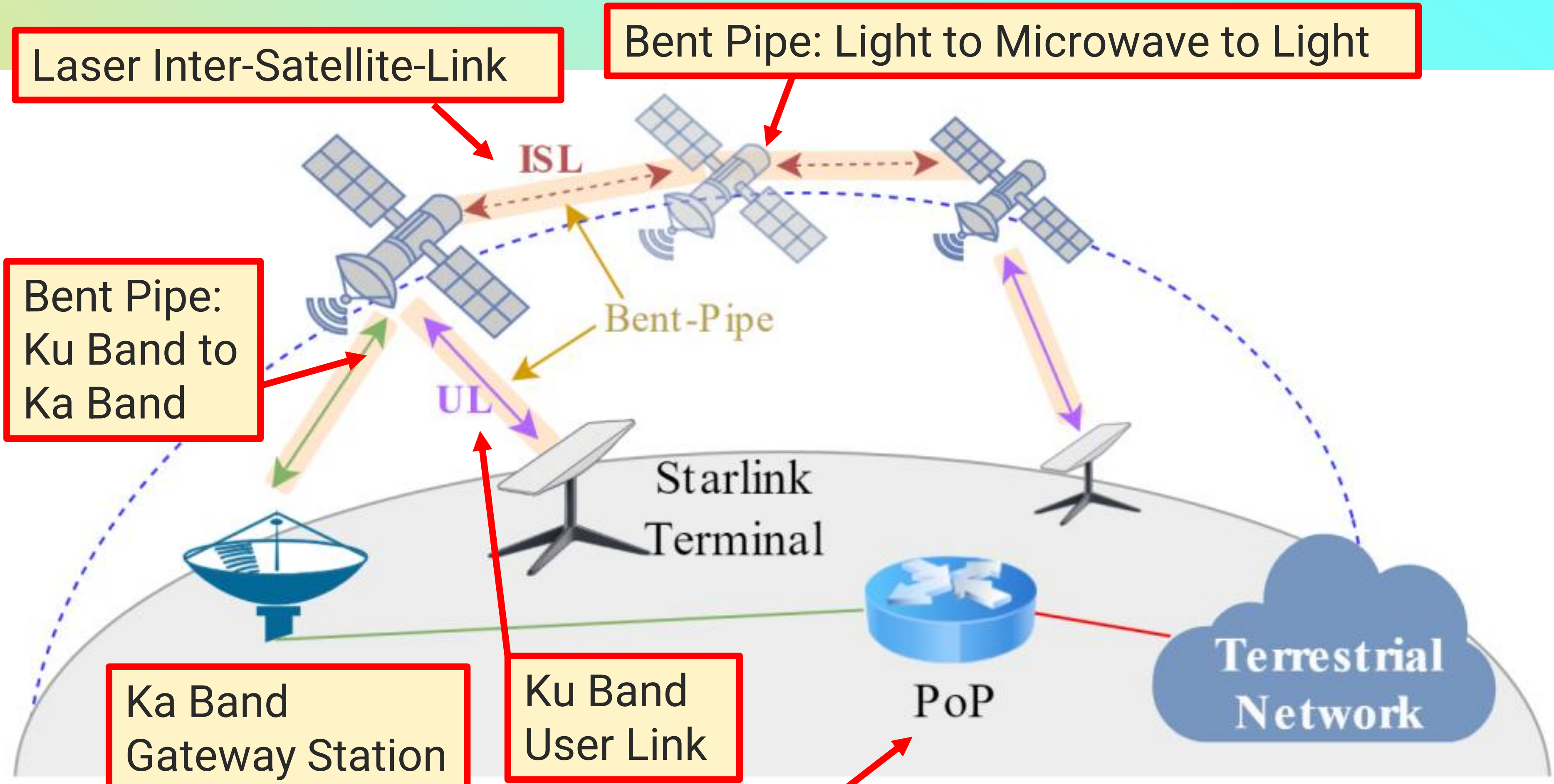


Constellation size over time
Total
Service
Burned
Inactive
Starlink: Dec 3, 2024
Total Satellites: 7316
In Service: 5749
Inactive: 925
Burned Out: 632
Inactive: In Space Spares
Total 7316
Service 5749
Inactive 935
Burned 632
7000
6000
5000
4000
3000
2000
1000
0
Total
Jan 2021
Jul 2021
July, 2022
Jul 2022
Jan, 2023
Jul 2023
Jan, 2024
July, 2024
Nov 29, 2024

# Starlink: Future Satellites

- V-band (40 to 75 GHz):
  - Plan for an additional 7518 slots
  - Orbit altitude ≈ 211 miles
  - Total number: 11,943 satellites
  - possibility of expanding to 34,400
- Higher Freqiemcy:
  - More bandwidth
  - Higher Data Rates (throughput)
- Harder to implement
  - Antenna beams are narrow
  - RF Power is Costly
  - Increasing weather attenuation --

# Starlink: Connectivity

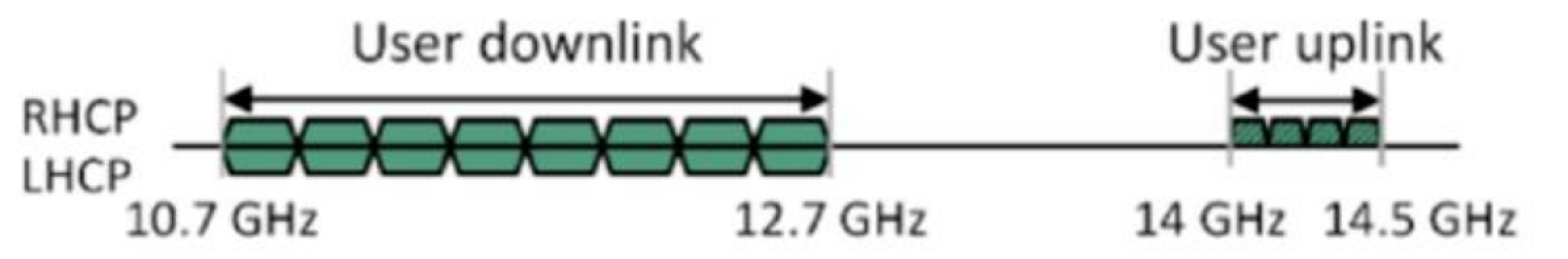


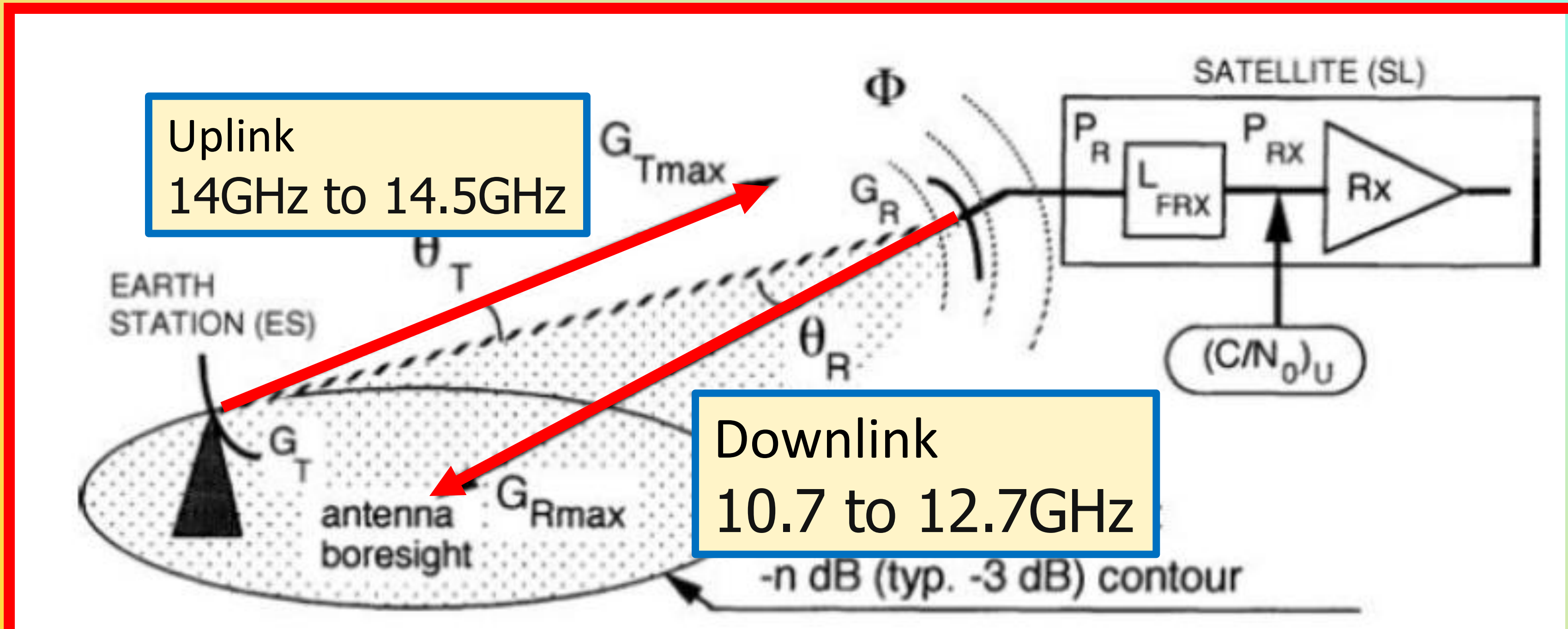

PoP (point of presence):

- ❑ Dedicated ground facility
- ❑ Starlink network connects to internet infrastructure.

# Starlink Frequencies: User Bands

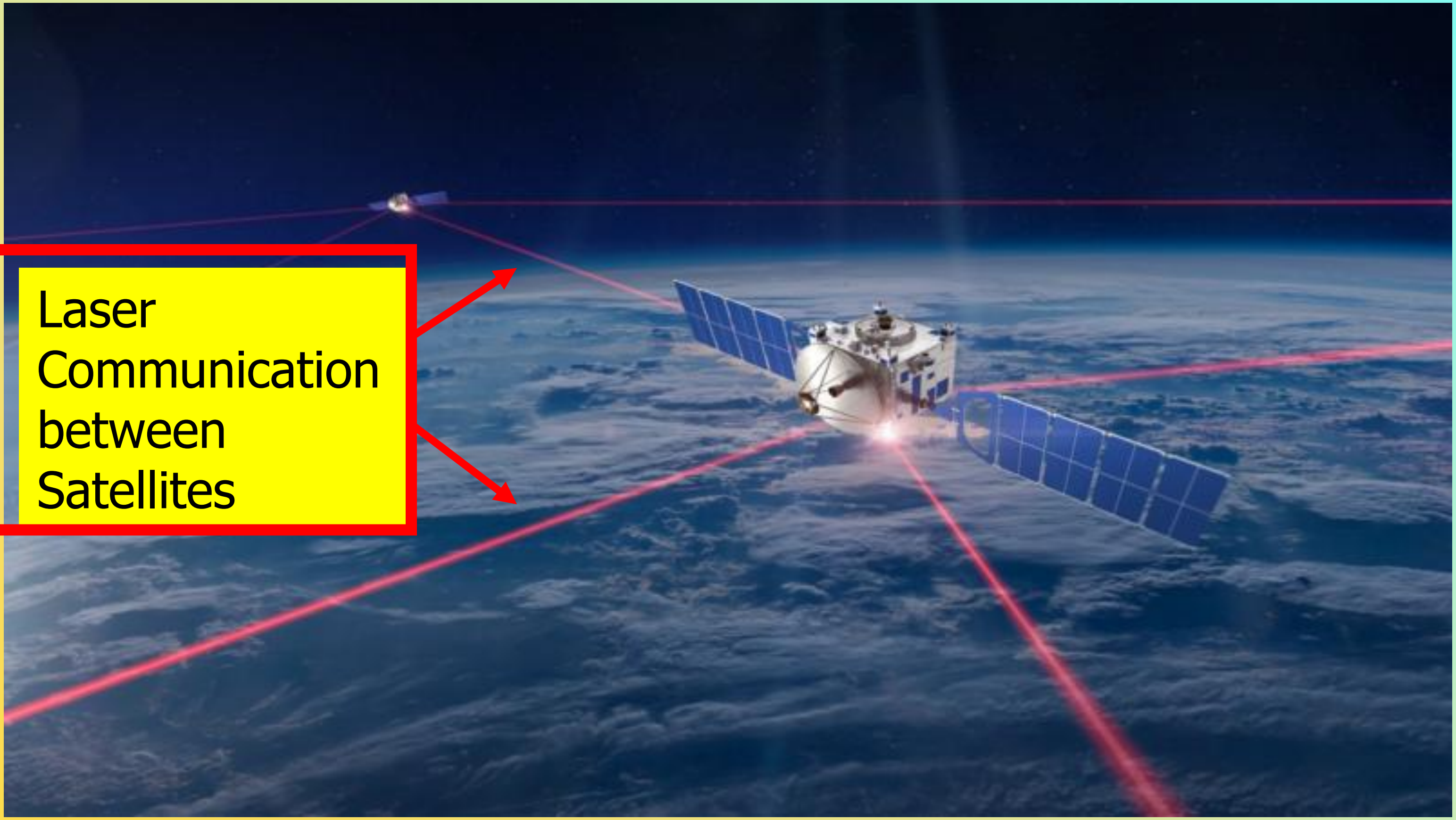
Uplink: Higher Frequency
More available power on the ground
(Actually, Less available power)



# Starlink Frequencies: Satellite to Satellite

- Infrared lasers that share information between satellites
- Inter-satellite laser communication
- Throughput: 5.6 Terabytes per second (Tbps) --



# Starlink Frequencies: Gateway Earth Stations

**Satellite to Terrestrial Infrastructure**

- Gateway Downlink:
  - 17.8GHz to 18.6GHz
  - 18.8GHz – 19.3GHz
  - 19.7GHz to 20.2 GHz
- Gateway Uplink
  - 27.5GHz to 29.1GHz
  - 29.5GHz to 30GHz

**Gateway Earth Stations**
Connect satellite data to the Communications infrastructure

**Uplink**: Higher Frequency
More available power on the ground: --

# Starlink: Frequency & EIRP (Effective Isotropic Radiated Power)

| Link Type | Frequency | Modulation | Emission Designator | Maximum EIRP | Half Power Beamwidth |
|---|---|---|---|---|---|
| Broadband Downlink (space-to-Earth) | 10.7-12.7 GHz | Up to 64 QAM | 240MD7W | N/A | 3.5° (boresight) 5.5° (at slant) |
| Broadband Uplink (Earth-to-space) | 14.0-14.5 GHz | Up to 64 QAM | 60M0D7W | 38.2 dBW | 2.8° (boresight) 4.5° (at slant) |

EIRP: +38.2dBW --

- ❑ 64QAM at Low BER
- ❑ 64QAM: BER increases ➔ 16QAM ➔ Slower Data
- ❑ 16QAM: BER increases ➔ 4QAM ➔ Slower Data

# *StarLink Modulation*

- *At 2000 MHz BW and 64QAM FEC = 0.873 (= 7/8)*
- *The total throughput of one StarLink satellite*
  - *2000MHz BW x 2(OFDM) x 5.11 (Efficiency)= 20.22 Gbit/S-*

| Modulation | Bits Per Sym | FEC | Data Bits Per Bits in Word | Efficiency, bit/Hz |
|---|---|---|---|---|
| QPSK | 2 | 0,5 | 1/2 | 0,989 |
| 8PSK | 3 | 0,75 | 3/4 | 2,228 |
| 8PSK | 3 | 0,833 | 5/6 | 2,479 |
| 16APSK | 4 | 0,666 | 2/3 | 2,637 |
| 16APSK | 4 | 0,75 | 3/4 | 2,967 |
| 32APSK | 5 | 0,90 | 9/10 | 4,453 |
| 64QAM | 6 | 0,772 | 3/4 | 4,5234 |
| 64QAM | 6 | 0,873 | 7/8 | 5,1152 |
| 64QAM | 6 | 0,948 | 18/19 | 5,5547 |

7 Data Words
1 Parity Word

# Space X-Starlink User Interface

Uses a flat phased array

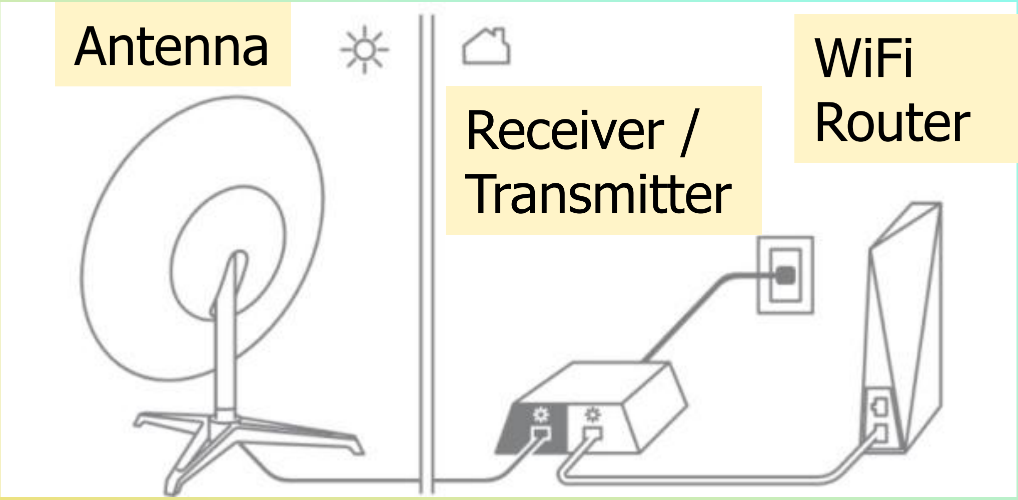
- Steering its beams to track Moving Space X satellites
- Terminal steers the transmitting beam
  - Lock on Receive beam
  - Transmit Beam uses a-prior satellite information

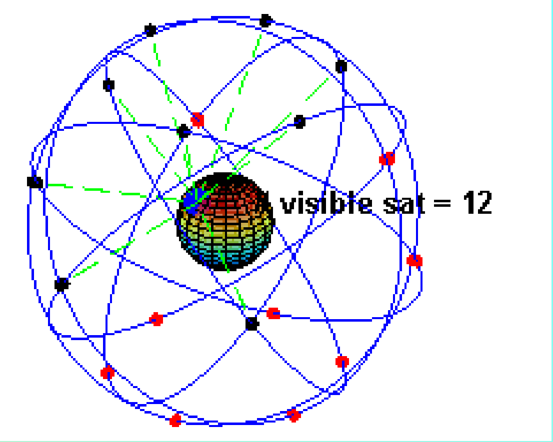
**Must adjust Transmitter power**

- Need a constant level at the Satellite antenna
- Adjusts Transmit Power compensate for variations
  - Antenna gain
  - Path loss •

19″ x 12″

# Space X-Starlink: Ground Station

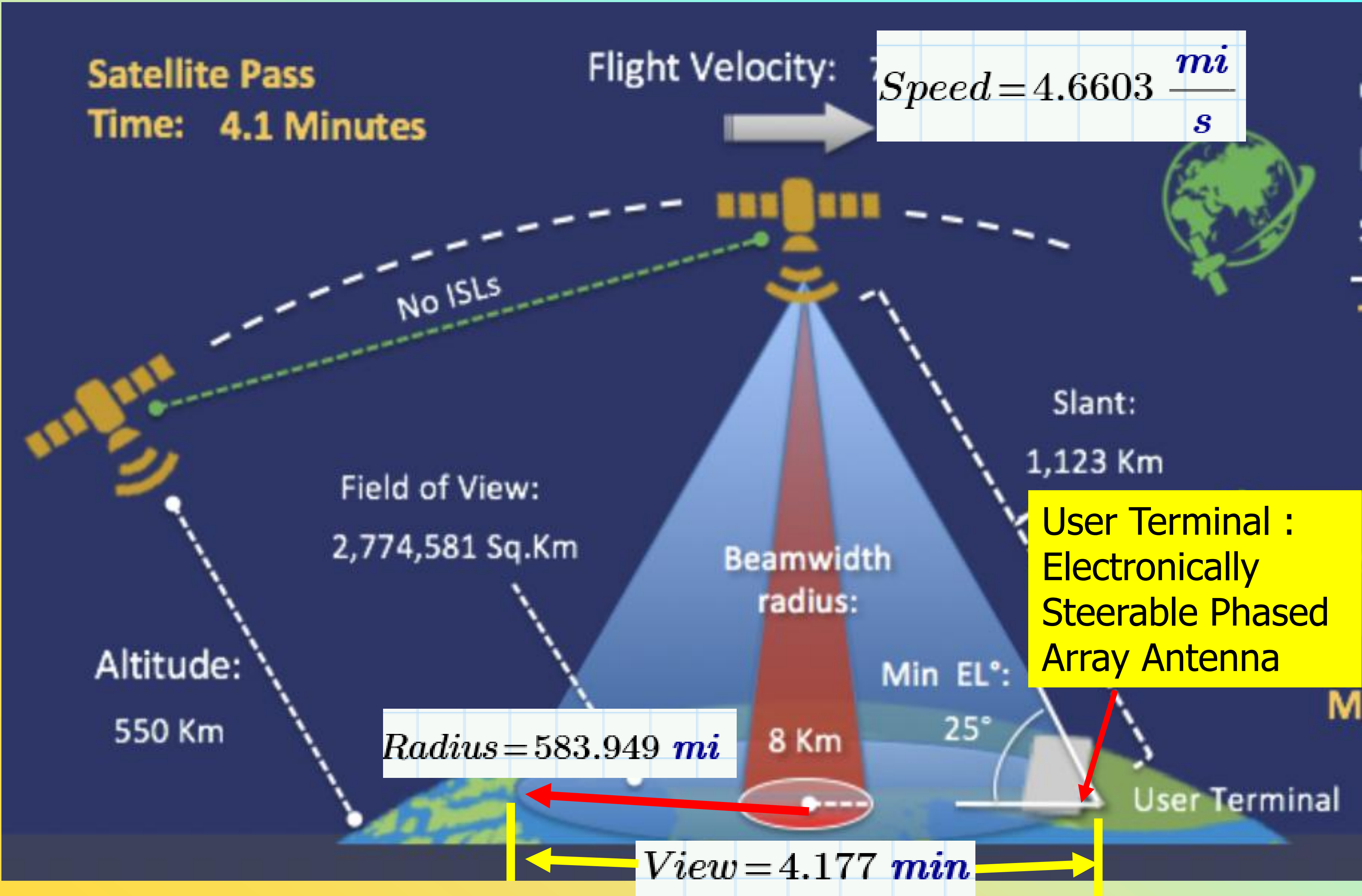



- Home antenna must be cleared of obstructions
  - Requires a clear view of the sky to connect
- Satellite can be at different angles (≈ 0˚ to 25˚)

- Satellite Signal is converted to WiFi bands
  - Dual Band: 2.4GHz and 5GHz same as a home router --

# Tracking a Fast-Moving Satellite




User Terminal : Electronically Steerable Phased Array Antenna

# One Web Satellite LEO System

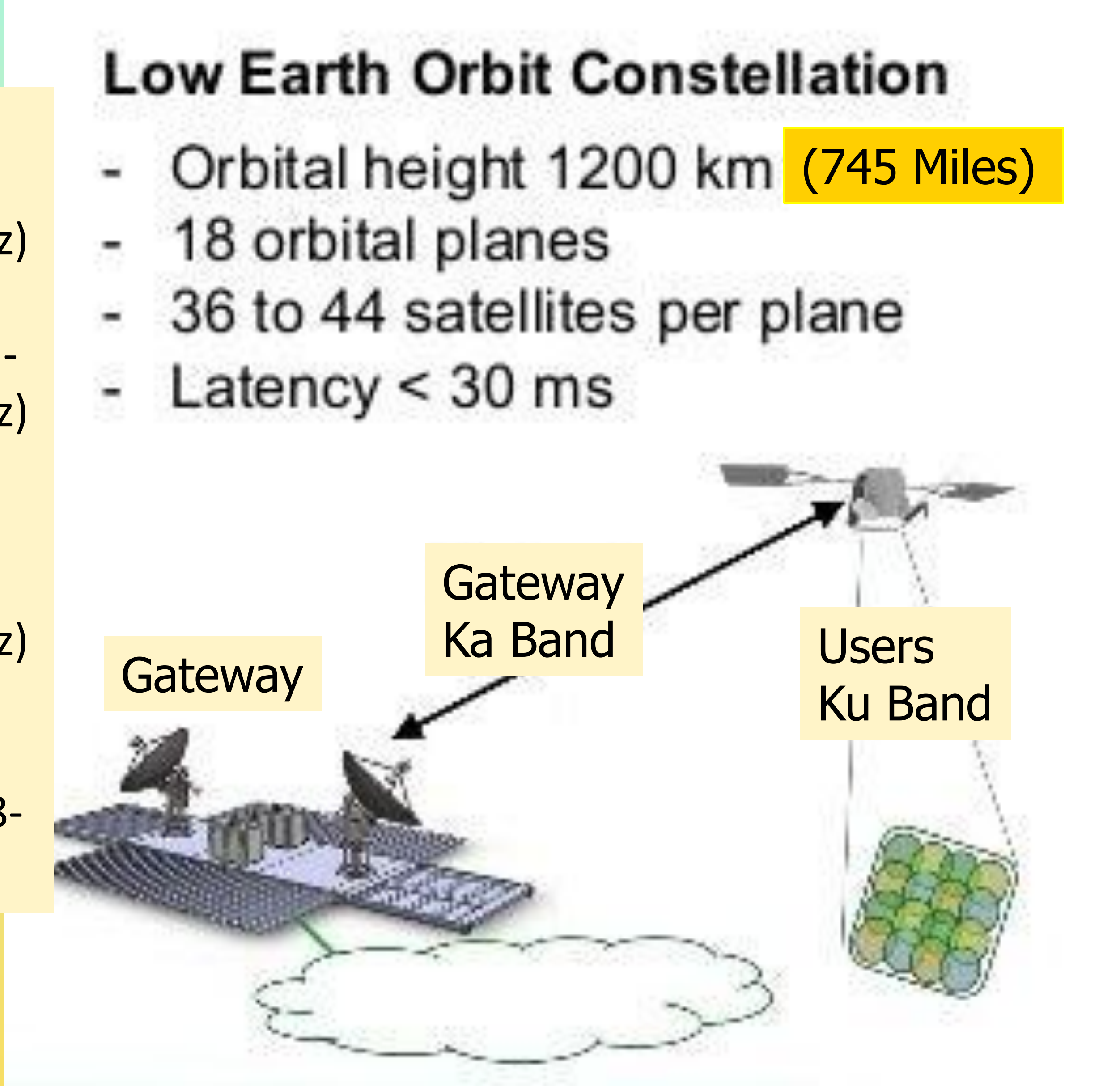
- ❑ Primarily Focused on
  - ❑ Businesses
  - ❑ Governments
  - ❑ Defense
  - ❑ Phone network operators
  - ❑ Clusters of communities
- ❑ Not individual domestic customers

- December 17, 2024
- 654 satellites in OneWeb's
- Current generation were launched between 2020 and 2023
- Constellation a design life extending to around 2027-2028.
- Operating in circular Earth orbits
- Ka (gateway) / Ku (User) at an altitude of 1,200 km (745 Miles)
- Higher Orbit ➔ less satellites required
- Coverage of most of the globe --

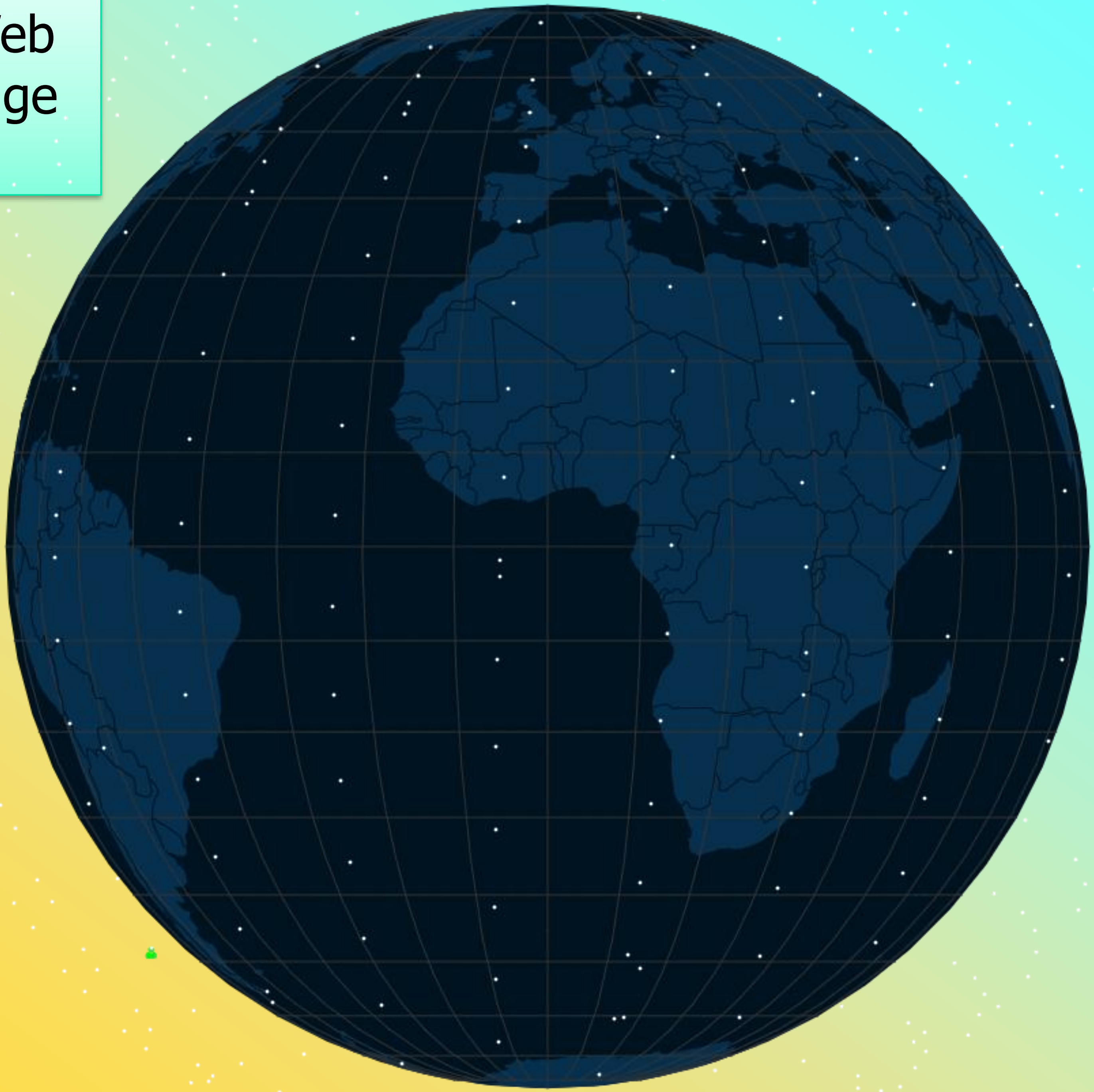
# One Web Satellite System Overview

- User Uplink:
  - 500 MHz BW in Ku-band (14.0-14.5 GHz)
- User Downlinks:
  - 2 GHz BW in the Ku-band (10.7-12.7 GHz)

- Gateway uplinks
  - 2.1 GHz BW in Ka-band (27.5-30.0 GHz)
- Gateway downlinks
  - 1.3 GHz BW in the lower Ka-band (17.8-19.3GHz) ---



# One Web Coverage Map



# One Web Ground Transmitter

Starlink

$$AltitudeSL := 550 \cdot km$$

$$AltitudeSL = 341.754\ mi$$

OneWeb

$$AltitudeOne := 1200 \cdot km$$

$$AltitudeOne = 745.645\ mi$$

- User Uplink:
- 500 MHz BW in Ku-band (14.0-14.5 GHz)

$$PowerDiff := \left(\frac{AltitudeOne}{AltitudeSL}\right)^2$$

$$PowerDiff = 4.76$$

Starlink

$$PowerSL := 5 \cdot W$$

$$PowerOne := PowerSL \cdot PowerDiff$$

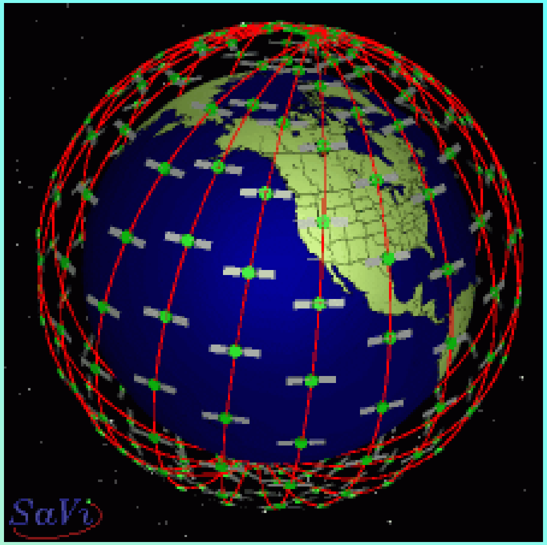
OneWeb

$$PowerOne = 23.802\ W$$

# OneWeb and Starlink

| | OneWeb | Starlink |
|---|---|---|
| # of Satellites (November 2023) | 630 | 5,500 |
| Bandwidth | Offers dedicated bandwidth options | Absence of bandwidth assurance, |
| Reliability | Consistent and trustworthy, | Reliable internet service, occasional hiccups |
| Latency | Sub-100 millisecond latency | Advertised: 20-40 ms, Field tests: 40-50 ms |
| Support System | 24/7 phone support, accessible troubleshooting | Exclusive reliance on email support, |
| Consumer Base Dynamics | Business-focused with an emphasis on IoT (Remote sensors) | Consumer-oriented, focusing on residential users in rural areas |

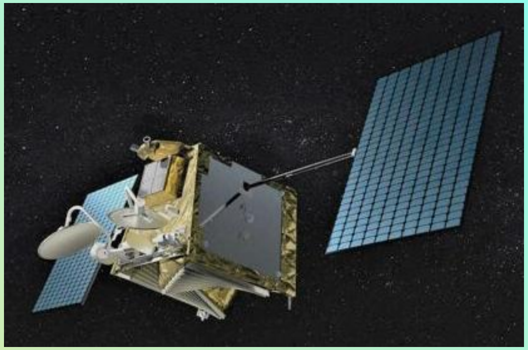
# Amazon: Project Kuiper




- Amazon Web Services (AWS)
  - Project Kuiper satellite internet venture
- Increase global broadband internet access
- Plans to put 3,236 satellites in low Earth orbit
  - ❑ FCC has given the company a 2026 deadline to launch at least half its planned satellites
  - ❑ 2029 for all 3236 Satellites

❑ Latitude from 56˚ north to 56˚ south.

  - ❑ Covers about 95 percent of the world's population
- Orbit between 590 and 630 kilometers (about 367 and 392 miles)
- Wants to expand the number of satellites to 7,774
  - Utilizing V-and Ku-band frequencies --



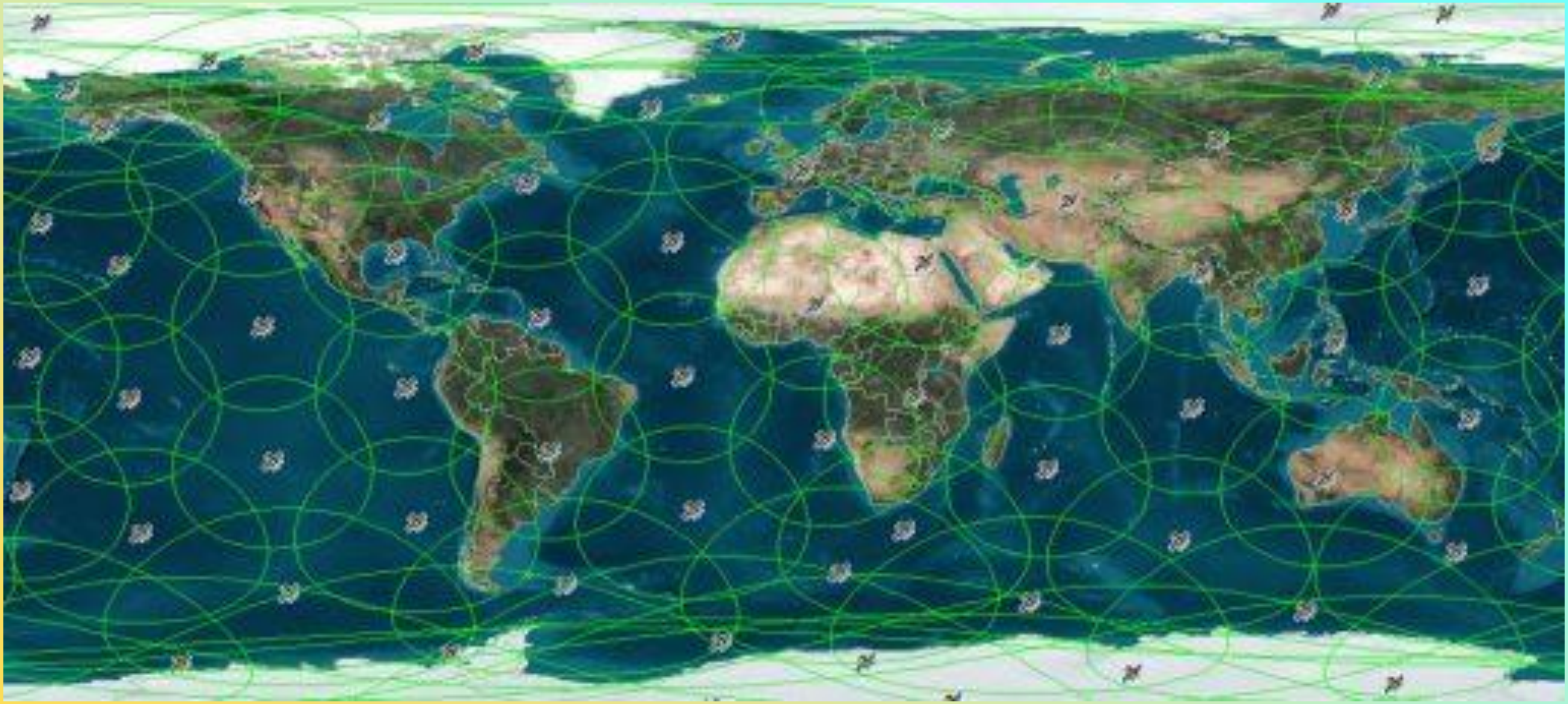
# IRIDIUM LEO

- Iridium provides global coverage
- Voice
- Fax
- Data
- Tracking services
  - Integrating GPS for satellite tracking

- 66 satellites (originally 77 satellites)
- 11 operational satellites in each of these six planes.
- 9 orbital spares and 6 satellites on the ground
- Data Rate: ≈ 9,600bits/s
- Global coverage
- LEO at a height of ≈ 485 mi

Voice (2.4 Kbps), Data (2.4 Kbps) --

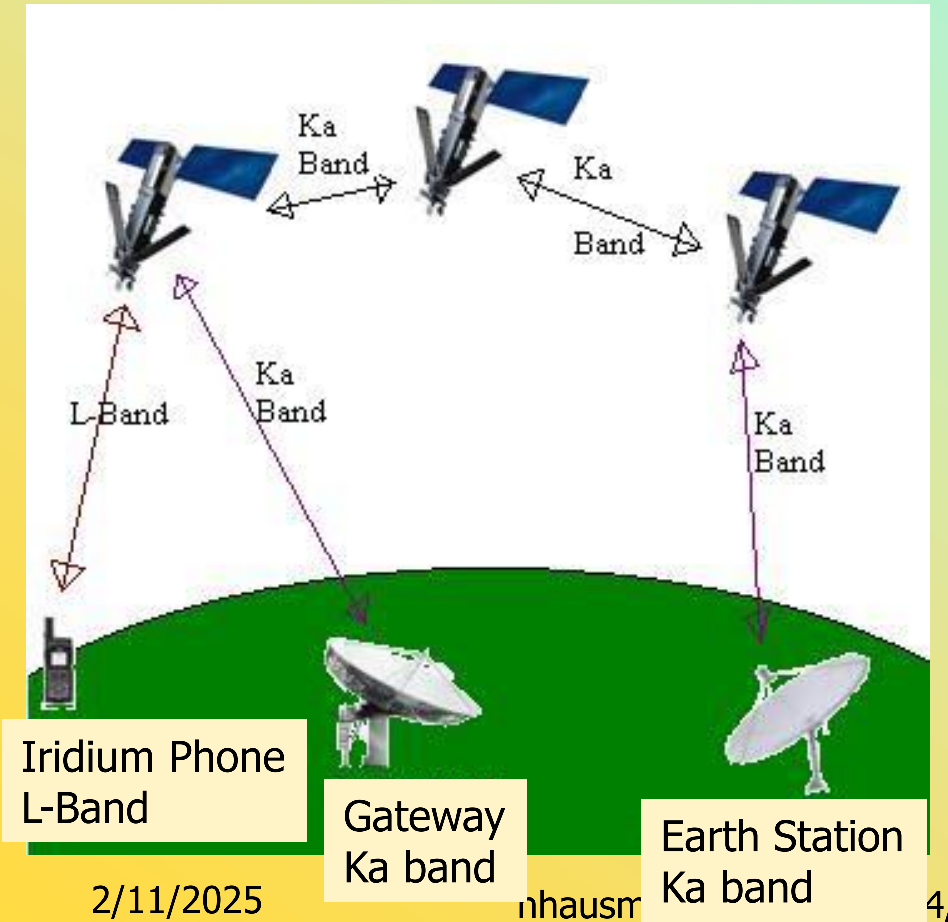
# IRIDIUM LEO



Satellite Coverage: 4000 Km

# IRIDIUM

- Satellite to Gateway
- Gateway to other Satellite
- Other Satellite to another terminal
- Invested ≈ $3 billion to replace its original satellite system



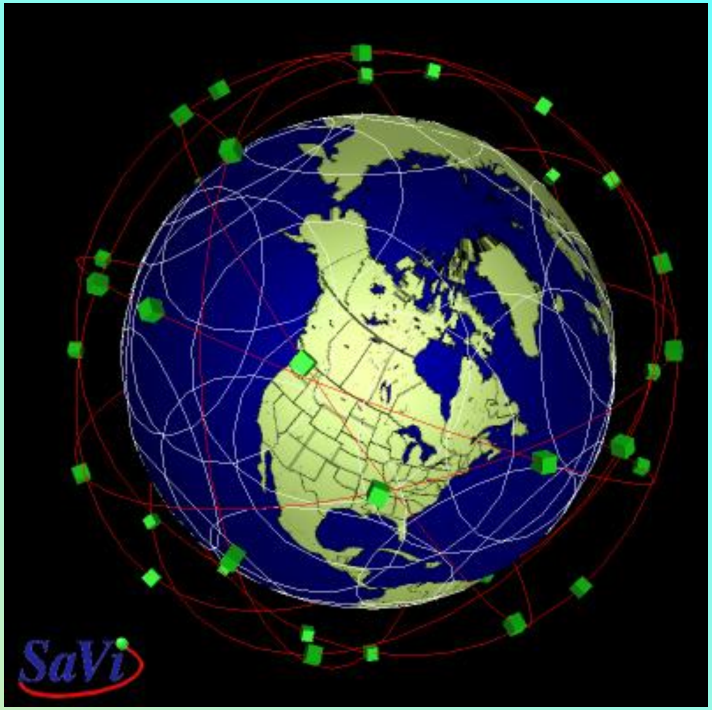

Iridium Phone L-Band


- L band for Iridium terminal
  - (1616 to 1626.5 MHz uplink and downlink)
- Ka band for intersatellite
  - 23.18 to 23.38 GHz link
- Ka band for gateway links
  - uplink from 29.1 to 29.3 GHz
  - downlink from 19.4 to 19.6 GHz). --

# GLOBALSTAR SATELLITES: LEO System

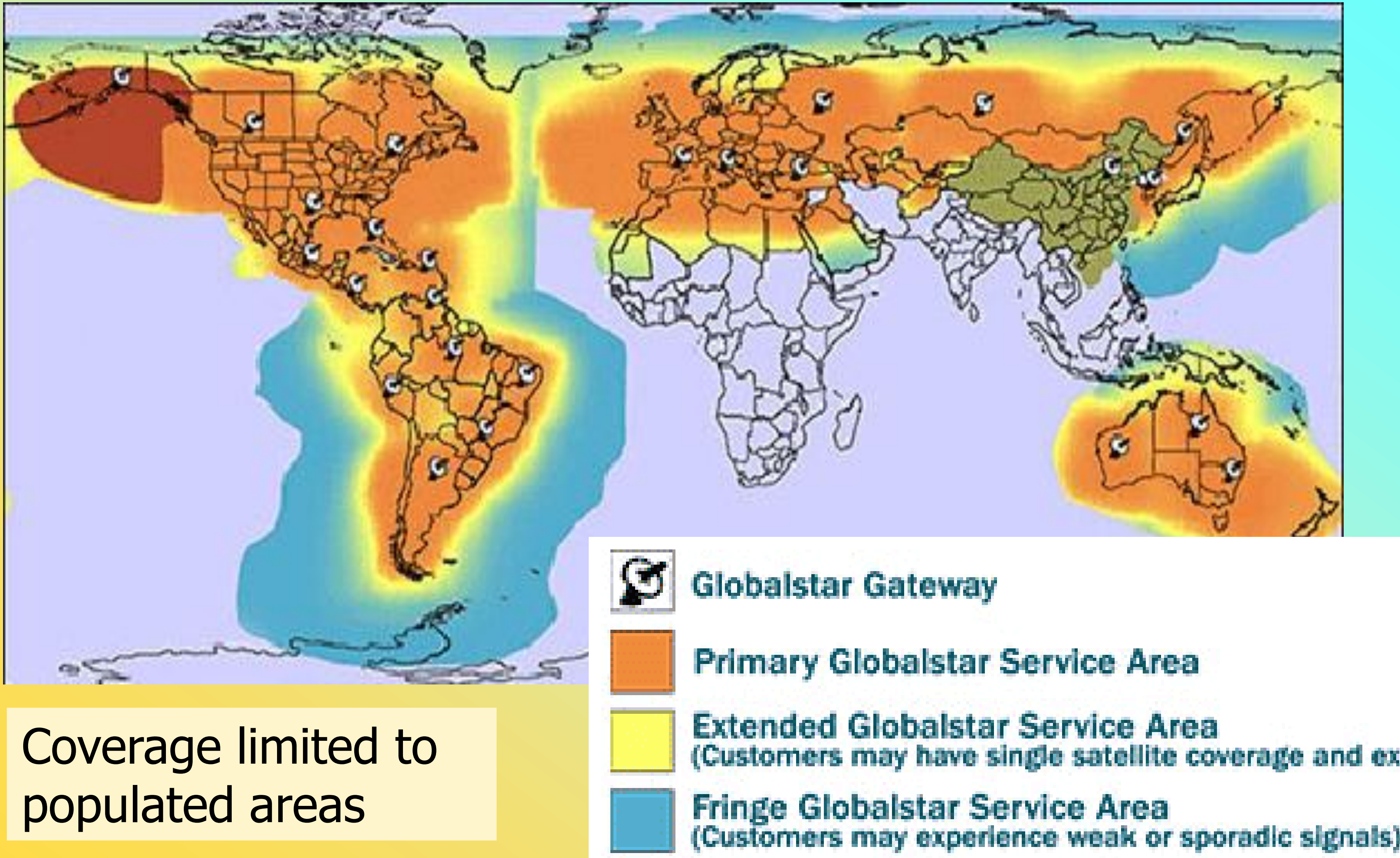
- Satellite phone & low speed data communications
- Satellites are placed in eight orbital planes of six satellites
  - 48 LEO satellites
- Inclined at 52°
- Service on Earth from 70° North to 70° South latitude.
- Operates at an altitude of 876 miles
- No intersatellite link:

  Ground gateways provide connectivity from satellites to Internet --




Globalstar's frequencies include:
- **Uplink**: 1610–1621.35 MHz, with 11.35 MHz of bandwidth
- **Downlink**: 2483.5–2500 MHz, with 16.5 MHz of bandwidth
- **Band n53**: 2483.5–2495 MHz, with 11.5 MHz of bandwidth

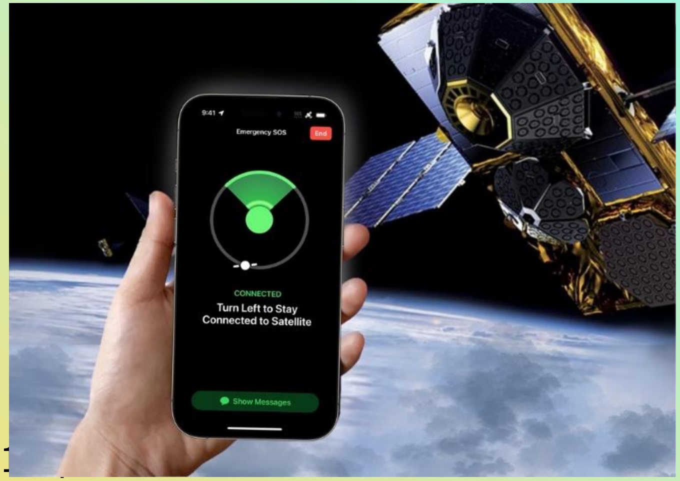
# Globalstar Coverage




Coverage limited to populated areas

# Globalstar: Apple's $1.7 billion Satellite Investment

- ❑ Apple has been using Globalstar's current network
  - ❑ 31 L-band satellites since 2022
  - ❑ Enable its latest iPhones to access emergency services
- ❑ Apple's plans to inject $1.7 billion for a new constellation
  - ❑ Improve space-based communications for iPhones.
- ❑ Capability includes basic SMS (Short Message Service) texting
- ❑ Currently does not provide voice and broadband
- ❑ Apple agreed to cover costs to replenish the constellation in 2022
  - ❑ Build 17 satellites, with options for up to 9 additional satellites --



# P2-02: MEO Satellite Systems

- ❑ O3B MEO Satellite System
- ❑ GPS (Global Positioning System) satellites

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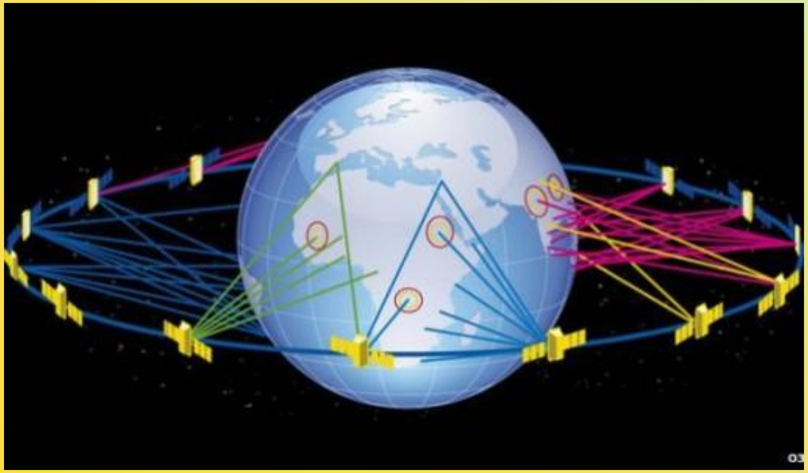
# O3B MEO Satellite System

- O3B: "Other 3 Billion People"
- Original Goal:
  - Internet Service to serve the Third World Population
- Circular orbit along the equator
  - Optimal coverage ±45° latitudes
- Orbital height: 8062km (5009 Miles)

- Earth Transmitter: 27.6 to 29.1 GHz
- Earth Receiver: 17.8 to 19.3GHz
- Transponder bandwidth: 216MHz;
- 2 polarizations
- Throughput of 1.2 Gbit/s per beam •

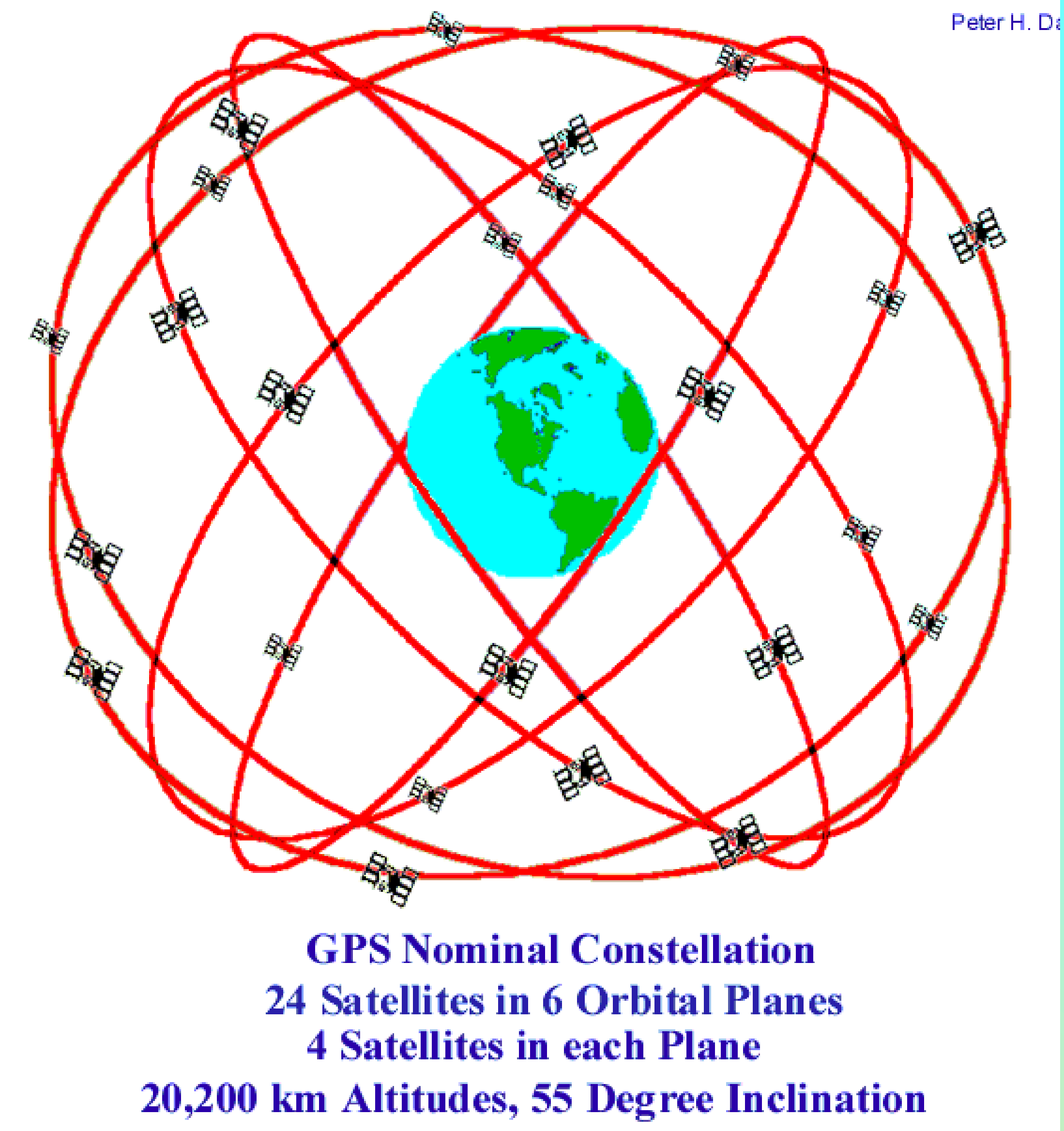


# O3B MEO Satellite System

- ViaSat Magazine: April 24, 2024
- SES' O3B mPOWER MEO System is Now Operational
  - Service Rollout to Follow
- 6 out of 13 O3B mPOWER satellites launched --

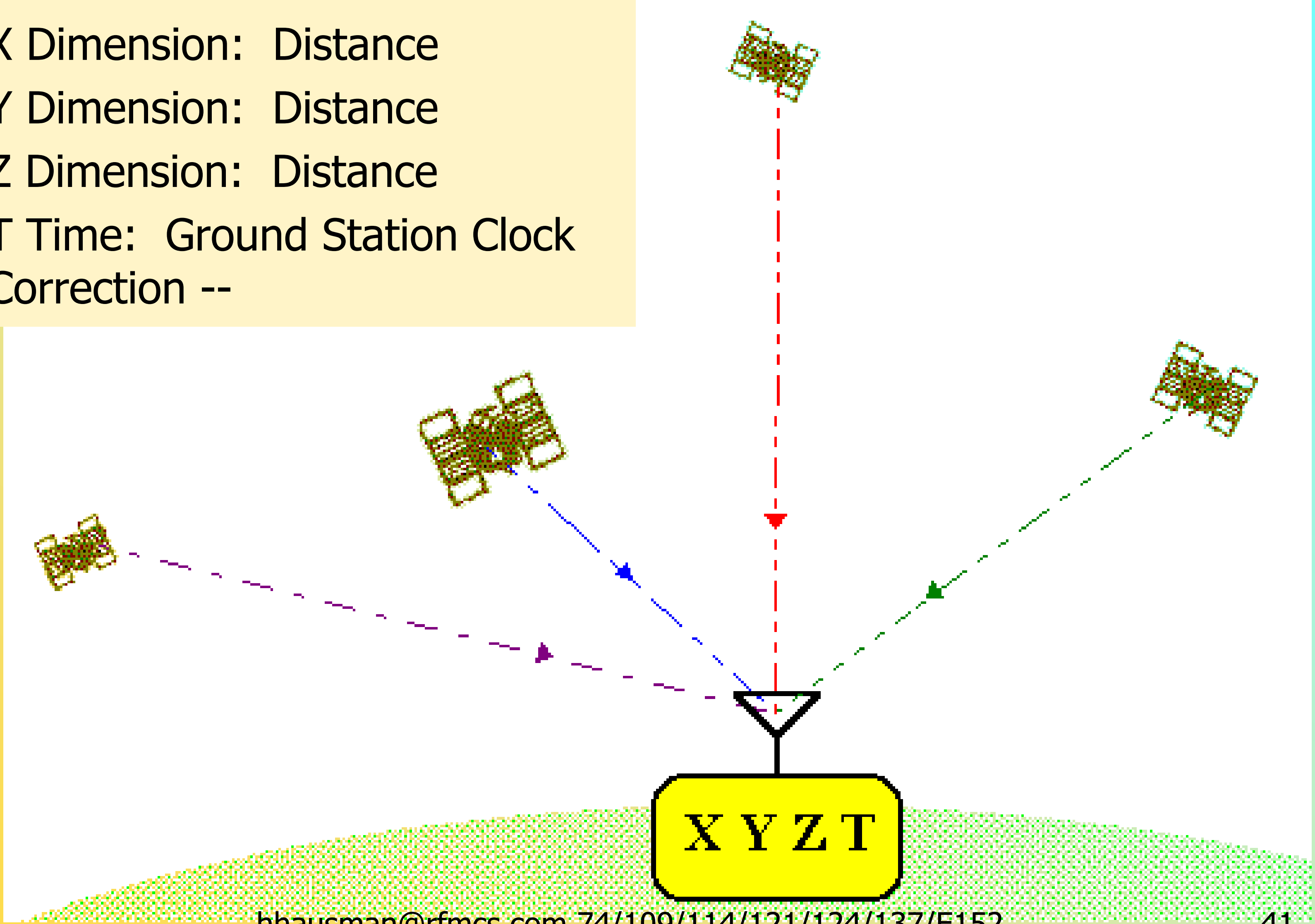
# GPS (Global Positioning System) satellites

- At least 24 operational GPS satellites
- MEO orbit:
  - Altitude 12,550 miles
- Each satellite circles the Earth twice a day.
- Constellation is arranged into six orbital planes
- 4 satellites per plane --



# GPS Satellites for Position Location

- Users view at least four satellites
- 4 Coordinates'
  - X Dimension: Distance
  - Y Dimension: Distance
  - Z Dimension: Distance
  - T Time: Ground Station Clock Correction --



Satellite Communications: Characteristics and Tradeoffs of Low, Medium, and Geostationary Orbital Systems

# P02-03 Direct Satellite to Earth Cell Service

A. Satellite Phones Systems
B. Starlink Direct to Cell

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# Satellite Phones Systems

**Advantages**

- Satellite phones work in most places on earth
- Offer Voice, Text, GPS, and SOS
- Phones work great with SMS (Short Message Services) Text
  - Send and receive text messages.
- SOS button
  - Provides GPS location information in emergency situations.

**Disadvantages**

- Satellite phones need a clear line-of-sight of the sky
  - Limited connectivity Indoors
- Insufficient bandwidth for Internet services --

# Some Current Telephone to Satellite Systems

Inmarsat

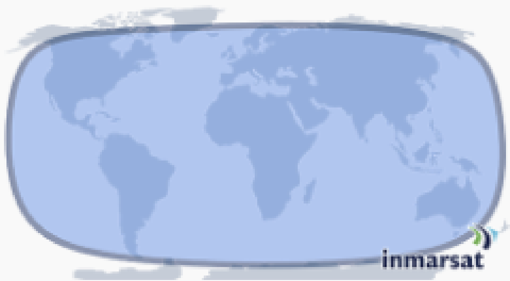
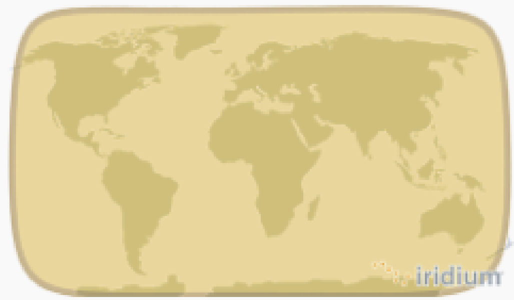
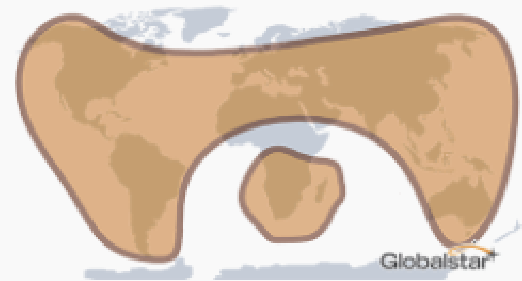
Inmarsat IsatPhone 2

Iridium

Iridium Extreme 9575

Globalstar


Globalstar GSP-1700

| Network | Inmarsat | Iridium | Globalstar |
|---|---|---|---|
| Coverage |   |   |   |
| Battery | 8h Talk/160h stand by | 4h Talk/30h Stand by | 4h Talk/36h stand by |
| SOS | ✓ | ✓ | X |
| GPS | ✓ | ✓ | ✓ |
| Size | 6.7"H - 3"W | 5.5"H - 2.3"W | 5.3"H - 1.3"W |
| Durability | -20°c +55°c IP65 | -20°c +55°c IP65 | IPX7 |
| Water res. | Jet water | Jet water | Waterproof |

# Starlink Direct to Cell Service: Gen 2 Satellites

- Starlink Direct to Cell service
  - Implemented on some satellites (V2)
  - Have an advanced "eNodeB" modem
  - Acts like a cell tower in space
  - Allowing network integration similar to a roaming partner.
- Provide access to:
  - Texting: Limited roll out
  - Calling (Future)
- It works with existing 4G and 5G LTE (Long Term Evolution) phones
  - No new hardware or apps Required
- Expected voice, data and IoT (Internet of Things) connectivity in 2025 --

# Starlink Direct to Cell Service: Gen 2 Saletilles

- Direct-to-cell service uses T-Mobile's Cell Phone Frequencies
  - **Earth-to-space**: 1910-1915 MHz
  - **Space-to-Earth**: 1990-1995 MHz
- 1st testing basic texting (SMS) services
- 320 of the more than 2,600 Gen2 (V2) Starlink satellites
  - Equipped with a direct-to-smartphone equipment

- Lower frequencies (700−800MHz) **penetrates** solid structures
  - 1910 to 1995MHz have limited Indoor capability
- Higher Frequencies have higher loss in free space --

# T-Mobile Network Frequencies

| Technology | Frequencies |
|---|---|
| 5GUC (Ultra Capacity 5G) | •Band n41 (2.5 GHz)<br>•Band n258 (24 GHz)<br>•Band n260 (39 GHz)<br><br>•Band n261 (28 GHz) |
| 5G (Extended Range 5G) | •Band n71 (600 MHz) |
| 4G LTE | •Band 2 (1900 MHz)<br>•Band 5 (850 MHz)<br>•Band 4 (1700/2100 MHz)<br>•Band 66 (Extension of band 4 on 1700/2100 MHz). |
| Extended Range 4G LTE | •Band 12 (700 MHz)<br>•Band 71 (600 MHz) |
| 2G | •Band 2 (1900 MHz) |

Band 2 Direct Cell service via Starlink satellite

# P2-04: Digital Communication

- ❑ Digital Communication
- ❑ Ultimate Link Goal: Bit Error Rate (BER)

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# Digital Communication

- We live in an Analog World
- Communicate in a Digital World
  - Bits: 1's & 0's
- Accurate Communication depends on correctly receiving the transmitted Bits: 1's & 0's
  - Key Parameter: Bit Error Rates (BER)
- Acceptable BER is application related
  - Voice
  - Video
  - Critical Data
- BER is related to
  - Carrier (C) to Noise (N) Ratio (C/N)
  - Bit Energy (Eb) to Noise (No) Ratio (Eb/No)

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

$f_b$ : Final Bit Rate
B: Symbol Bandwidth

$$f_b \geq B \quad - -$$

# Ultimate Link Goal: Bit Error Rate (BER)

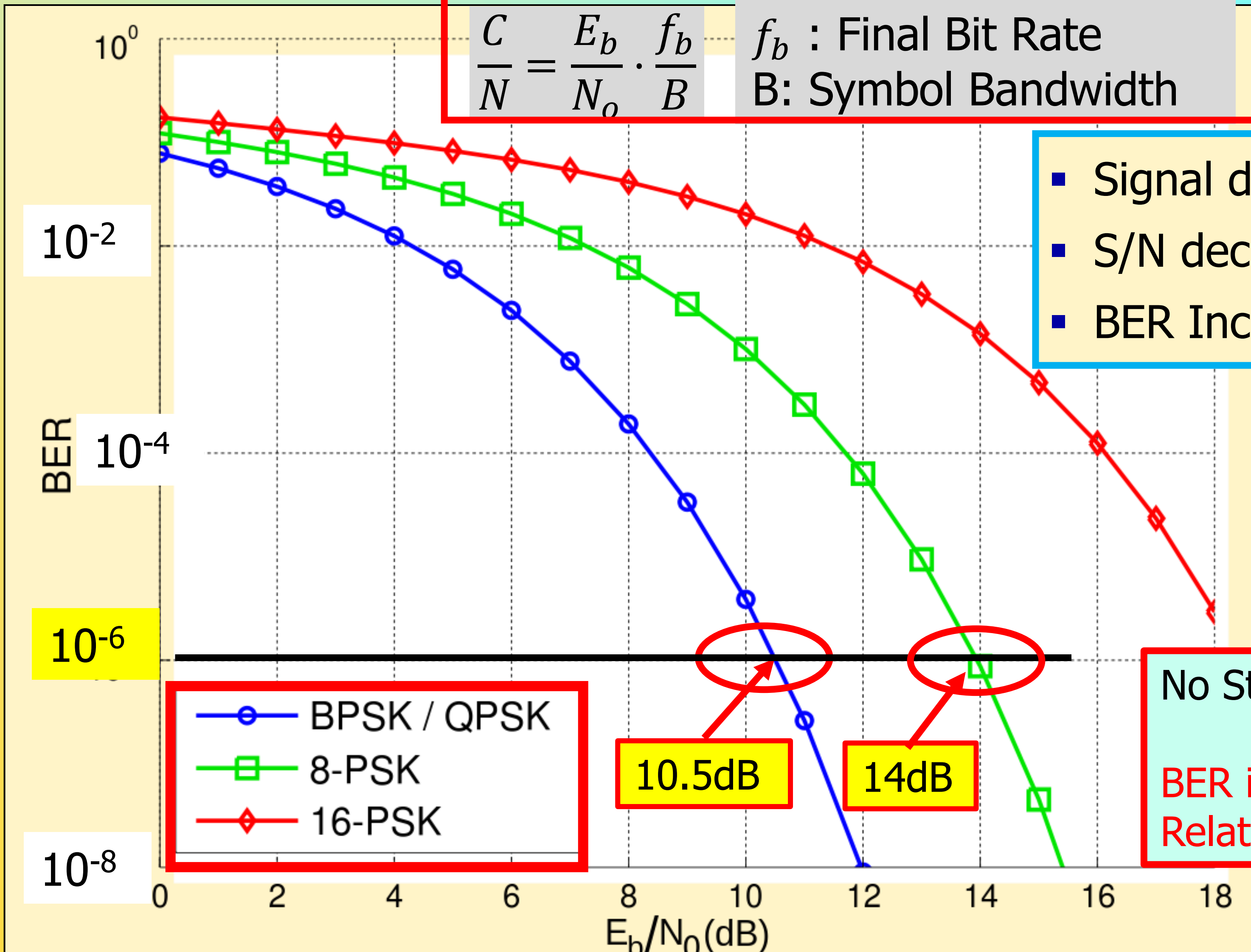
Bit Error Rate ➔ Carrier to Noise Ratio (C/N) ➔ $E_b/N_o$

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

$f_b$ : Final Bit Rate
B: Symbol Bandwidth

$$f_b \geq B$$

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




No Standard for BER

BER is Application Related --

# P2-05: Vector Modulation

- ❑ **Vector Modulation**
- ❑ Quadrature Amplitude Modulation
- ❑ Gray Codes
- ❑ Forward Error Correcting Codes

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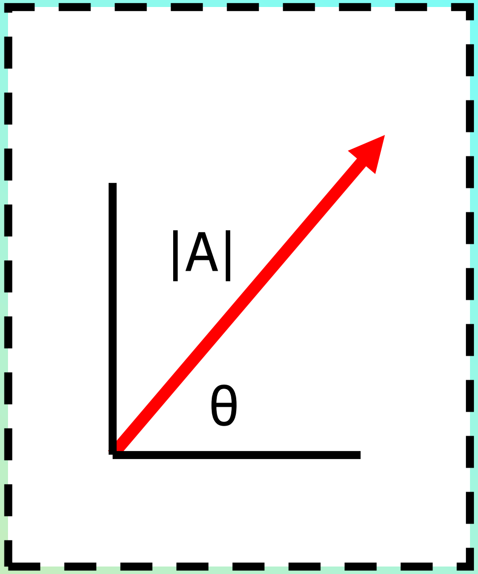
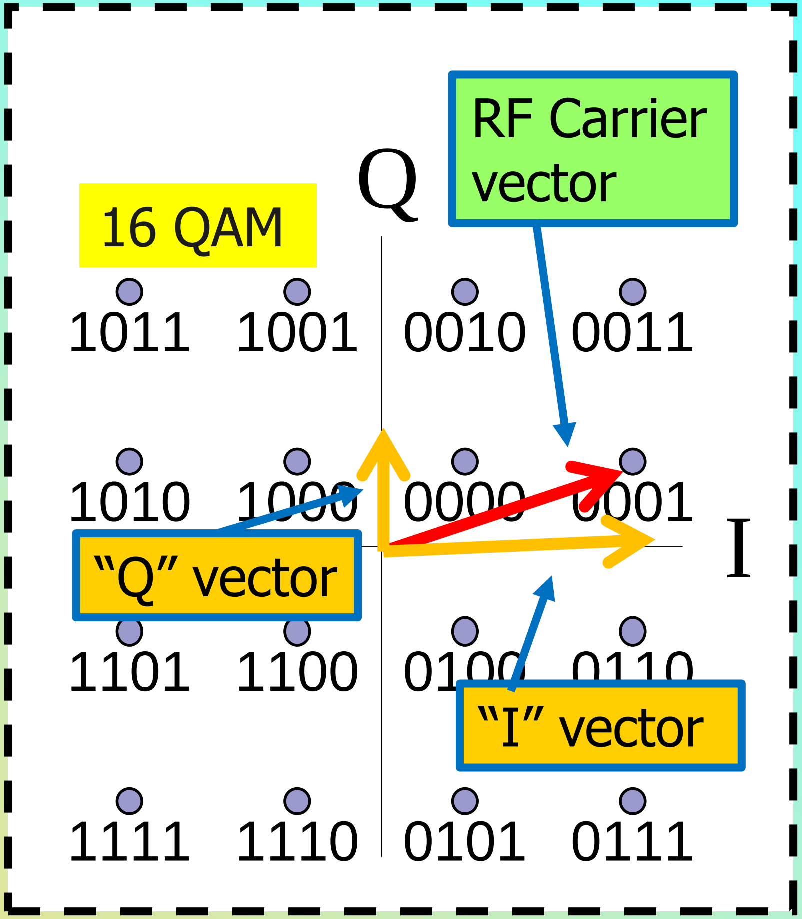
# Vector Modulation

- Digital Communications has almost universally replaced Analog Communications
  - Analog requires higher S/N than digital
- Digital Transmission via Vector Modulation
  - RF Carrier is a vector
    - Amplitude (|A|)
    - Phase information (θ)
  - Vector location defines a symbol
- A Symbol is a collection of Bits (1's & 0's)--



# 16QAM (Quadrature Amplitude Modulation)

- Constellation Points:
  - Sum of "I" & "Q" Vectors
- 16 Positions (RED Vector)
- 4 bits per position
  - 4 bits per Symbol
  - Bit Rate is 4 times Symbol Rate

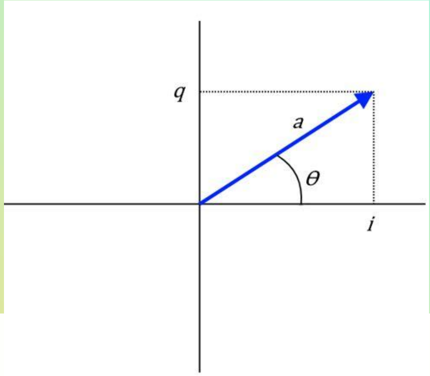



$$\frac{C}{N} = \frac{E_b}{N_o} \cdot \frac{f_b}{B}$$

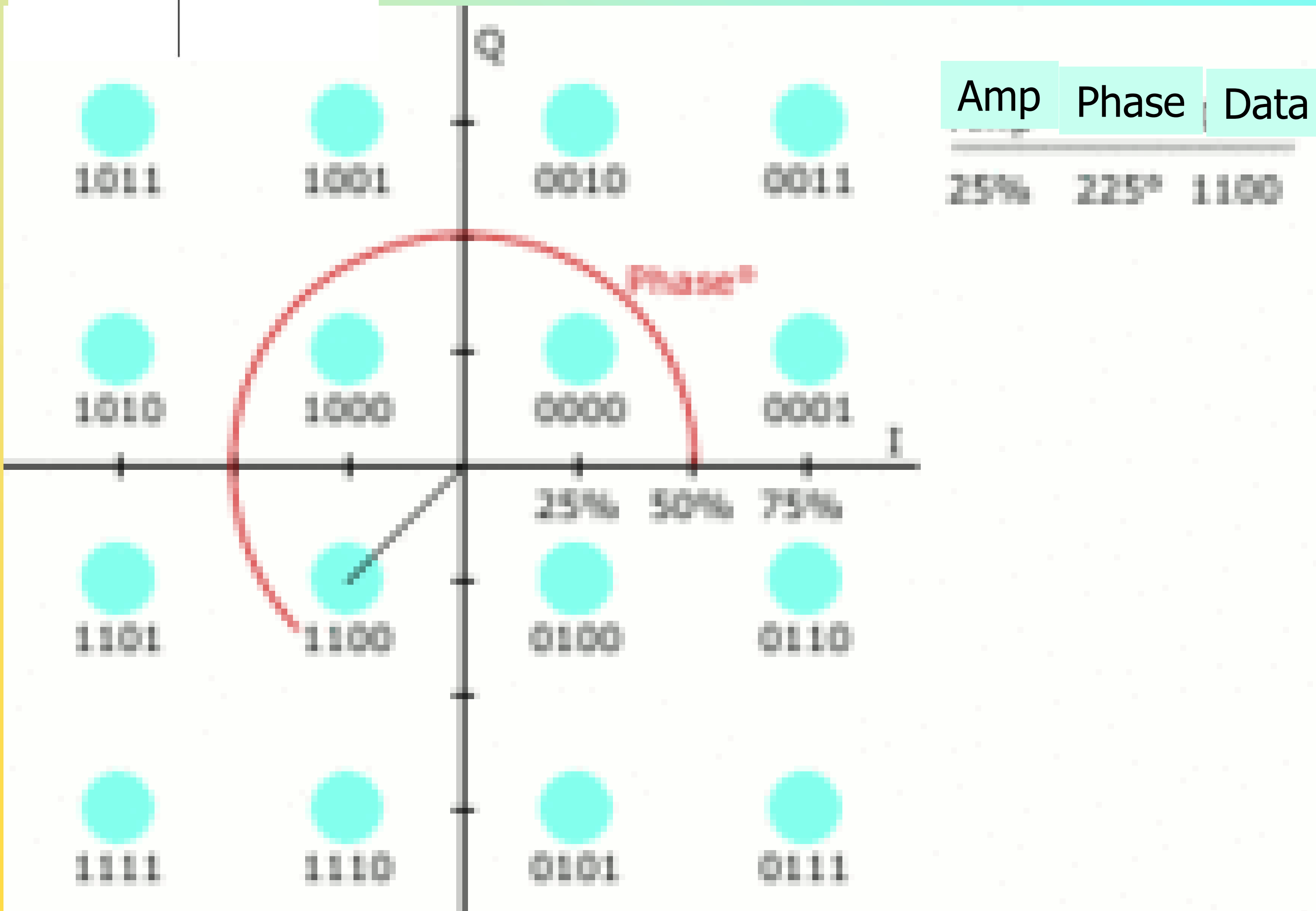
$f_b$ : Final Bit Rate
B: Symbol Bandwidth

$$f_b = 4 \cdot B \quad --$$

# 16QAM (Quadrature Amplitude Modulation)

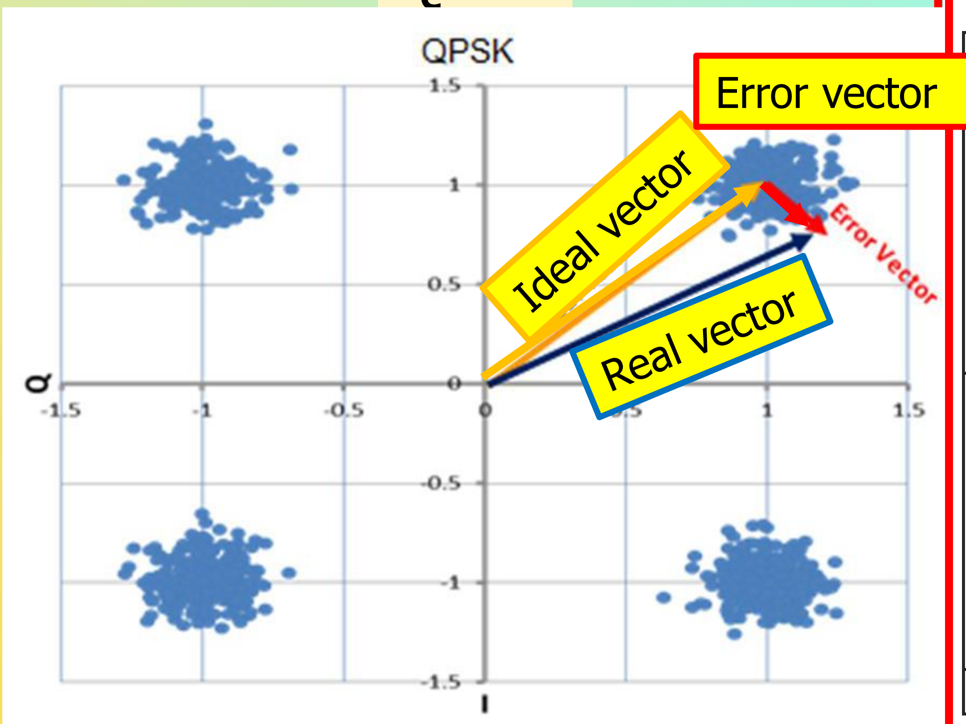



- RF vector points to a symbol
- 4 Bits per symbol

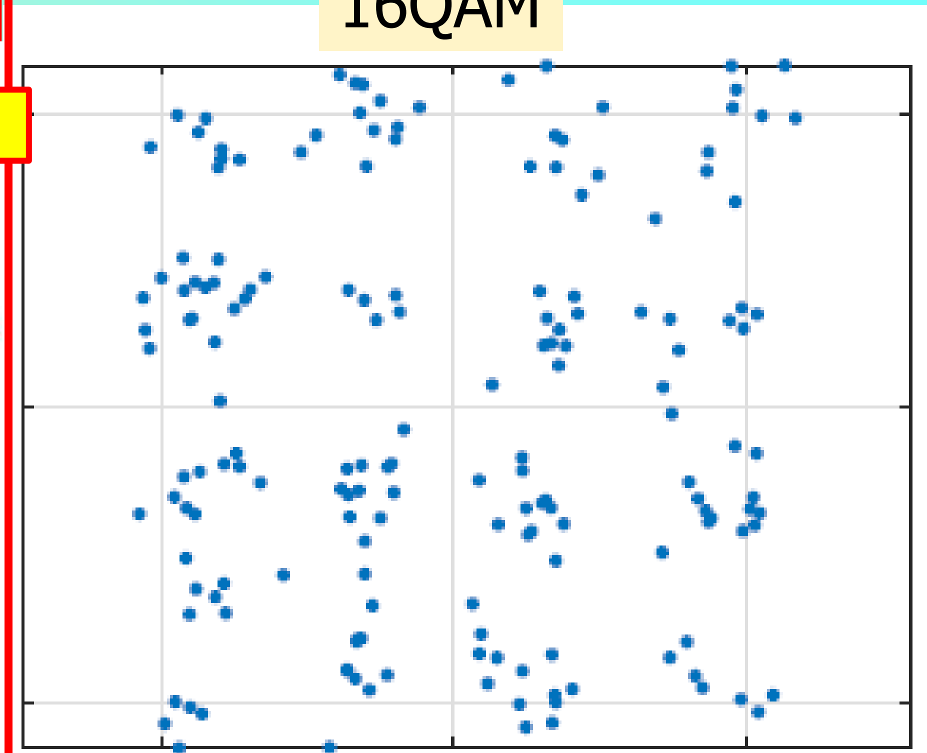


# Vector Errors

QPSK



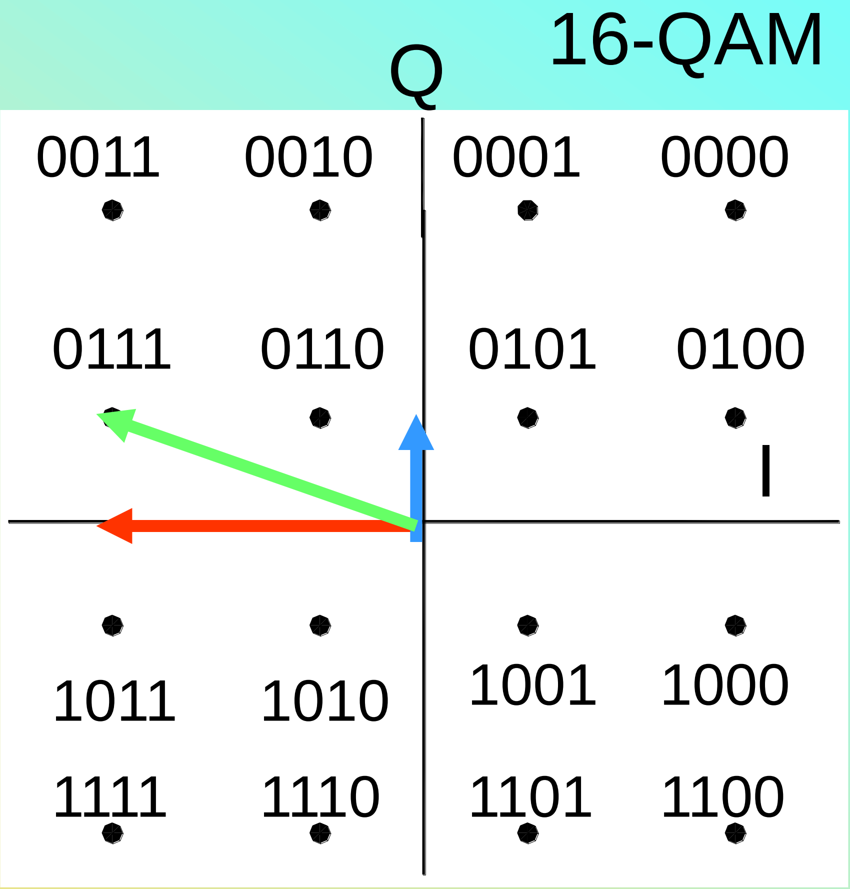

16QAM



- ❑ Note: Vector Phase & Amplitude Errors
- ❑ 4QAM (QPSK) is less prone to Symbol Errors
- ❑ Vector Errors are typically to adjacent positions --

# Gray Code

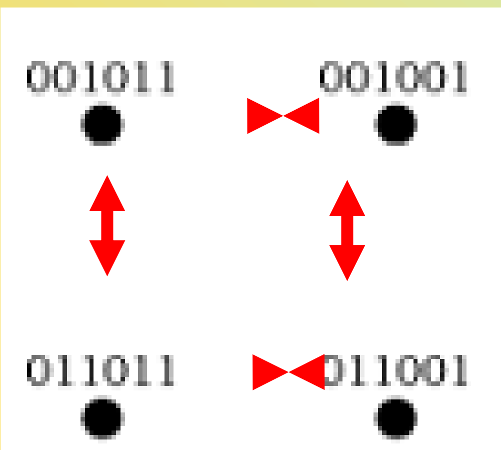
- Adjacent positions differ by a single digit
- Errors are typically "single bit"
- Enhances the ability to correct data without retransmission
  - Forward Error Correction (FEC) --

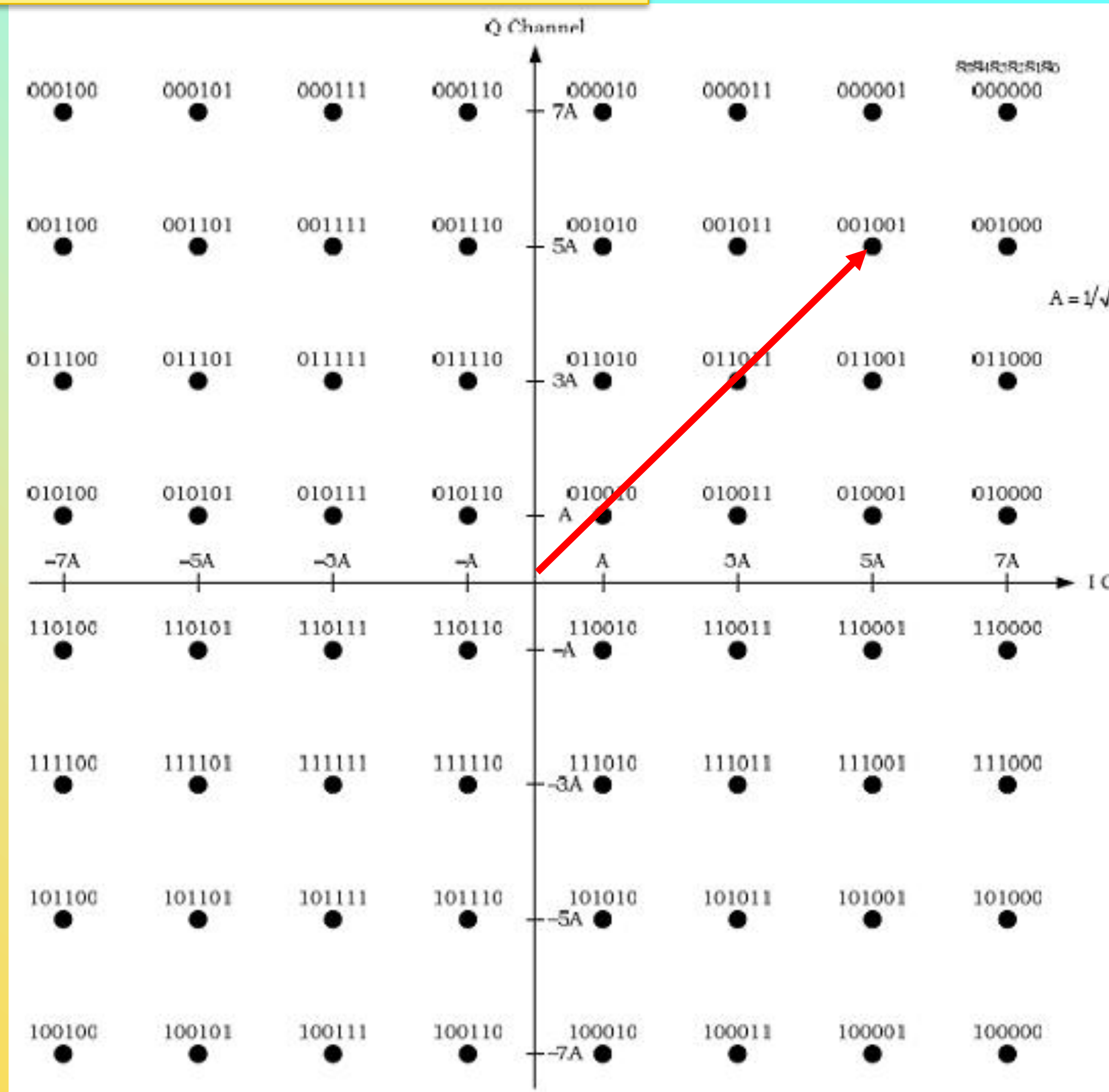



Transmitted 16-QAM Data, 4 bits/symbol

# 64QAM: 6 Bits per symbol

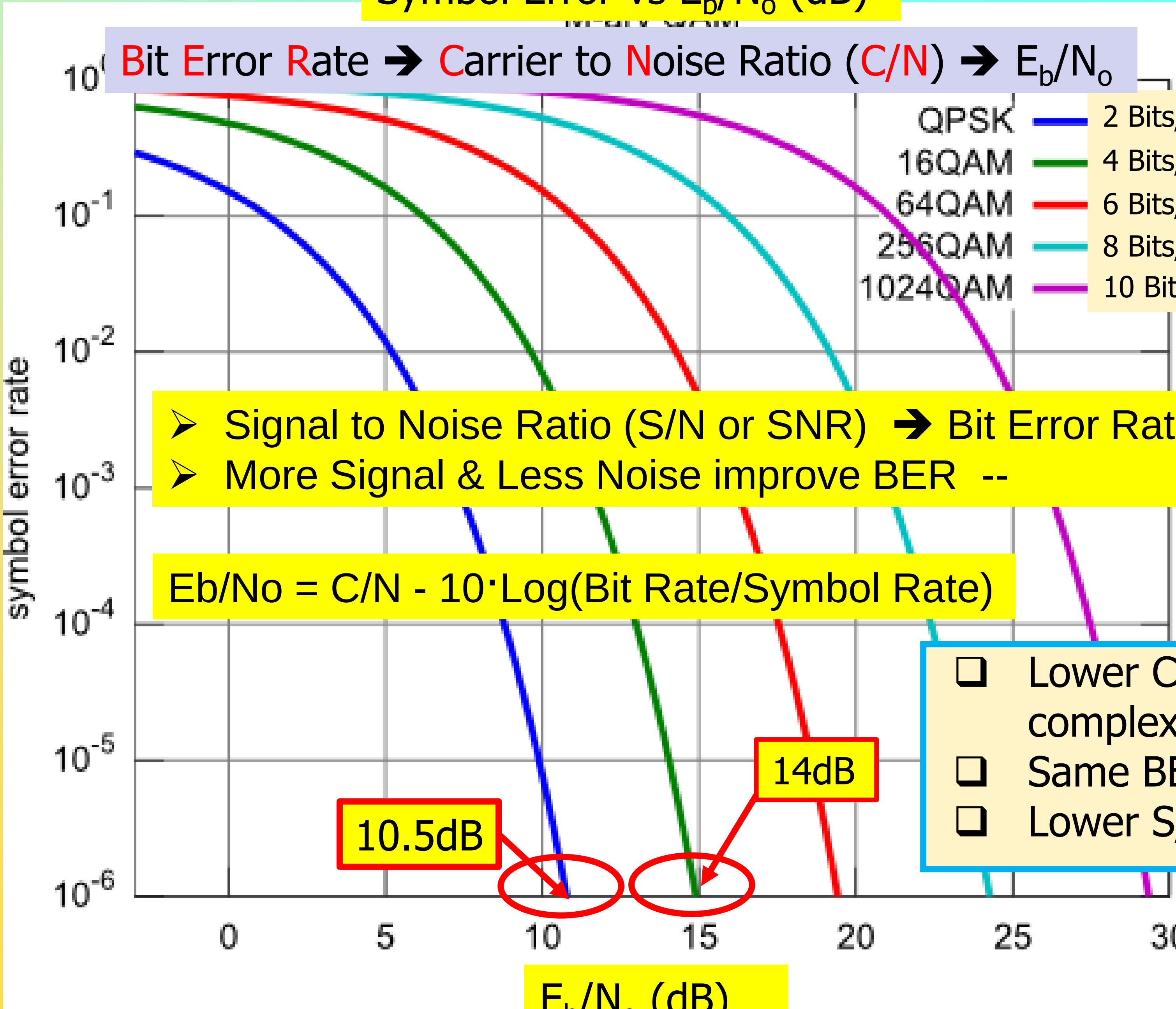
Note:
Gray Code



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

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




- ➢ 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)

- ❑ Lower Constellation complexity
- ❑ Same BER
- ❑ Lower S/N ⇩

# Forward Error Detection

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

- 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
- Even number of “1’s”

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

| | | | | | | | Parity Bits |
|---|---|---|---|---|---|---|---|
| 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 |

Parity Word

Bit Error

Parity Error

| | | | | | | | Parity Bits |
|---|---|---|---|---|---|---|---|
| 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 |

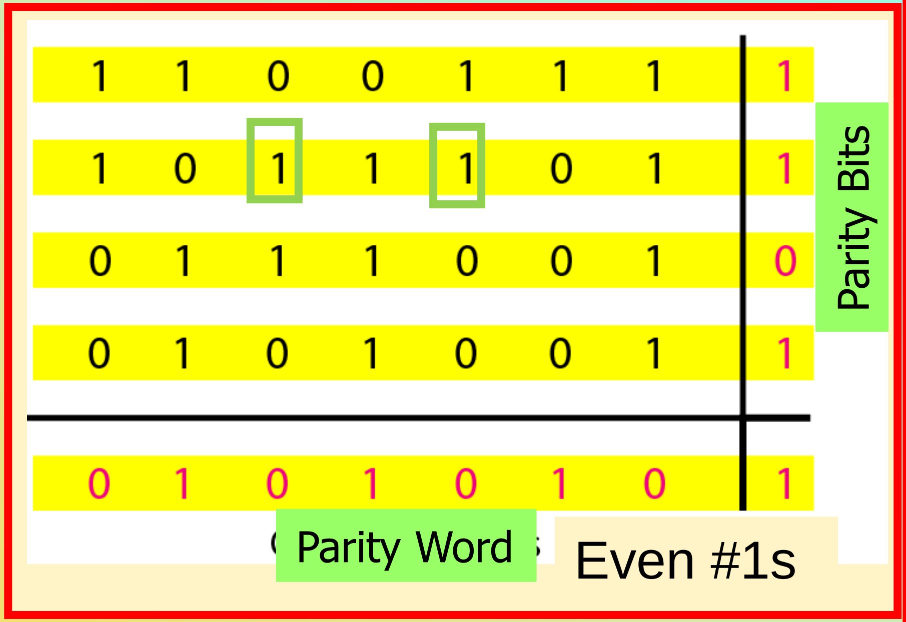
Parity Word

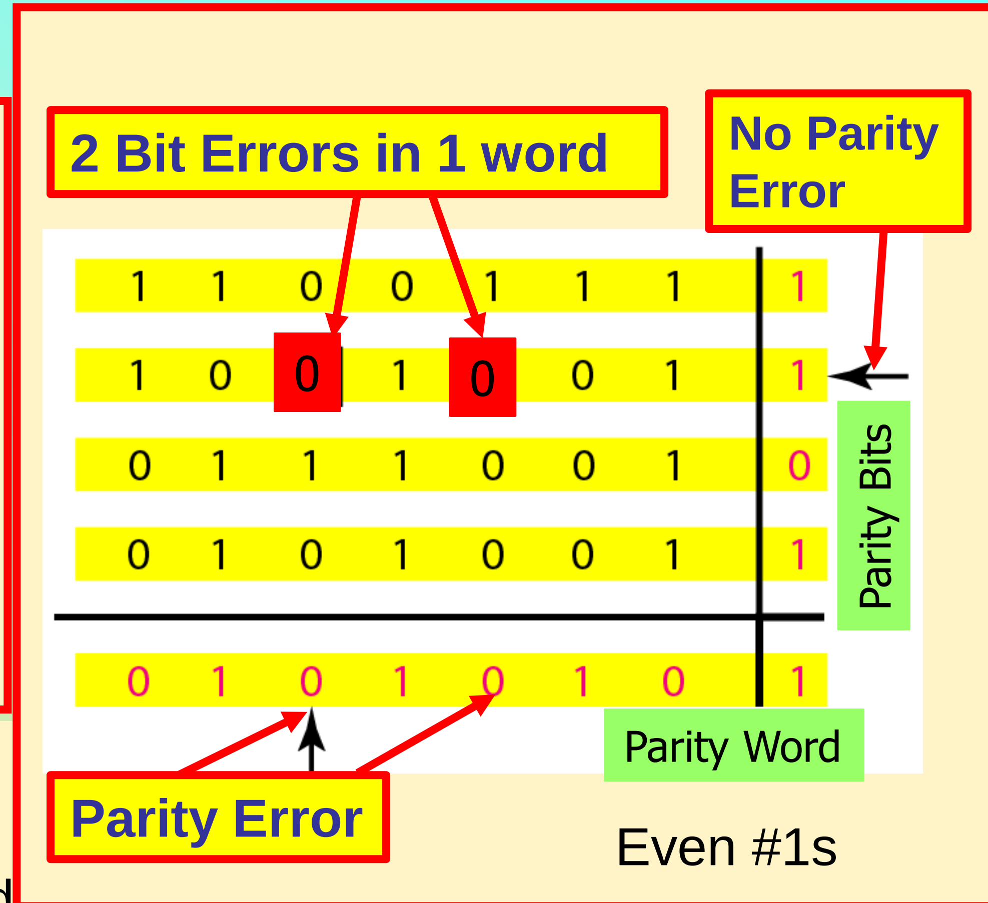
Parity Error

(Even #1s)

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

# Forward Error Correction




- 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 --

## P2-06: Satellite Communication Link: Example

- Communications Link:
  - Factors to Consider in Determining $C/N_0$
- **Effective Isotropic Radiated Power (EIRP)**
- **Path Loss (PL)**
- **Signal Reception - G/T and C/N**
  - **` Gain/(Noise Temperature): G/T**
  - **Carrier to Noise Ratio (C/N)**

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# Communications Link: Factors to Consider in Determining $C/N_0$

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

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

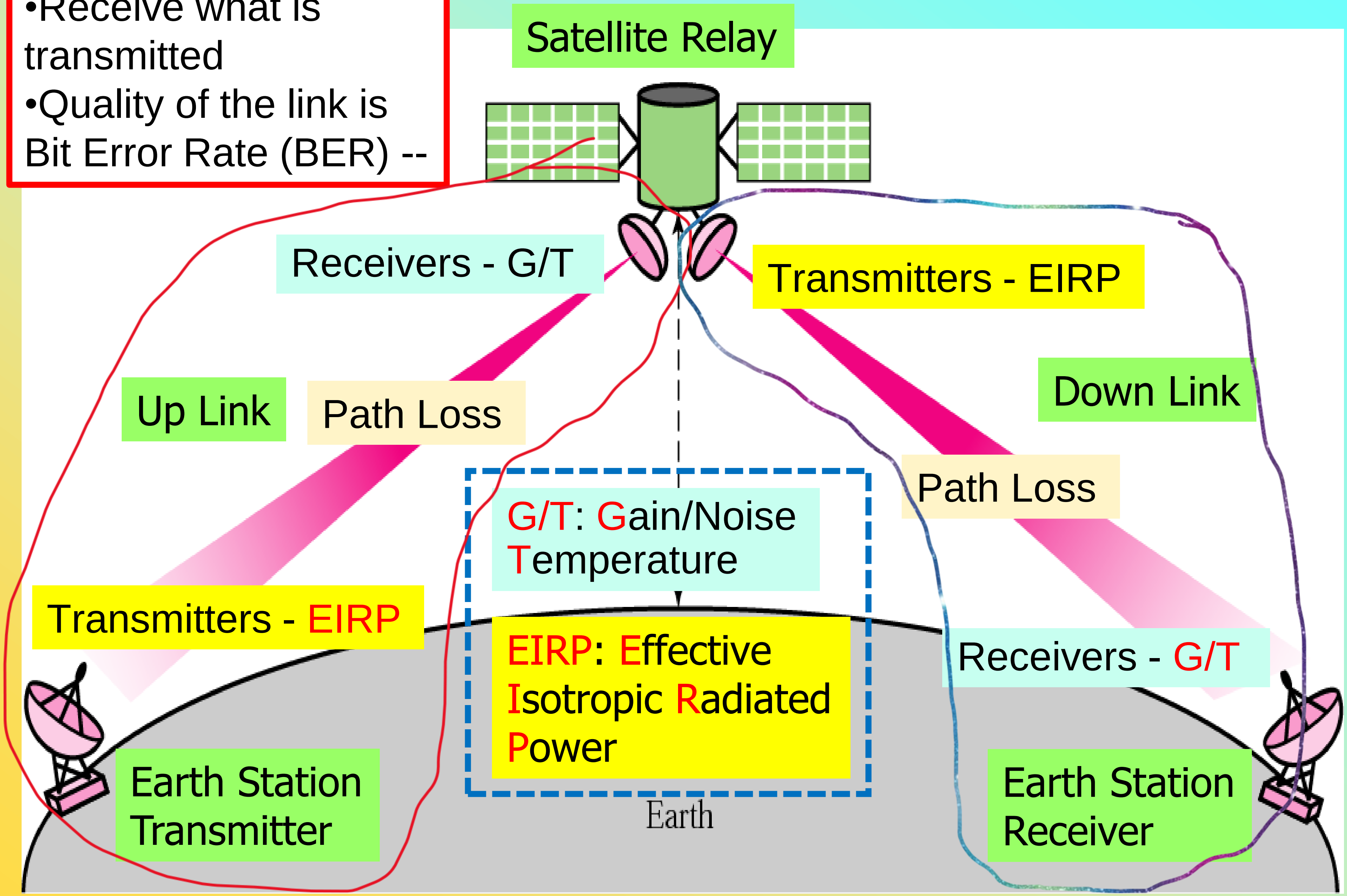
- EIRP
  - Effective Isotropic Radiated Power
  - Antenna Gain x Output Power
- Path Loss
  - Distance to Satellite
- G/T
  - Antenna Gain (G) divided by Noise Temperature (T)
- Using Minimum Bandwidth (B)
  - Bandwidth is costly --

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

--

# Satellite Link

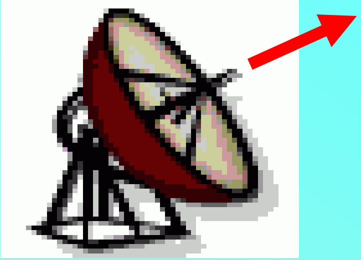
- Receive what is transmitted
- Quality of the link is Bit Error Rate (BER) --

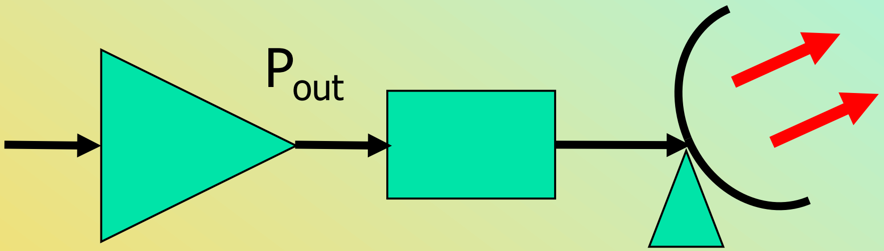


# Signal Transmission – EIRP

**EIRP: Effective Isotropic Radiated Power**

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

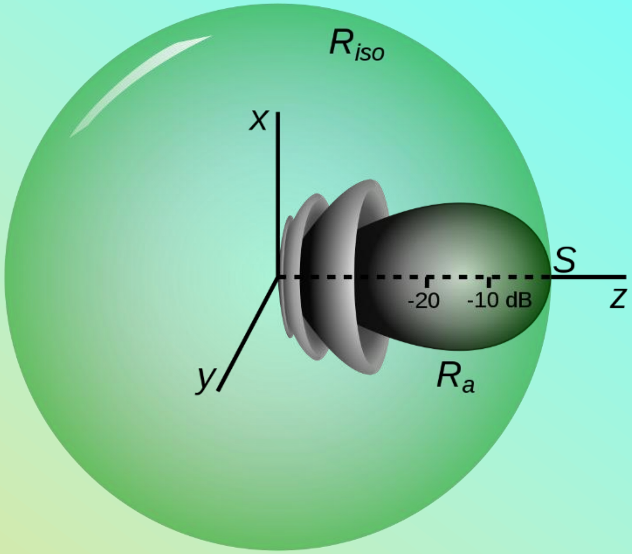





Power Amplifier

Passive Loss ($L_p$)

Directional Antenna Gain ($G_P$)




Isotropic Radiator

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

--

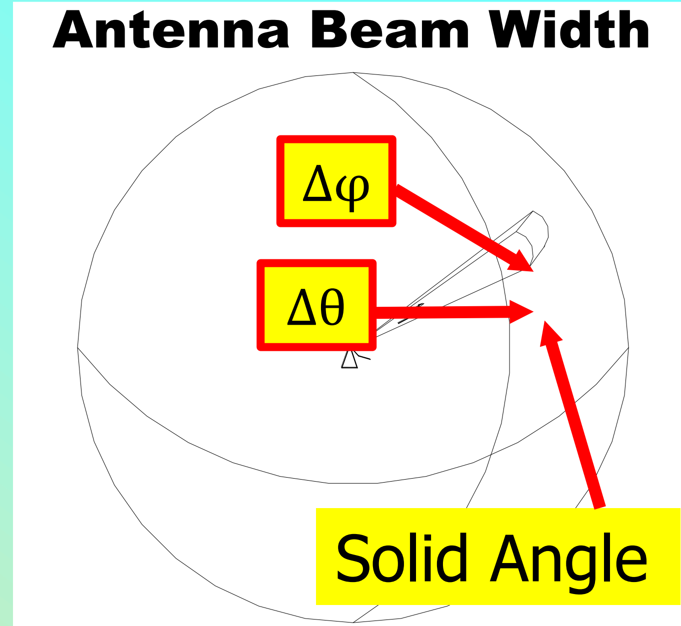
# Estimating Antenna Gain

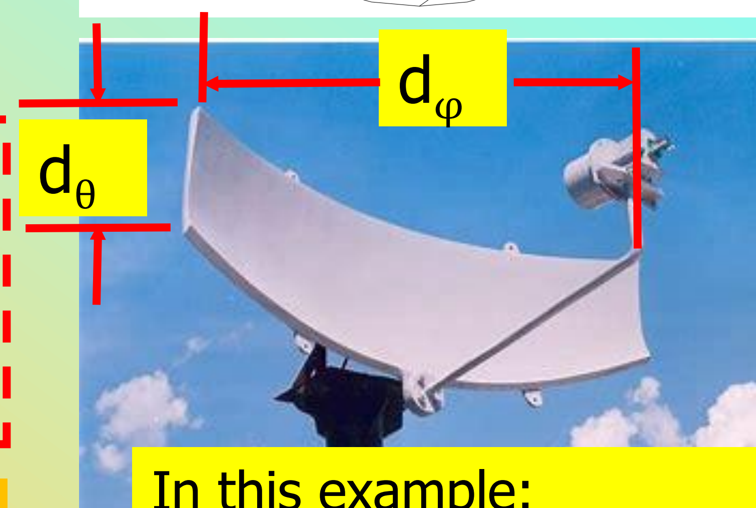
- Estimating antenna gain ($G_p$)
  - $\Delta\theta \approx (\lambda/d_\theta)$ (radians)
    - $d_\theta$ is the antenna dimension along the angle "θ" axis
    - Large antenna means small $\Delta\theta$
  - $\Delta\varphi \approx (\lambda/d_\varphi)$ (radians)
    - $d_\varphi$ is the antenna dimension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

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

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

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




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

# Estimating Ground Antenna Gain


$$c = 299792458\ \frac{m}{s}$$

$$Ft := 14000 \cdot MHz$$

$$\lambda := \frac{c}{Ft}$$

$$\lambda = 0.8431\ in$$

$$El := 19 \cdot in$$

$$Az := 12 \cdot in$$

$$AntGain := 4 \cdot \pi \cdot \frac{Az}{\lambda} \cdot \frac{El}{\lambda}$$

$$AntGain = 4031.1301$$

$$AntGaindB := 10 \cdot \log(AntGain)$$

$$AntGaindB = 36.0543 \quad \text{dB}$$

# Starlink: Frequency & EIRP

| Link Type | Frequency | Modulation | Emission Designator | Maximum EIRP | Half Power Beamwidth |
|---|---|---|---|---|---|
| Broadband Downlink (space-to-Earth) | 10.7-12.7 GHz | Up to 64 QAM | 240MD7W | N/A | 3.5° (boresight) 5.5° (at slant) |
| Broadband Uplink (Earth-to-space) | 14.0-14.5 GHz | Up to 64 QAM | 60M0D7W | 38.2 dBW | 2.8° (boresight) 4.5° (at slant) |

EIRP (dBW) = $P_{out}$(dBW) – $L_p$(dB) +$G_p$(dB)

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

$AntGaindB = 36.0543$ dB

$EIRPg := 38.2$ dBW

$LpdB := 4.5$ dB Estimated

$PoutgdB := EIRPg + LpdB - AntGaindB$

$PoutgdB = 6.6457$ dBW

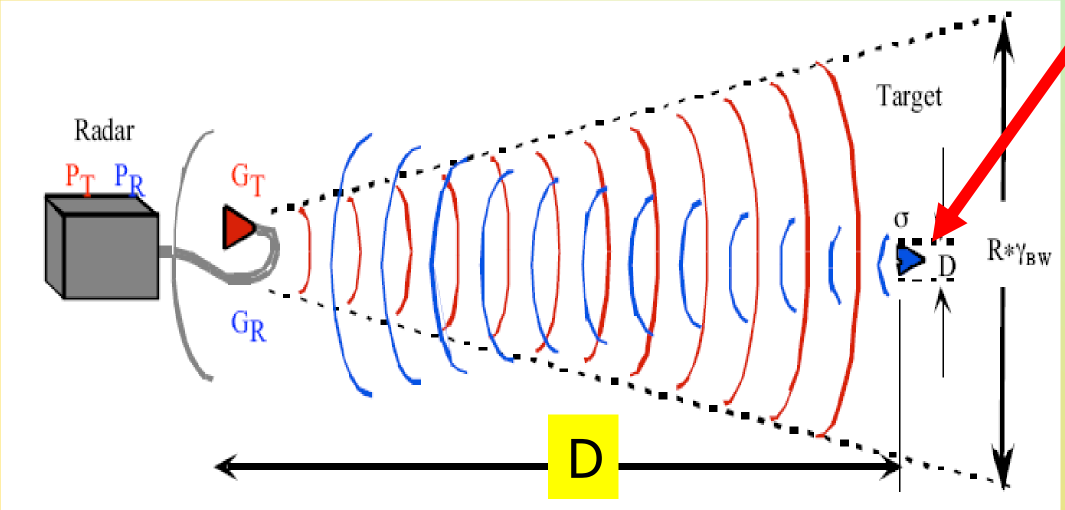
$Poutg := 10^{\frac{PoutgdB}{10}} \cdot 1 \cdot W$

$Poutg = 4.6193\ W$ --

# 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



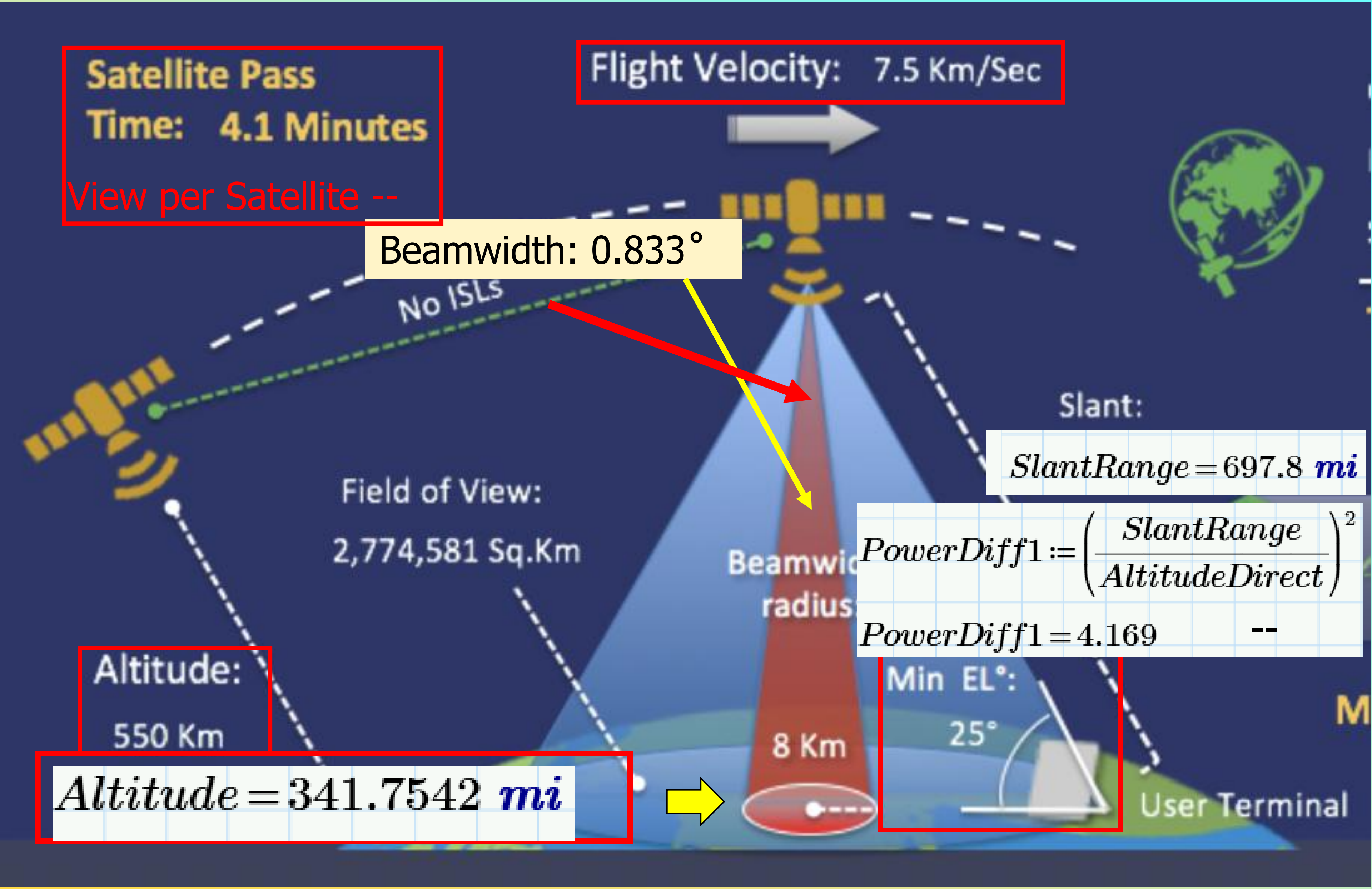

Receiving antenna sees less of the wave front as the distance increases

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

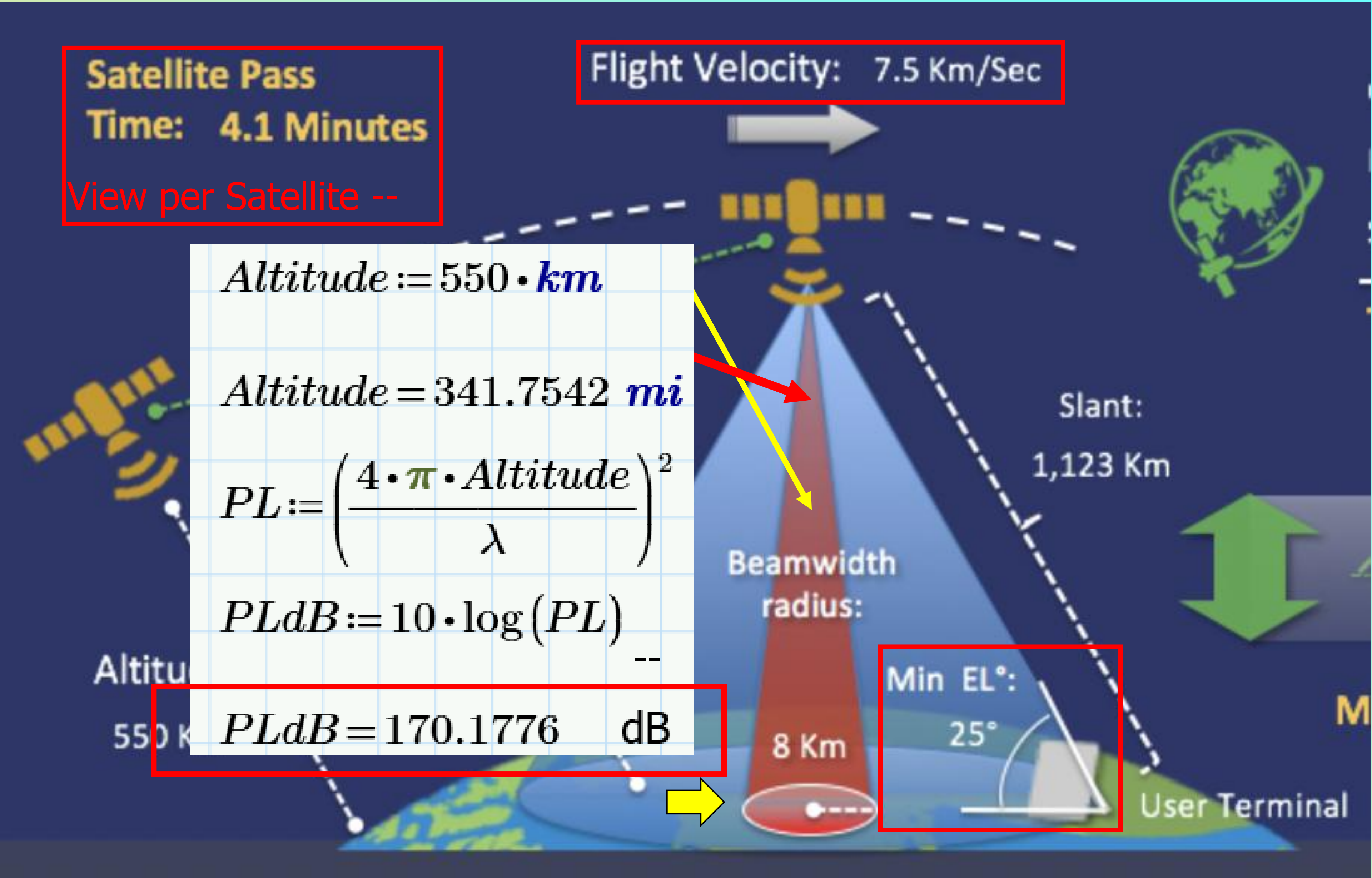
"λ" is the wavelength
"D" is the Distance Traveled

Path Loss in dB = 10·Log($P_L$) --

# Starlink LEO Earth Footprint: Relative Path Loss



# Starlink LEO Earth Footprint: Relative Path Loss




$$Altitude := 550 \cdot km$$

$$Altitude = 341.7542\ mi$$

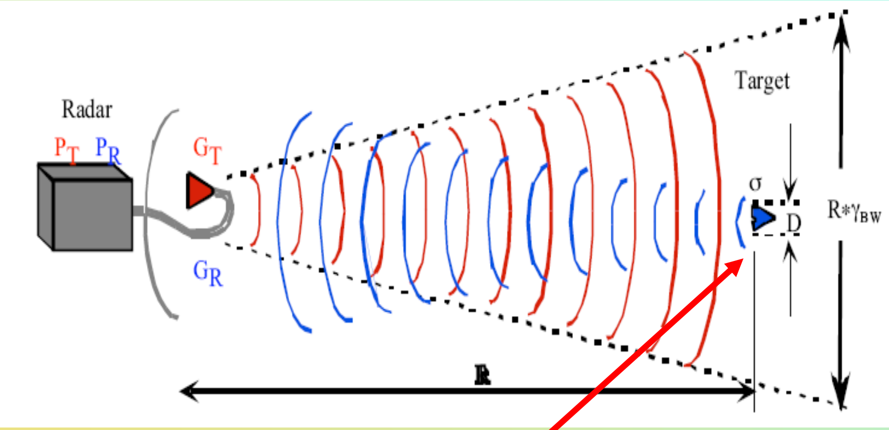
$$PL := \left(\frac{4 \cdot \pi \cdot Altitude}{\lambda}\right)^2$$

$$PLdB := 10 \cdot \log(PL)$$

--

$$PLdB = 170.1776\ \text{dB}$$

# Signal Reception - G/T & C/N




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

C/N (dB) = EIRP(dBm) –Path Loss (dB) + G/T (dB) + k·T·B (dBm)

G/T (dB): Includes NF

k·T·B (dBm): Thermal Noise

NoisedBm = 10·Log(k·T·B) is a function of Bandwidth

| Starlink Satellite Receiver Parameters | |
|---|---|
| Antenna gain (Grx) | 42.7 dB |
| Noise temperature (Tn) | 300 K |

## G/T : Satellite Receiver

$$GRxdB := 42.7\,dB$$

$$Tn := 300 \cdot K$$

$$GTdB := GRxdB - 10 \cdot \log\left(\frac{Tn}{1 \cdot K}\right)$$

$$GTdB = 17.9288\ dB$$ --

# Thermal Noise Calculation

PERFORMANCE. Starlink users typically experience download speeds **between 25 and 220 Mbps**, with a majority of users experiencing speeds over 100 Mbps. Upload speeds are typically between 5 and 20 Mbps.

Thermal Noise Calculation

$$BW := 5 \cdot MHz$$

$$T := 300 \cdot K$$

$$Nt := k \cdot T \cdot BW$$

$$NtdBm := 10 \cdot \log\left(\frac{(k \cdot T \cdot BW)}{1 \cdot mW}\right)$$

$$NtdBm = -106.8383 \text{dBm} \quad \text{--}$$

# 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)

Carrier Level into antenna | Receiver G/T | Thermal Noise

C/N (dB)=Carrier [dBm] + G/T[dB] - 10·Log(k·T·B) [dBm] --

# Signal Reception - C/N

- 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 (dB) = EIRP(dBm) –Path Loss (dB) + G/T (dB) + k·T·B (dBm)

Includes NF (G/T (dB))

Thermal Noise (k·T·B (dBm))

$EIRPdBm = 68.2$ dBm

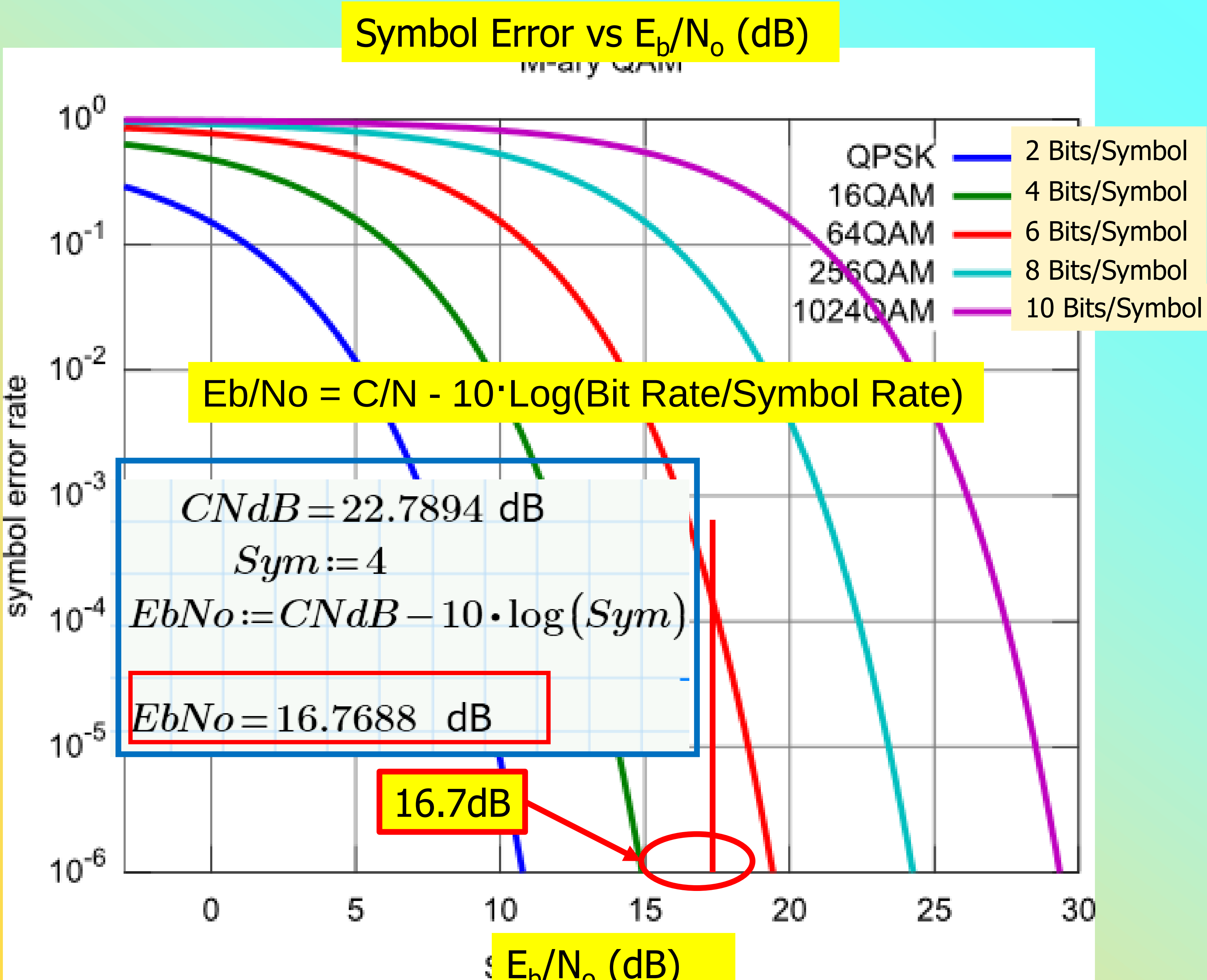
$PLdB = 170.1776$ dB

$GTdB = 17.9288$ dB

$NtdBm = -106.8383$ dBm

$CNdB := EIRPdBm - PLdB + GTdB - NtdBm$

$CNdB = 22.7894$ dB --



Symbol Error vs $E_b/N_o$ (dB)
M-ary QAM
symbol error rate
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0
5
10
15
20
25
30
QPSK 2 Bits/Symbol
16QAM 4 Bits/Symbol
64QAM 6 Bits/Symbol
256QAM 8 Bits/Symbol
1024QAM 10 Bits/Symbol
Eb/No = C/N - 10·Log(Bit Rate/Symbol Rate)
$CNdB = 22.7894$ dB
$Sym := 4$
$EbNo := CNdB - 10 \cdot \log(Sym)$
$EbNo = 16.7688$ dB
16.7dB
$E_b/N_o$ (dB)

# Questions and Comments

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