Fundamentals of Satellite Communications, Part 1

Howard Hausman

President

MITEQ, Inc.

Hauppauge, NY 11788

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Fundamentals of Satellite Communications Part 1

- Satellite Communications Introduction
- Types of Satellite Services
- Satellite Configurations
- Geostationary Satellites
- Non-Geostationary Satellites
- Satellite Configurations
- Frequency Reuse / Polarization
- Earth Station Antennas
- Major Earth Stations Components
- Satellite Communications Summary
- Part 2 – Communication System Link Analysis
- Part 3 – Specifying Subsystems for Data Communications -

Satellite Communications Introduction

- Are Satellites a Cost Effective Means of Communications? Answer is NO.
  - Limited Frequency Spectrum
  - Limited Spatial Capacity (Orbital Slots)
  - High Equipment Cost
- Land lines and Fiber are Much More Cost Effective
  - Fiber Reuses Spectrum, Multi-Fiber Cables
  - A few multi-fiber cables can have as much information as all the satellites in orbit
  - Land Line Infrastructure is In Place -

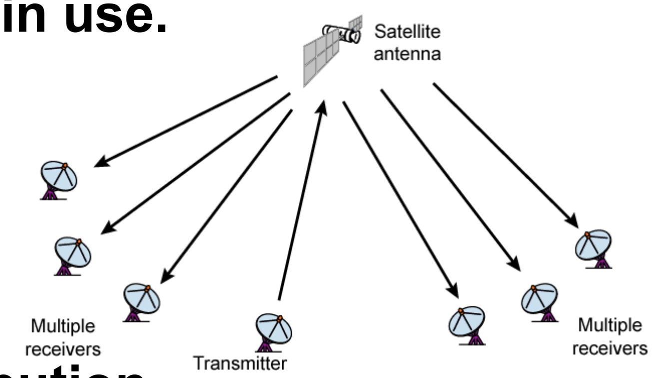
Satellites Provides Capabilities Not Available with Terrestrial Communication Systems

- Adaptable to the needs of different customers
- Variable Information Rates
- Mobility
- Cost advantage over building land lines for a limited population
- Versatility in use Paging, Voice, Data, Video
- No geographical obstructions that prohibit landlines
- Quick implementation – e.g. News Gathering
- Alternate routing or redundancy as required
- Cost is independent of distance
- Cost effective for short term requirements e.g. Sporting Events -

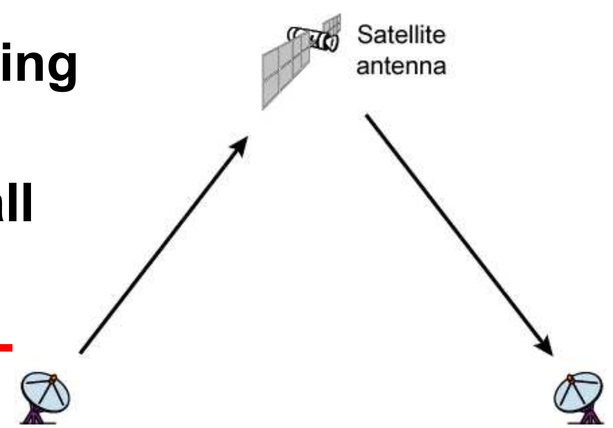
Types of Satellite Services

Fixed Service Satellites (FSS)

- Communication to non-moving satellites.
- Generally Earth Station is not moving when in use.
  - Low Cost Tracking antennas are making communication on the move a reality
- Types of service
  - Video:
    - Broadcast: Television network distribution
    - Satellite News Gathering (SNG).
  - Voice:
    - Telecommunications traffic / connecting cells.
    - Connecting cellular telephone to small islands
  - Data: Internet, Business to Business -



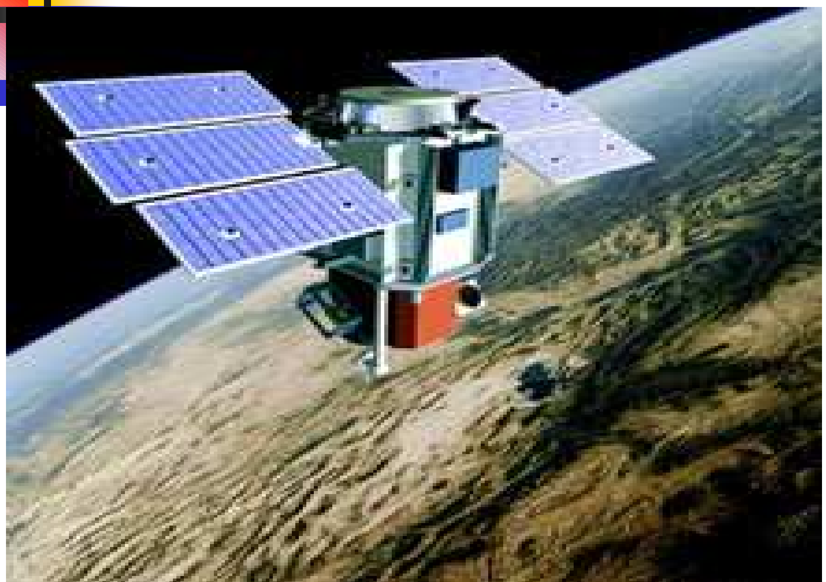
(b) Broadcast link



Satellite Industry Issues and Concerns

- Frequency spectrum
- Orbital Slots
- Regulatory inconsistencies
  - Signals reach multiple countries
- Consolidation of manufacturers
- Multiple standards
- Quality control versus production lead time
- Rapid change in telecommunications requirements
  - Digital Television
- Rapid deployment of Fiber optics -

Satellite Configurations & Stabilization



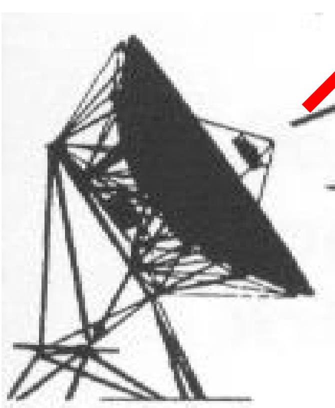
Satellite Components

- Propulsion System
- Telemetry
- Attitude Control
- Fuel
- Batteries
- Power & Thermal Control
- Solar Arrays

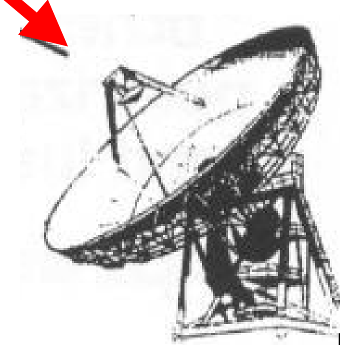
- ❑ LNA
- ❑ Down Converter
- ❑ High Power Amplifier
- ❑ Filter

Up Link Path Loss

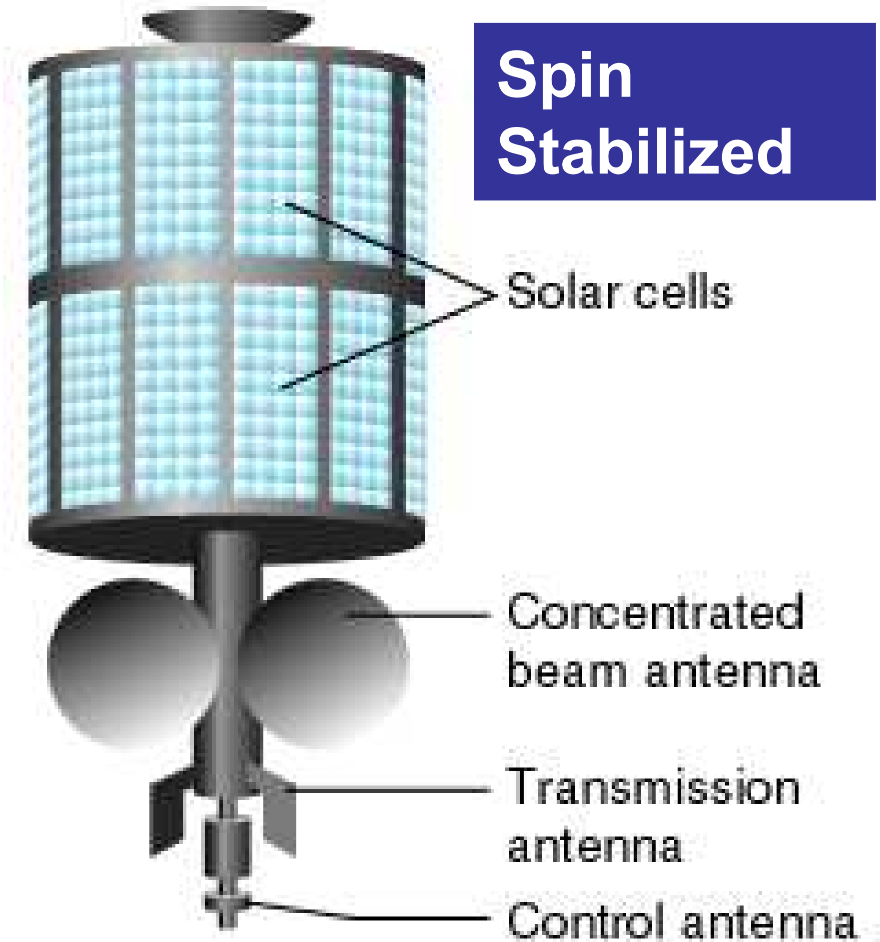
Down Link Path Loss



❑ Up Link Frequency Always Higher than Down Link Frequency -

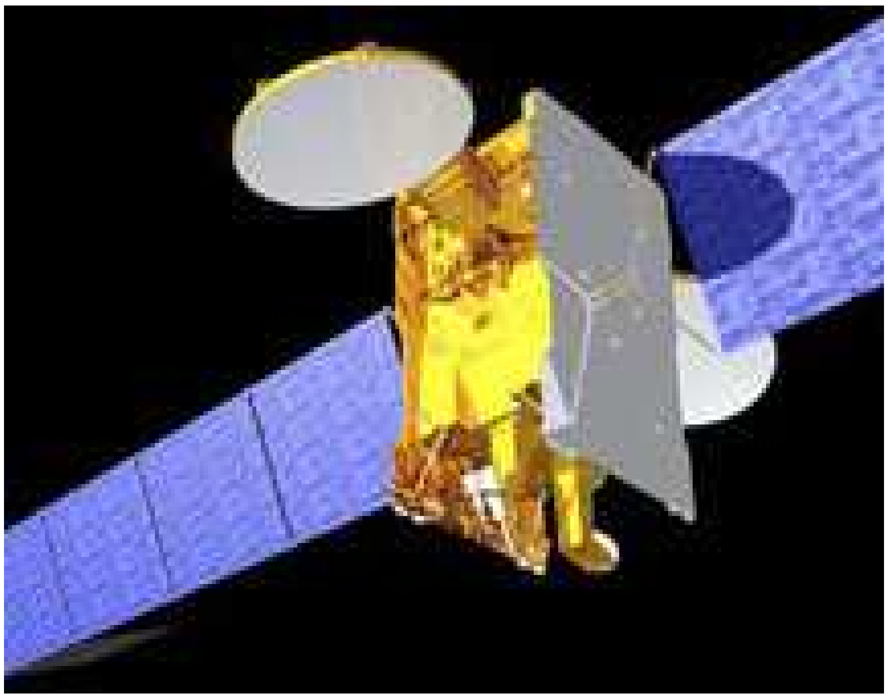


Spin Stabilized Satellites



- Satellite Body is Spin Stabilized (60-100 RPM)
- Gyroscopic stability
- Spins to minimize thermal effects
- 1/2 the solar cells face the sun at one time
- More efficient for smaller satellites
- Antenna must de-spun -

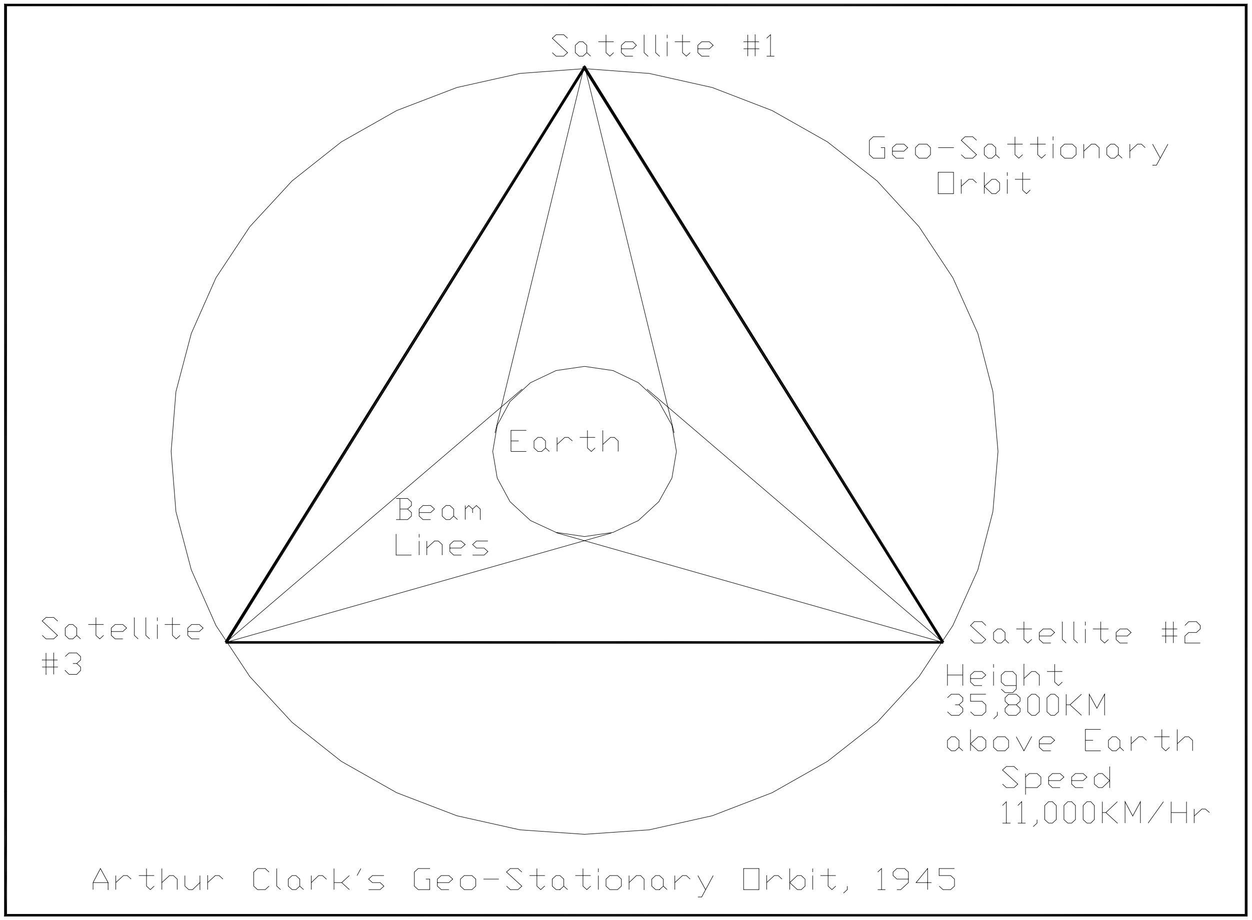
Body Stabilized Satellites



- All solar cells face the sun
- Thermal control more difficult
- Requires more stabilization control
- More solar cells than Spin Stabilized Satellites
- Better design for larger satellites -

Geo-Stationary Satellites

In a British magazine, "Wireless World", May, 1945, Arthur Clark, a renown science fiction author, wrote a paper predicting that three geo-stationary satellites would provide complete global telecommunications coverage.



Sir Arthur Clark wrote '2001, A Space Odyssey' Died this year 2008 -

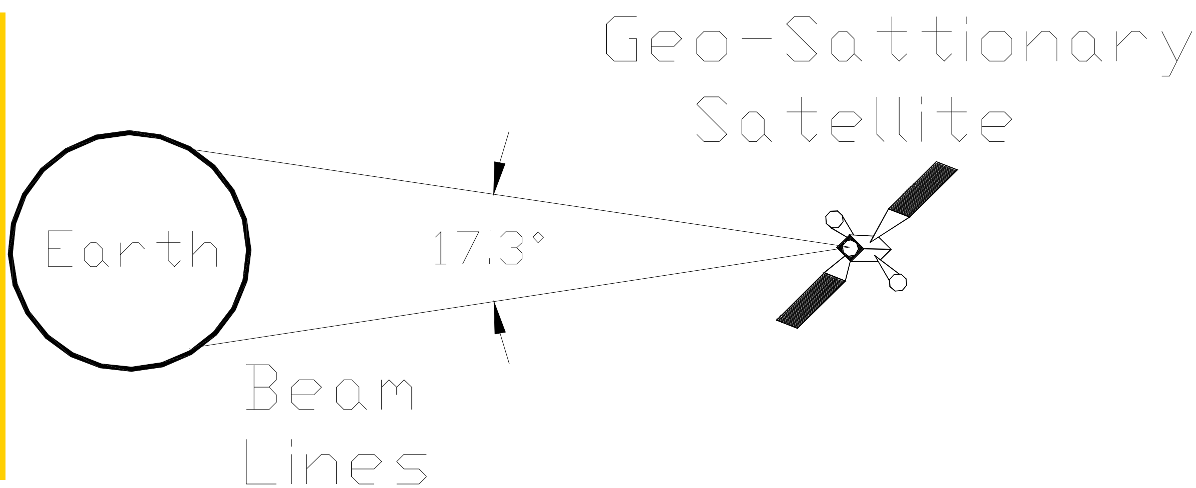
Geo-Stationary Satellites (Continued)

- Clark Orbit, which is Equatorial Circular
- 35,800km (22,300 Miles) above the Earth traveling at a speed of 11,000km/hour
  - One Orbit takes 24 hours
  - Synchronous with the spinning of the Earth
- Satellites headed for geosynchronous orbit first go to a Geostationary Transfer Orbit (GTO)
  - Elliptical orbit with apogee about 23,000 miles.
  - Firing the rocket engines at apogee then makes the orbit circular.
- A Single Satellite is visible from ≈ 1/3 of the earth's surface, excluding extreme Polar Regions.
- Cannot see latitudes greater than ± 77°
- Orbital locations are regulated by the International telecommunications Union (ITU) -

Geo-Stationary Satellites Beams

- Generally satellites must be spaced at least 1.5° to 2° apart (2° ≈ 911 miles or 1,466 Km).
  - Earth Station antenna will illuminate multiple satellites if they are spaced closer
- Orbital slots are measured in degrees going East from Greenwich meridian = 0°

- Satellite antenna beam width is 17.3° for full earth coverage -



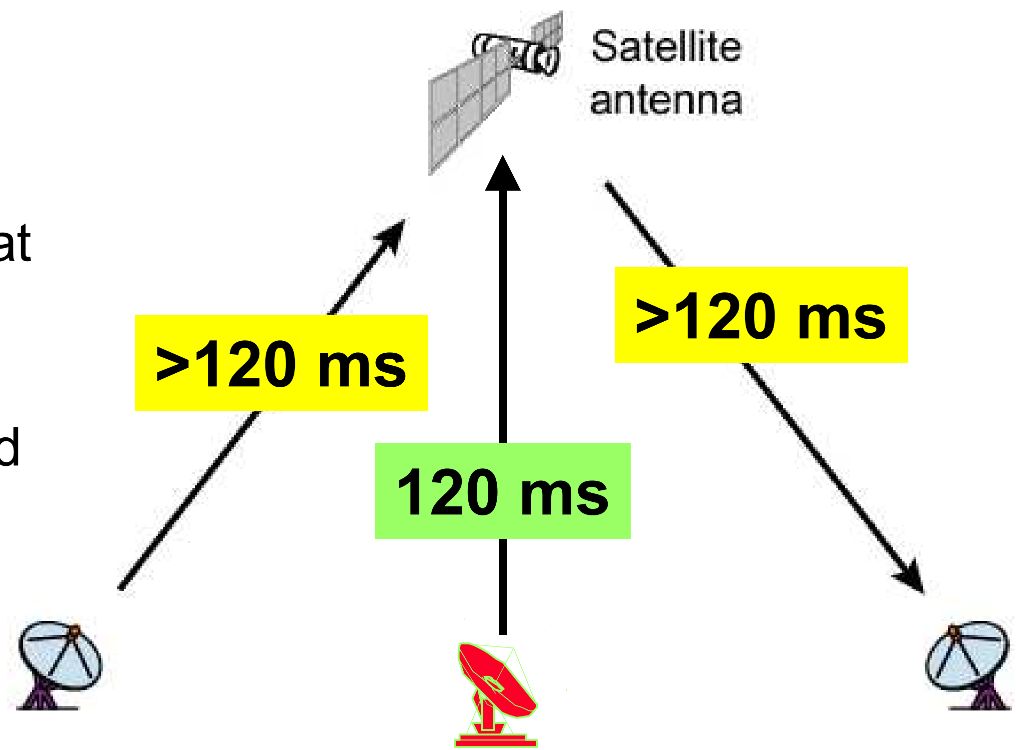
Advantages/Disadvantages of Geo-Synchronous Orbits

- **Advantages:**
  - **No ground station tracking required**
  - **No inter-satellite handoff, permanently in view**
  - **Three satellites give full earth coverage**
  - **Almost no Doppler shift, yields reduced complexity receivers**
- **Disadvantages:**
  - **35786 km orbits imply long transmission latencies**
  - **Weak received signal**
  - **Poor coverage at high latitudes (>77 degrees) -**

Satellite Link Delays

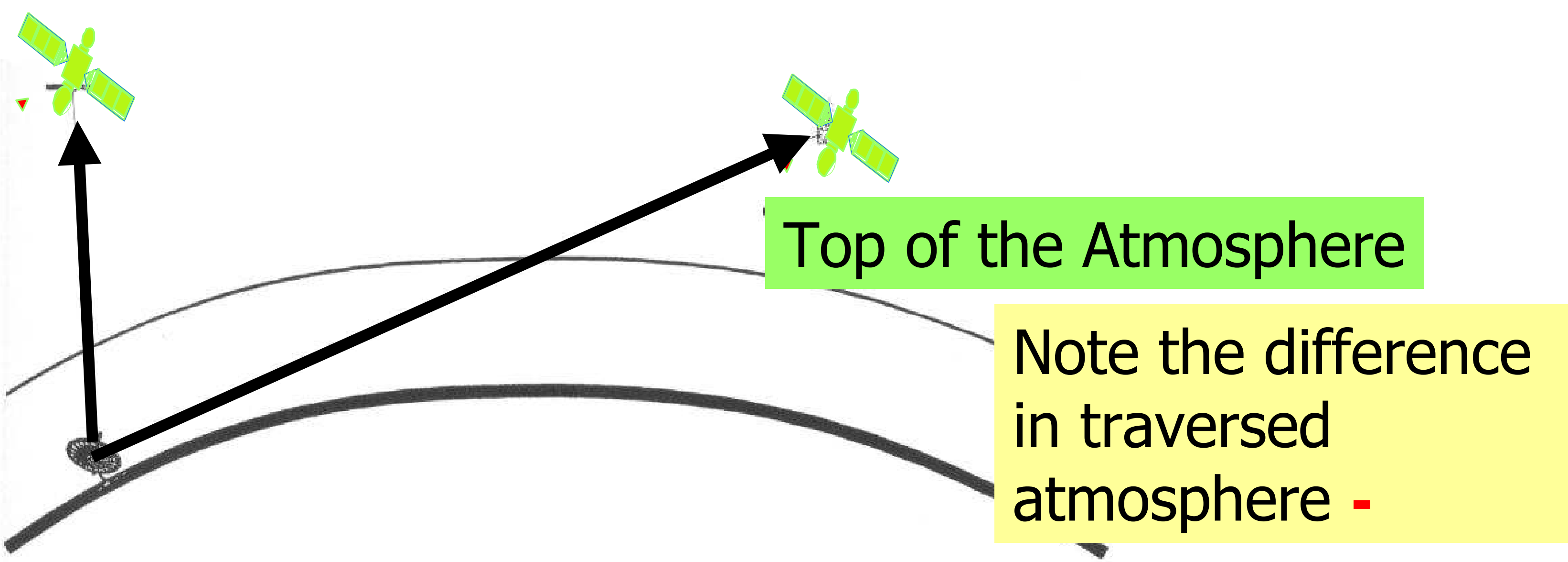
- Satellite to the surface of the Earth is 22,300 miles
- Two way transmission is 44,600 miles
- C = speed of light = 186,282 miles per second

- <u>239 milliseconds Minimum delay</u>
  - Transmit and receive stations on the equator at the same longitude as the satellite.
- Typical signals may required two hops through the satellite, i.e. around 500mSec
  - 500mS echo is barely distinguishable -

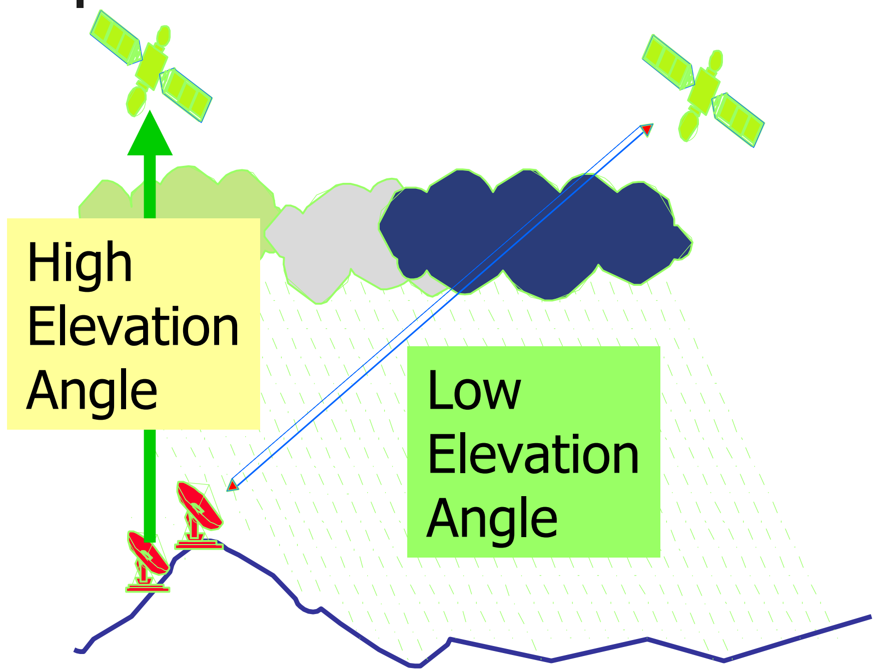


Elevation & Slant-Range

- Not All Satellites are located above the Earth Station
- At Higher Elevation Angles
  - Signals Traverse Less Atmosphere
  - Overall Slant-Range is Reduced.
- Signal Strength is Inversely Proportional to the Square of the Distance
- Atmospheric Effects are Significant at Low elevation



Elevation Angles & Atmospheric Effects



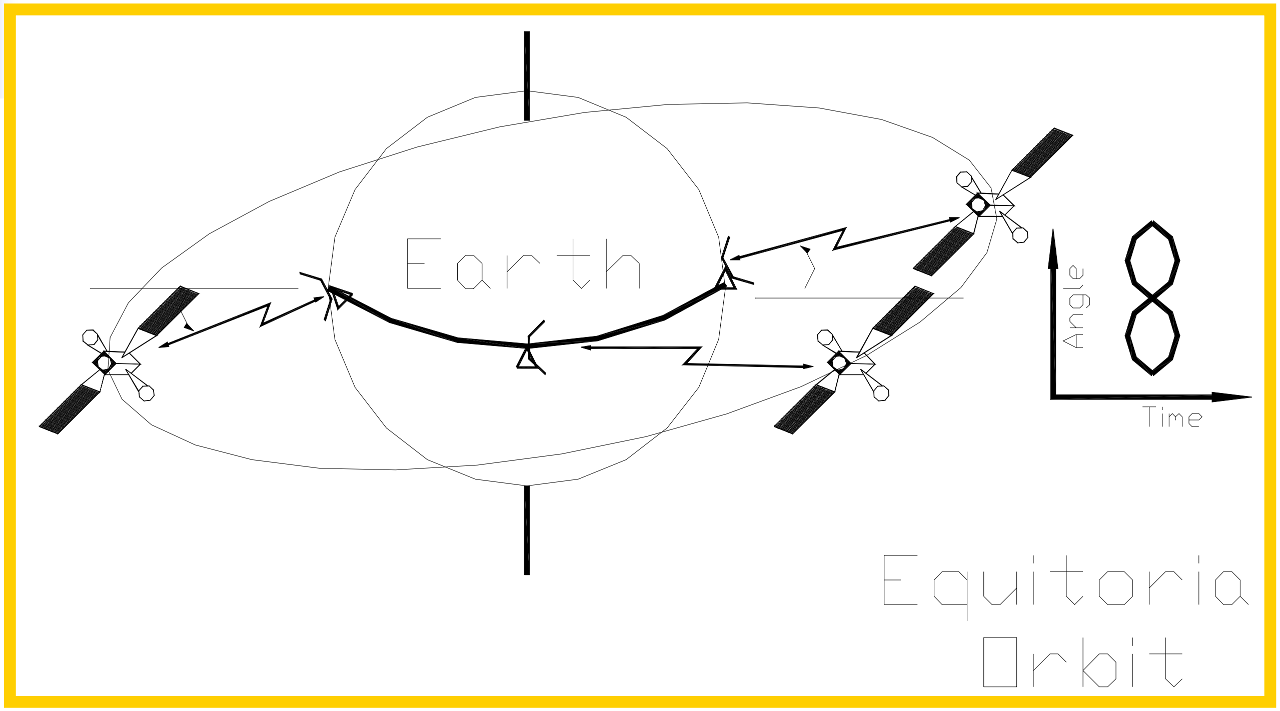
- ❑ **Minimum Elevation Angles**
- ❑ **C-Band Elevations ≥ 5°**
- ❑ **Ku-Band Elevations ≥ 10°**

- **Atmospheric Effects are critical to signal path Loss**
- **22,300 miles Earth to Satellite**
  - **1st 5 miles is most critical**
  - **> 5 miles at low angles of elevation**
- **Atmospheric Problems**
  - **Potential interference from terrestrial sources.**
  - **Increased atmospheric absorption**
  - **Partially depolarizes signal -**

Geo-Stationary Satellite Movement

- North-South perturbations
  - Due to gravitational pulls of the Sun and Moon (Similar to Tidal Effects)
  - North-South perturbations are the largest
  - Most demanding on satellite fuel reserves
- East-West perturbations
  - Due to lumpiness of the Earth
  - Incorrect satellite velocity & altitude -

North-South Satellite Movement



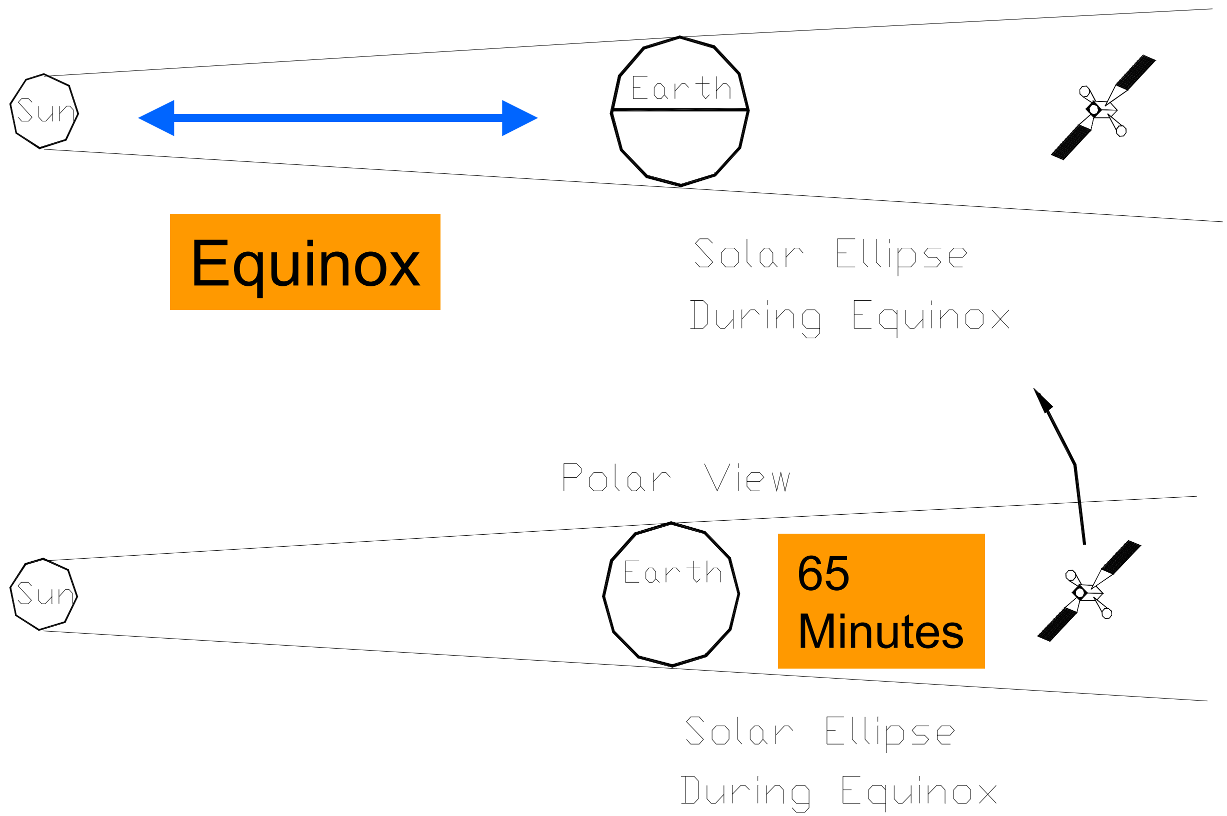
- An Object **not exactly over the equator**, transcribes a figure eight pattern to an observer on Earth
- Satellite lateral errors can be as much as $\pm 3°$ at end of life
- Looks like an up and down motion two times every 24 hours
- Large Earth Station Antennas must track the motion -

Satellite Orbit Stabilization & Life

- Positioning is regularly corrected to within ± 0.1°
- Without correction the movement in the North-South direction will be about 0.85 ° per year
  - ± 15° over the satellites typical 12 year lifetime
- Life of satellite is determined by how much fuel is stored to correct its position
  - Last remaining fuel is used to move the satellite out of orbit
- Satellite fuel capacity is typically designed for 13 years, because the satellite technology becomes obsolete.
- Satellite life can be extended by making less frequent position corrections
- Allowing ± 3° latitude shift can extend the satellite life as much as 3 years. -

Solar Outages Due to a Solar Eclipse

- Satellites experience a solar eclipse two times a year
- Vernal & Autumnal equinoxes for about 6 weeks each year.
- Satellites are in the earth's shadow for a few minutes to as much as 65 minutes on the day of the equinox.



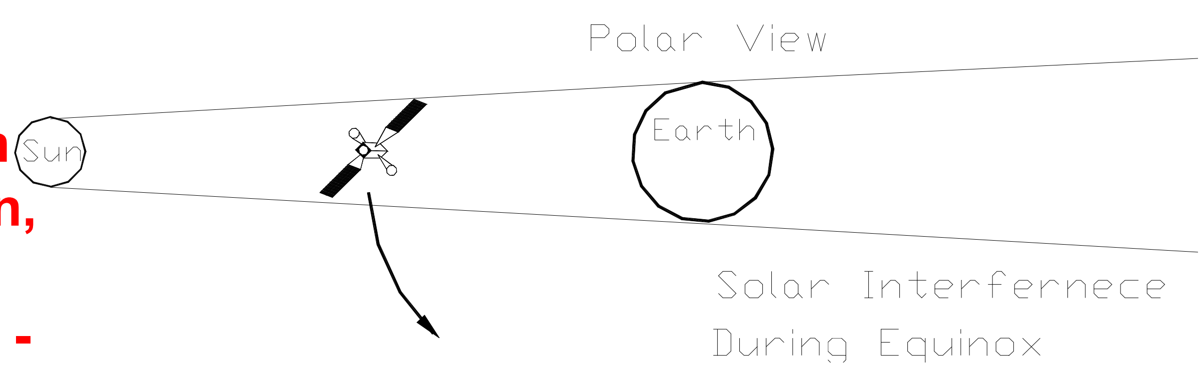
During Eclipse

- No Solar power - Need battery power
- No Solar warming - Requires heaters.

Satellite Eclipse of the sun

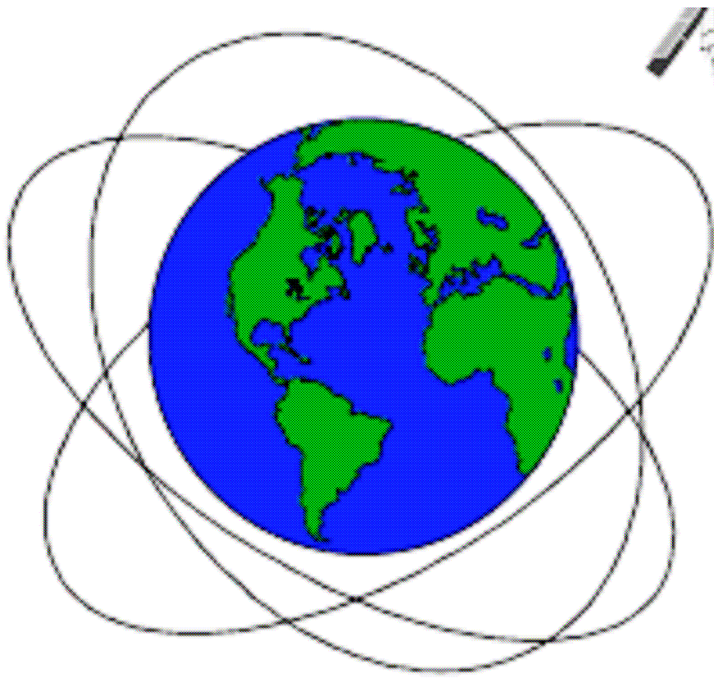
- For about five days during the eclipse season (65 days) <u>the sun passes behind the satellite</u> with respect to the earth station.
- The <u>background noise builds</u> up as this event unfolds
  - Plateaus for about 10 minutes.
- The <u>satellite may be unusable</u> (due to lower C/N) for this period
  - Traffic may have to be switched to another satellite.
- <u>Outage occurs around noon</u>
  - Larger diameter receive antennas (small beam width) exhibit this a shorter time and fewer days

- Tracking: <u>mode is usually turned off</u> to prevent the Earth Station from the tracking the Sun, which at this time is a higher source of energy. -



Non-Geostationary Satellites

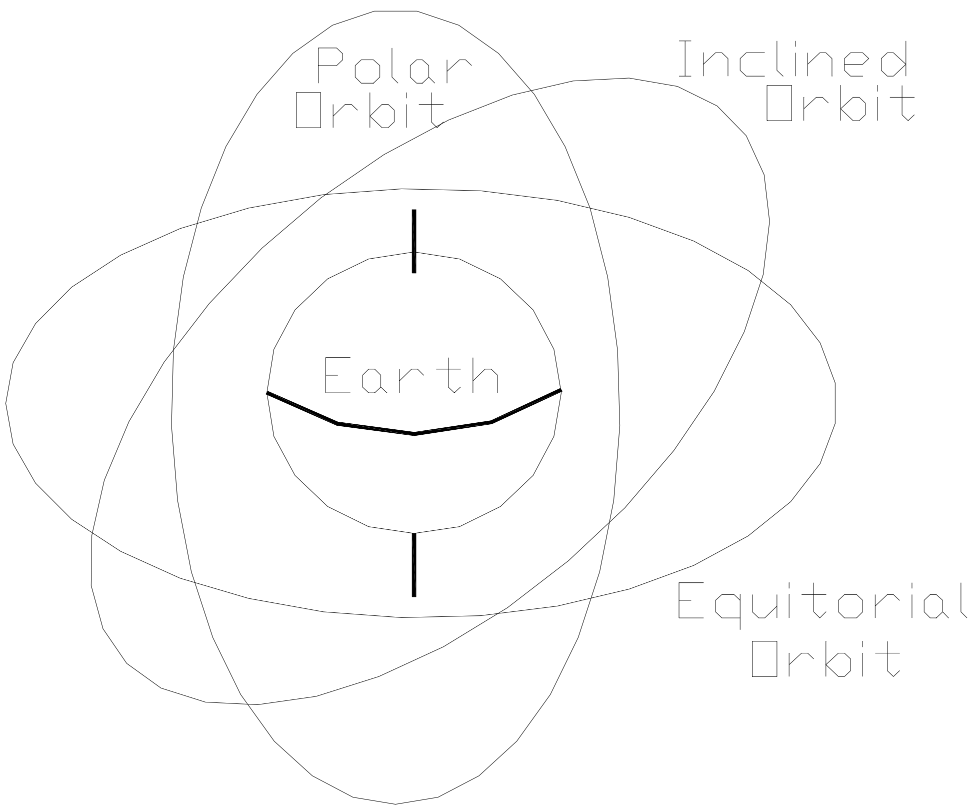
Medium Earth Orbits (MEO)
Low Earth Orbits (LEO)

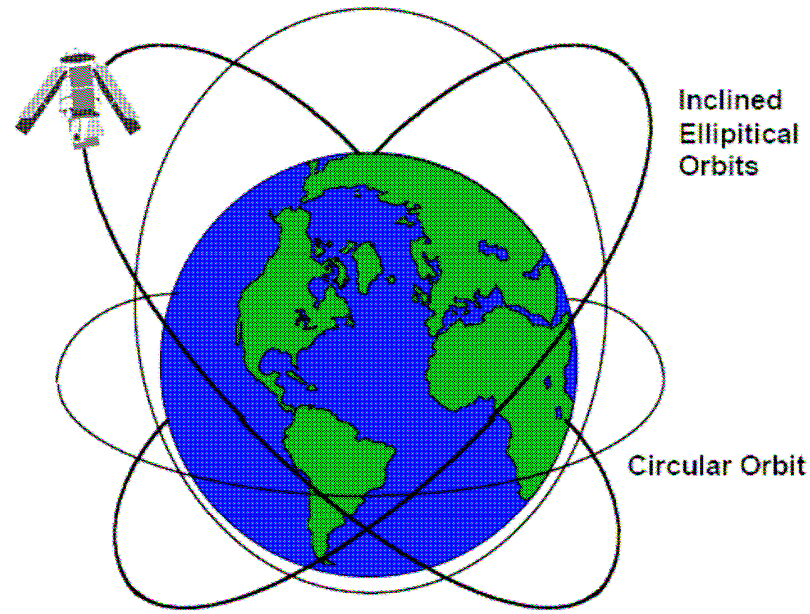


Medium Earth Orbits
Height: 6000-12000 miles
Rotation Period: 5-12 hrs.

Low Earth Orbits
Height: 100-300 miles
Rotation Period: approx. 90 min.

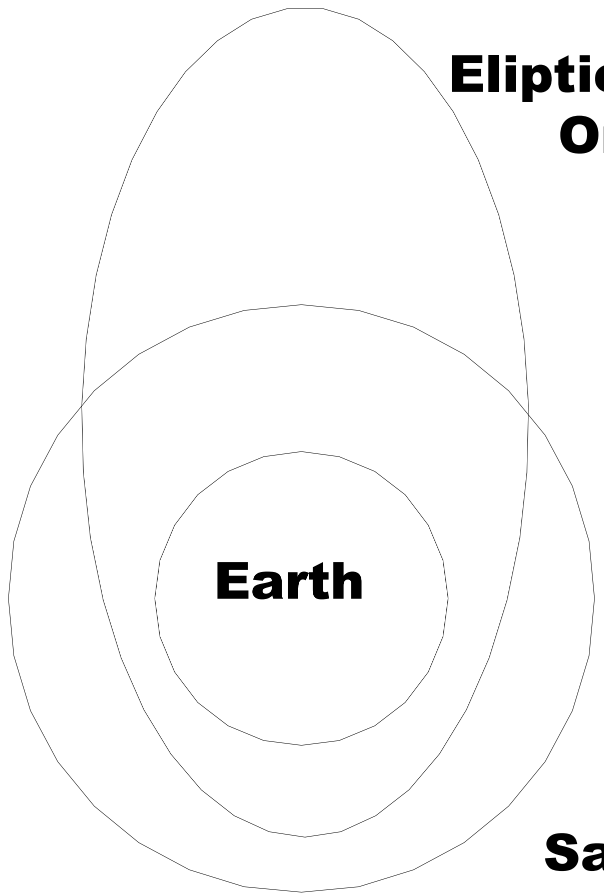
Types of Orbits





- **Polar**
- **Equatorial**
- **Inclined** -

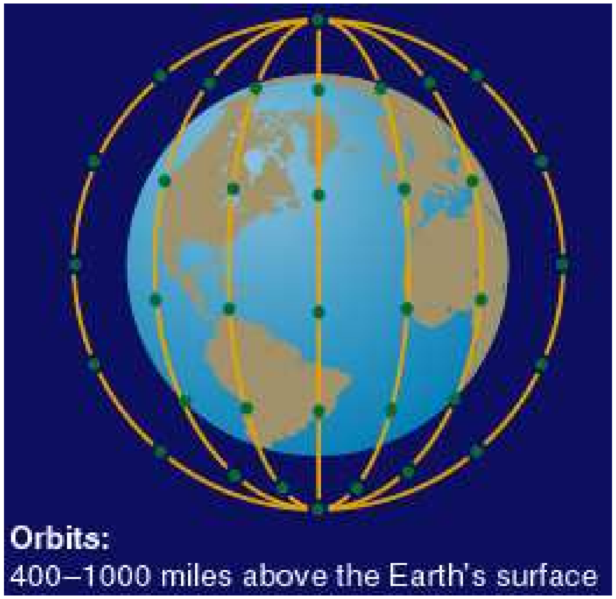
Orbit Shapes



- Circular
- Elliptical -

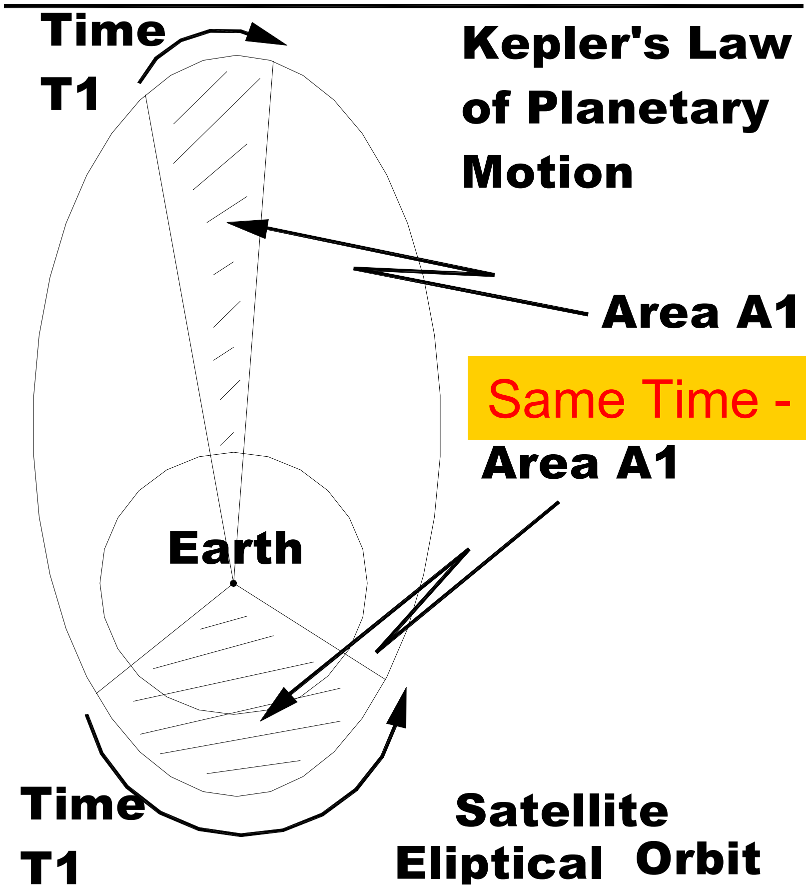
Polar Circular Orbital Characteristics

- Full global coverage with a single satellite
- Continuous communications requires many satellites
  - Iridium uses 66 satellites
- Transfer of information between satellites
  - Information is handed off from satellite to satellite like a cellular system
  - Satellite moves and customer stays relatively still



- Constellation of satellites separated in time and angle
  - Every customer is always in the foot print
- Higher orbits require fewer satellites
  - More terrestrial up-link (User) RF power -

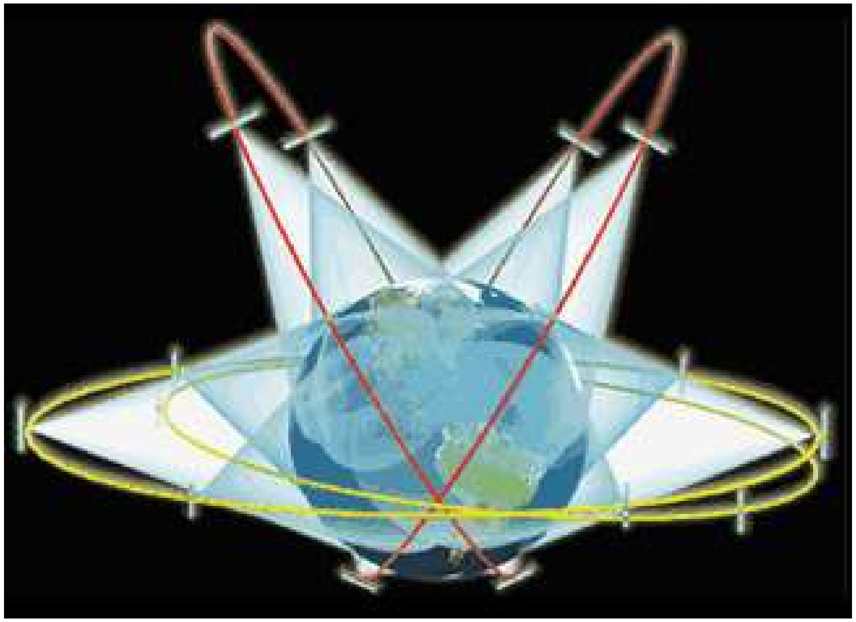
Kepler's laws of Planetary Motion



- In the early 17th century, Kepler discovered the three laws of planetary motion:
- The orbits of the planets have the same physics as earth satellites.
- 1.The law of orbits: Planets move in elliptical orbits with the Sun at one of the foci.
- 2.The law of areas: the line from the Sun to a planet sweeps out equal areas in equal times.
- 3.The law of periods: The square of the period is proportional to the cube of the ellipse's major axis.

Elliptical Satellite Orbits

Inclined Elliptical Orbits allow asymmetrical time coverage over different sectors of the Earth



- **Geostationary satellites do not provide coverage for the Polar regions**
- **Elliptical orbits cover the same area per unit time in all parts of the ellipse, Satellite travel slower further away**
- **To serve Polar Regions establish an Inclined Orbit with the apogee over the Polar regions**
- **Most of the satellites orbital time is over the Polar region -**

Low Earth Orbit Advantages/Disadvantages

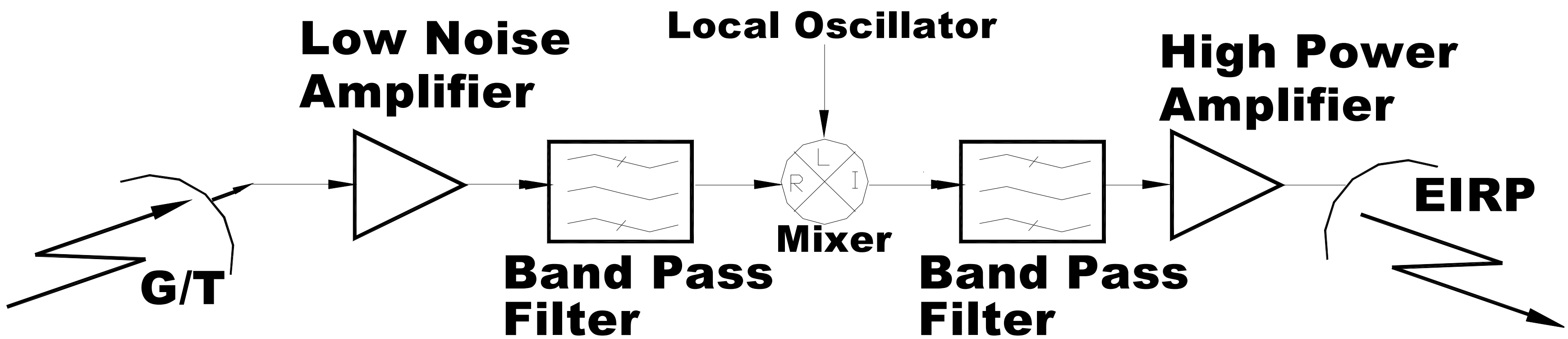
- Advantages:
  - Reduced launch costs to place in low Earth orbit
    - e.g., airplane/booster launched
  - Reduced pass loss
  - Lower Power, Lower cost satellite ($0.5-2M)
  - Much shorter transmission delays
- Disadvantages:
  - Short visibility from any point on earth, as little as 15 minutes
    - Potentially large constellations
  - Radiation effects reduce solar cells and electronics lifetimes
    - Van Allen radiation belts limit orbit placement
      - Belt 1: 1500-5000 km
      - Belt 2: 13000-20000 km -

LEO Example: IRIDIUM

- Voice (4.8 kbps), Data (2.4 kbps), Fax, Location Services
- 66 satellites in 6 polar orbits (780 km)
  - Iridium has an atomic number 77
    - Original design called for 77 satellites
- 48 spot beams per satellite forming "cells"
- 230 simultaneous duplex conversations
- Satellite-to-satellite links as well as to ground
- Ka band @20 GHz to gateways & crosslinks,
- L band at 1.5GHz to handheld units
- FDMA uplink, TDMA downlink
- Supports satellite handoff during calls -

Satellite Configurations: Bent Pipe

- Keep the satellite simple
- RF to RF – Frequency Translator
- C-Band Earth Station Transmits typically at 5.925 GHz to 6.425GHz
- Earth Station Receives signals at 3.7GHz to 4.2 GHz
- Satellite has a fixed Local Oscillator at 2.225 GHz
- Satellite transmits at a lower frequency (Less loss) -



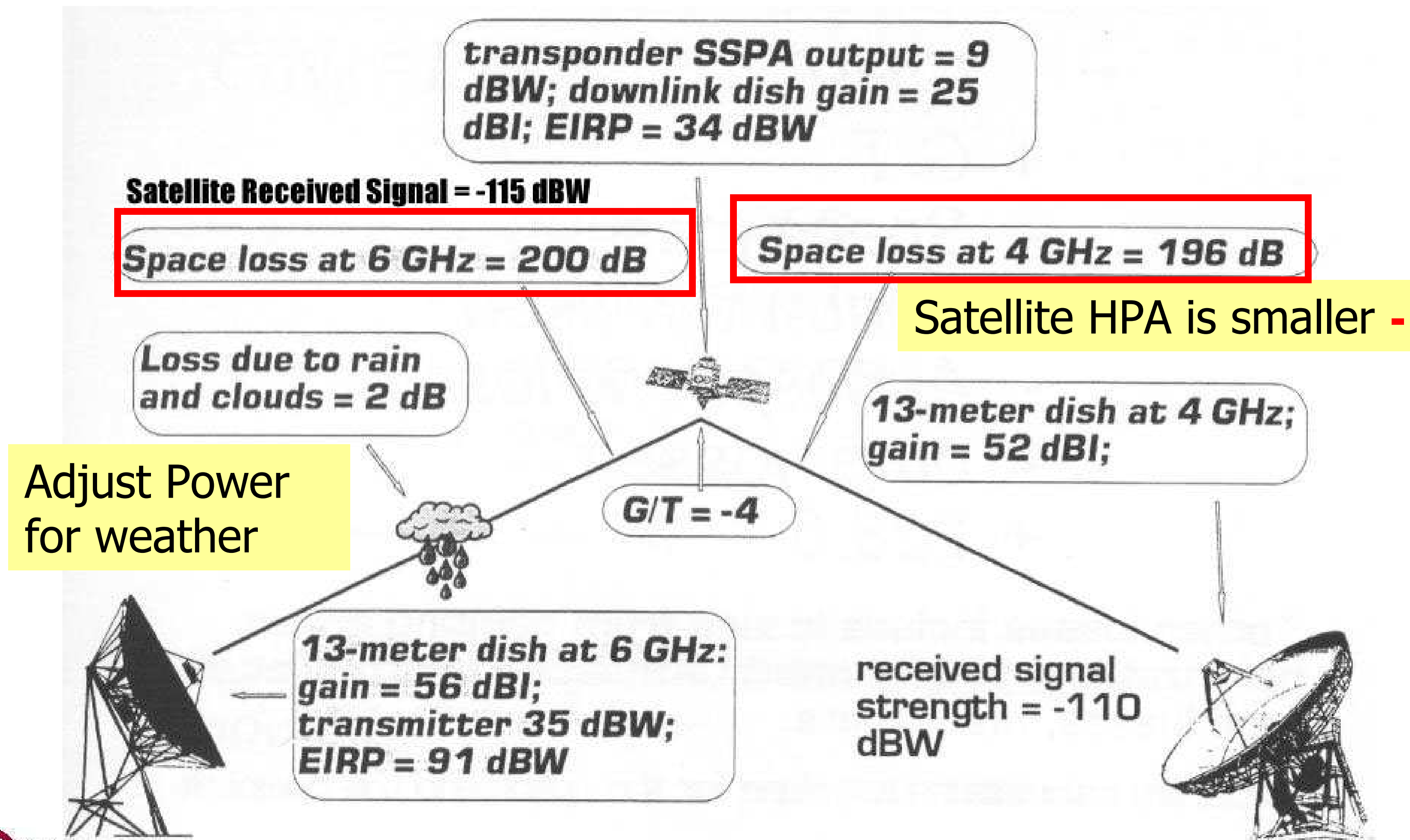
Satellite Transponder

On-Board Processing vs. Bent Pipe

- More control over signal routing
- Higher Cost, more complicated, Higher failures
- Typical Configurations
  - RF to IF → Microwave switch matrix → IF to RF
    - Allows Changing Signal Path Transponders
  - RF to IF → Demodulator → Baseband → Modulator → IF to RF
    - Reprocessing eliminated accumulative noise
- Intersatellite Links, Handing off Signals
  - some LEO's
  - Military satellites
  - NASA TDRSS system -

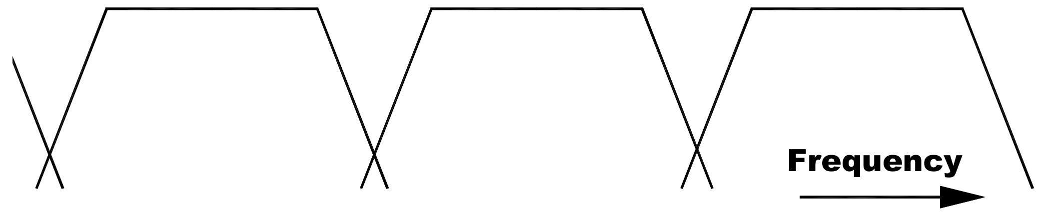
Typical C-Band Link

- This Example Ignores Line, Atmospheric, and Other Losses.
- Does Not Include C/N Requirement Data.



Satellite Transponders

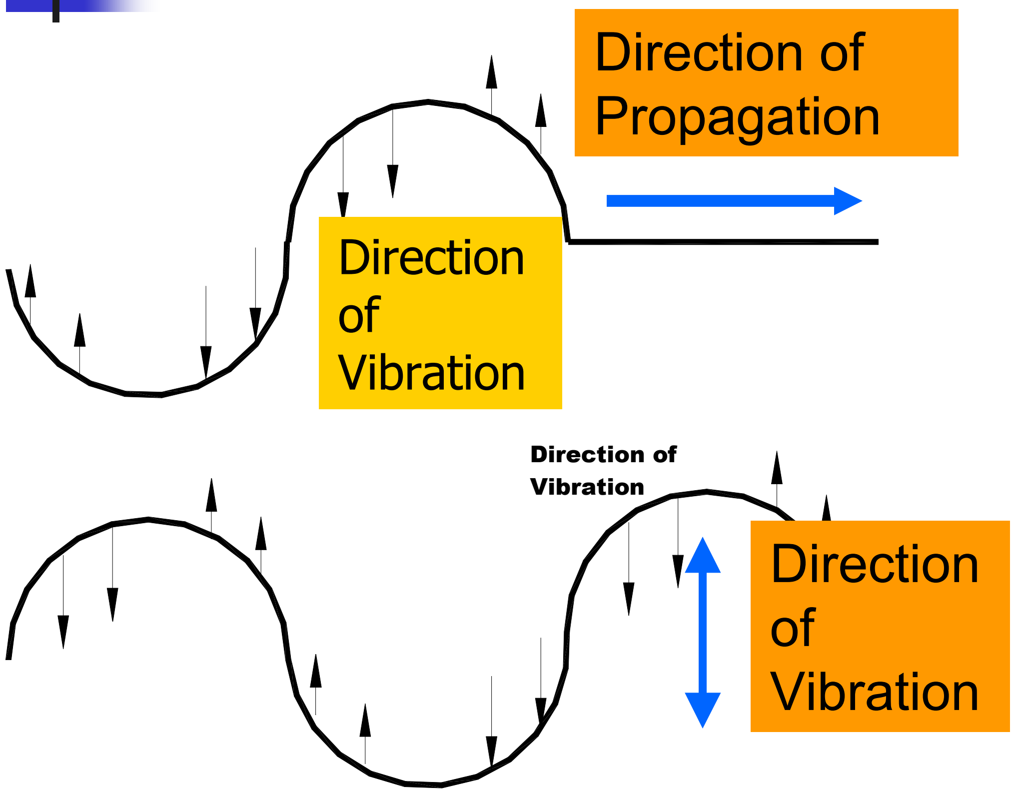
Satellite Bandwidth (Typically 500 MHz to 750MHz) is broken up into segments called transponders



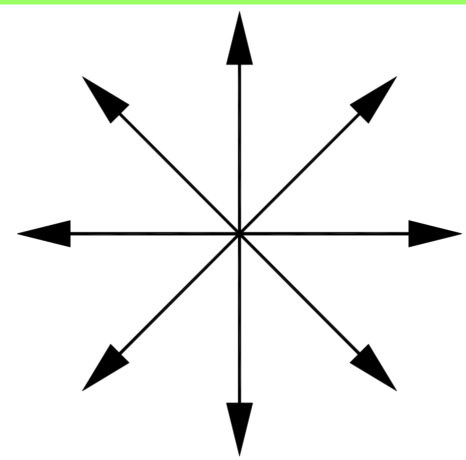
- **Transponders are characterized by:**
  - **Center Frequency**
  - **Bandwidth**
  - **Down Link power (Satellite EIRP)**
    - **Different bandwidths have different power**
    - **All signals to a satellite must have the same power spectral density**
  - **Polarization -**

Frequency Reuse by Polarization

Electromagnetic Wave Behavior



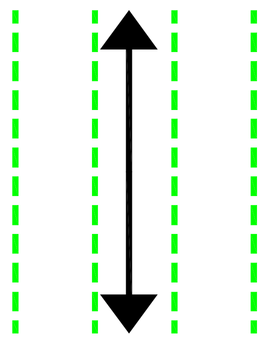
Non-Polarized Electromagnetic Wave Viewed Head-On



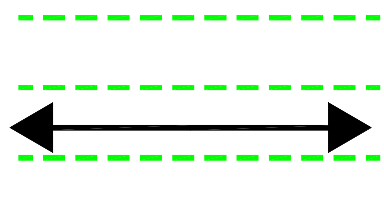
Polarization **Refers to the orientation of the electric field vector as a function of time. -**

Linear Polarization

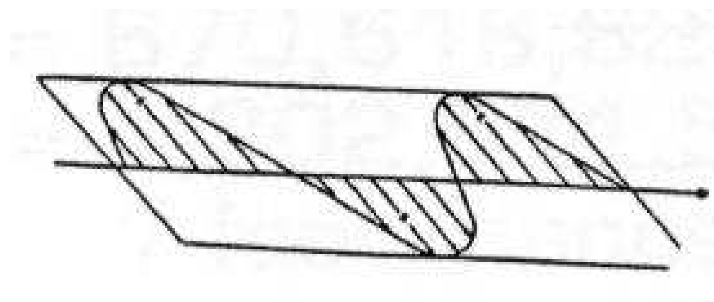
Vertically Polarized Wave



Horizontally Polarized Wave

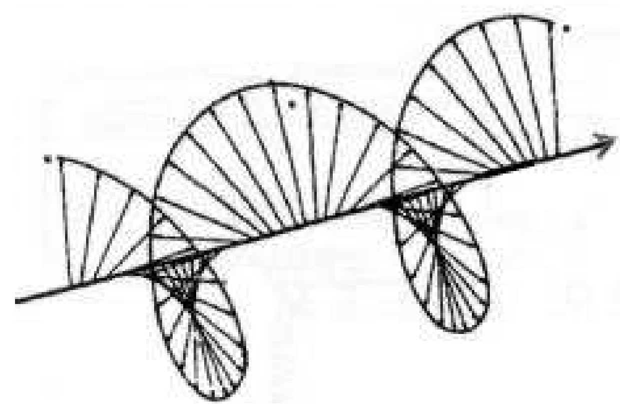


Electromagnetic Wave Transmits in a single plane

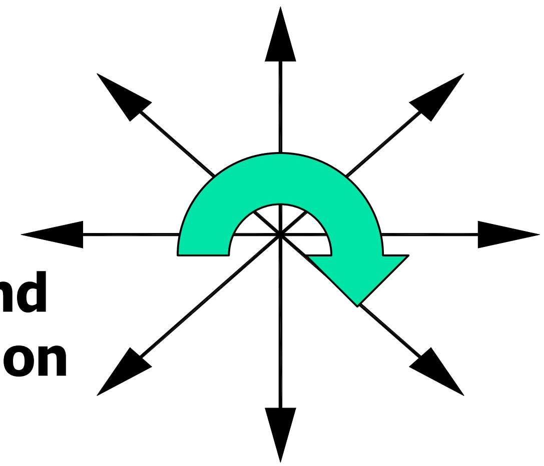


❑ **Linear Polarization requires precision alignment of the transmitter and receiver, i.e. Satellite & Earth Station -**

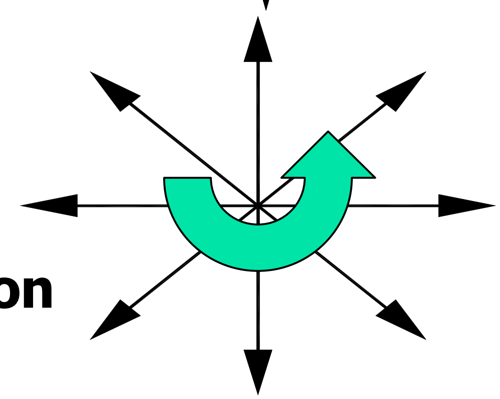
Circular Polarization



- Electromagnetic Plane rotates clockwise with time
  - Right Hand Polarization
- Electromagnetic Plane rotates counterclockwise with time
  - Left Hand Polarization
- A Right Hand Polarized Satellite signal is Left Hand Polarized at the Earth Station
  - Mirror Image -

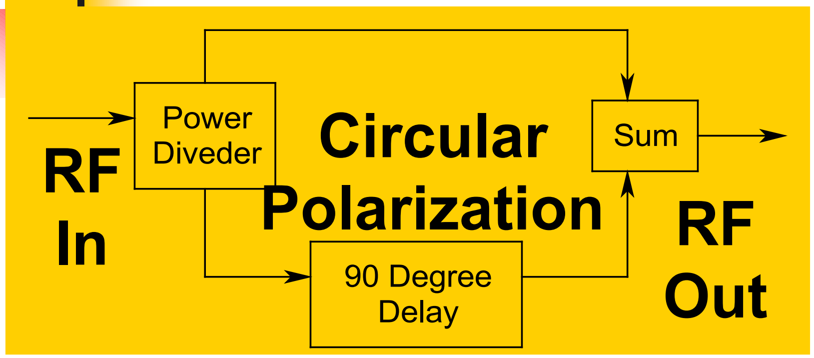


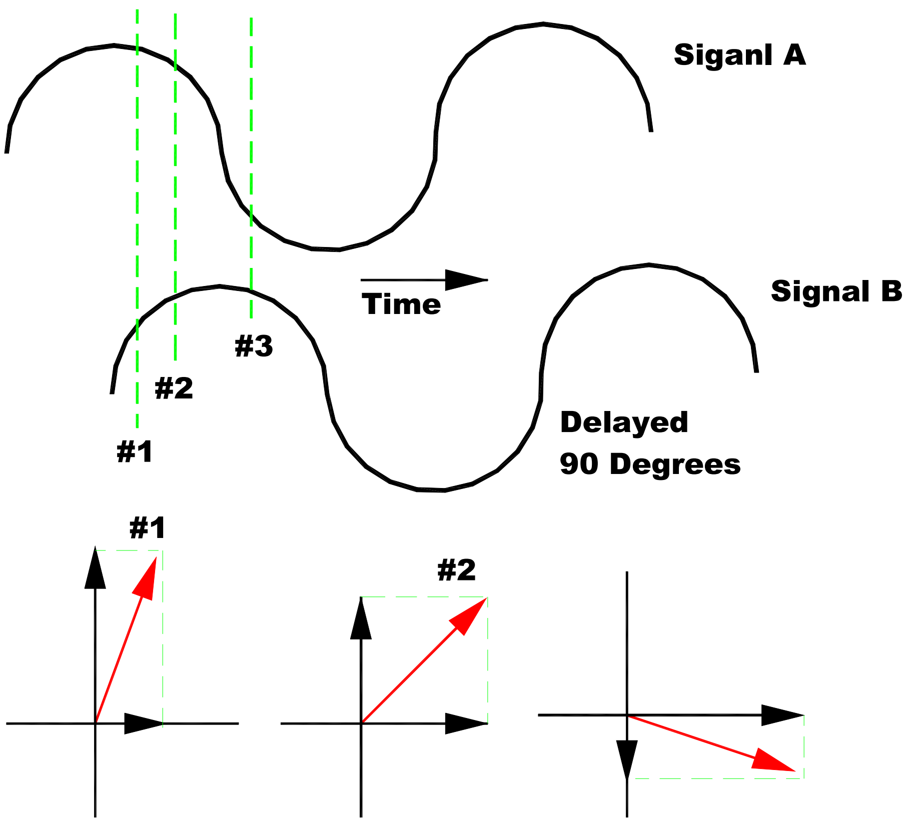
Right Hand Polarization



Left Hand Polarization

Creating Circular Polarization

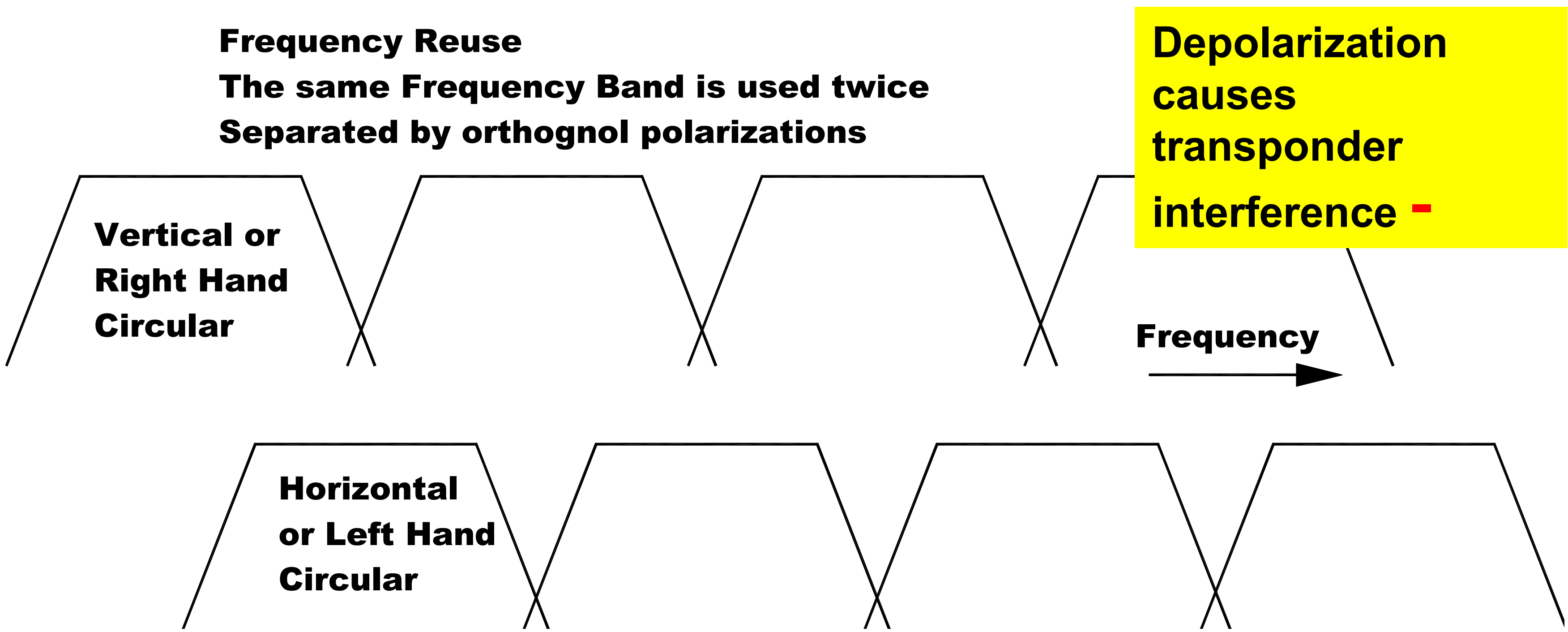




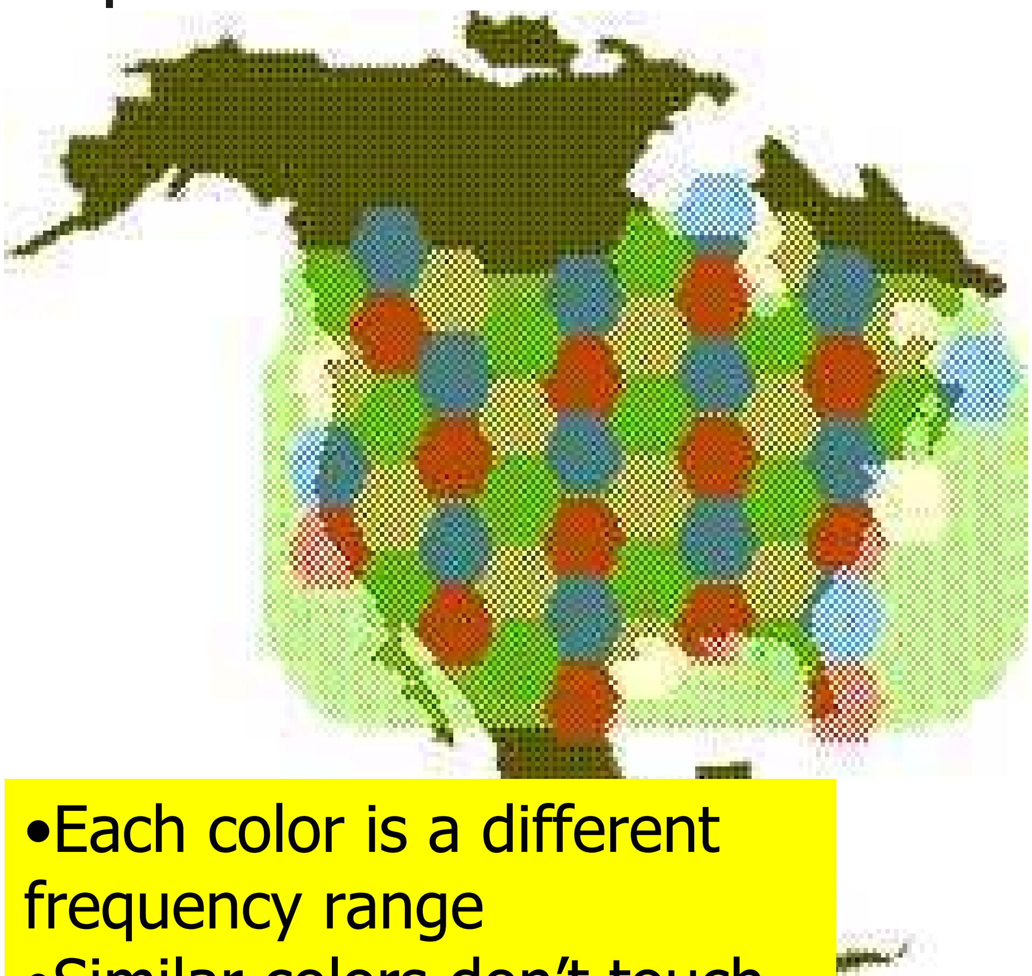
- Circular polarization is achieved
  - Splitting the linearly polarized signal into two orthogonal vectors
  - Delaying one with respect to the other by a quarter wave length (90°)
  - Summing the vectors -

Polarization and Frequency Reuse

- Frequency Reuse is receiving and transmitting signals at the same frequency, but with orthogonal polarization.
- Linear polarization needs absolute alignment
- Circular requires no alignment but more effected by rain
- Transponder Frequencies are offset to minimize interference



Spatial Reuse – Spot Beams



•Each color is a different frequency range
•Similar colors don't touch -

- Ka Band uses multiple narrow beams
- Focused beams cover a much smaller area
- Hundreds of miles across, rather than thousands of miles with Lower Frequency FSS
- Form coverage cells
- Adjacent cells use different frequency ranges
- Frequency range reused many times over a wide geographical area

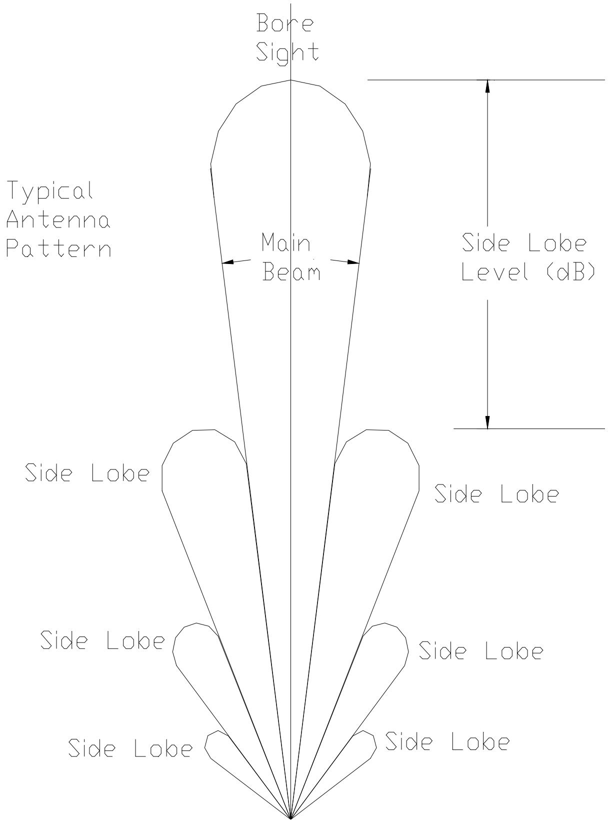
Advantage of Spot Beams

- Large increase in overall capacity
- Spot beams provide 30 to 60 times the system capacity of the FSS
- Capacity of 30 Gbits/Sec makes satellite broadband services a long-term, economically viable business
- Flexible Spatial Redundancy with Phase Array Spot Beams

Service is restored by moving beams to effected areas -

Earth Station Antennas

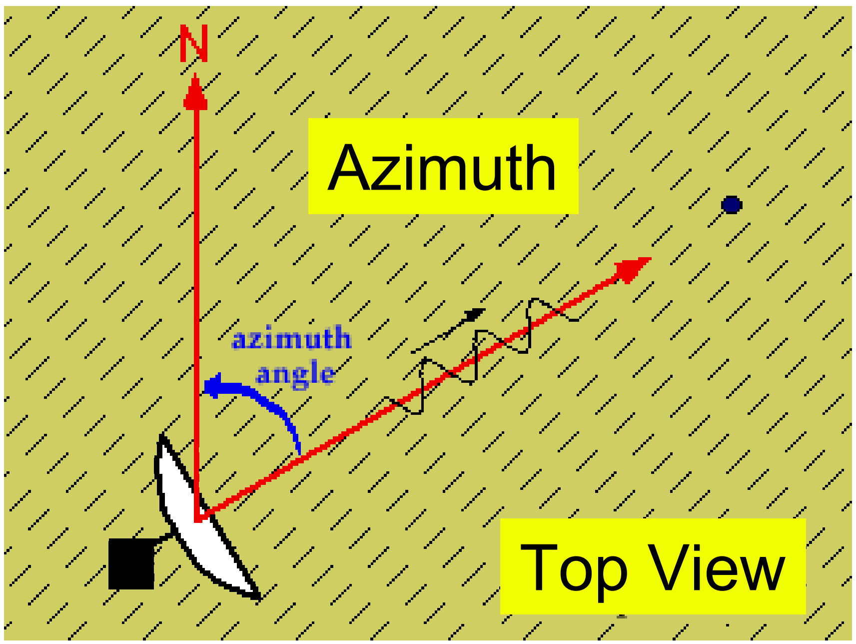
Antenna Mounts

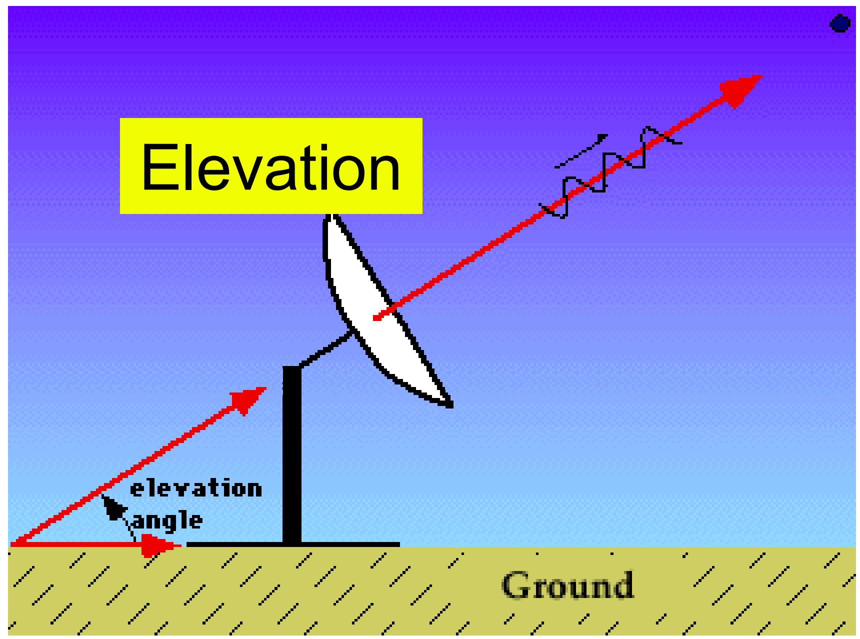


- **Fixed:**
  - **views one satellite**
  - **Inexpensive**
- **Elevation-Azimuth:**
  - **Vertical and horizontal movement**
  - **Narrow Beam Width**
  - **High Gain -**

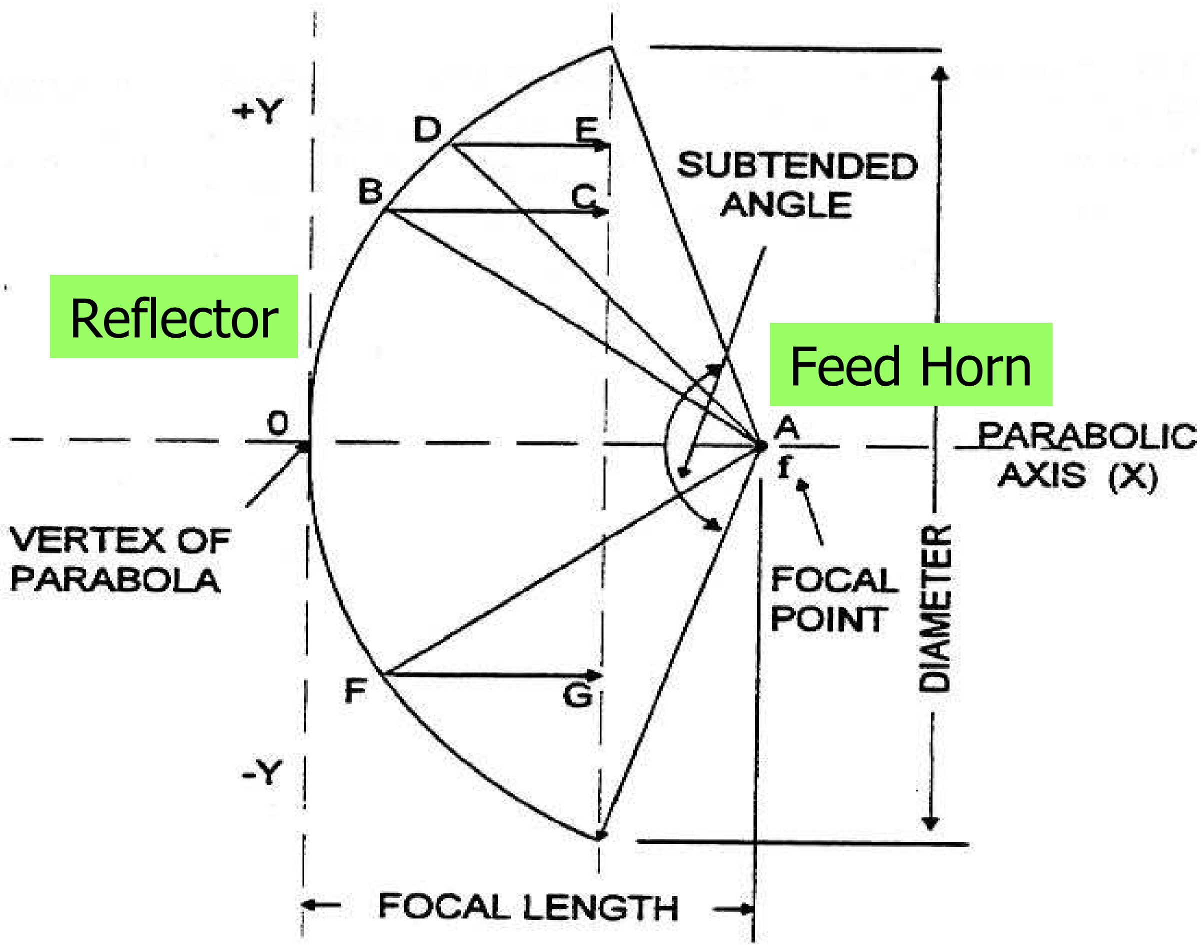
Azimuth & Elevation Angles

- Azimuth is the axis of angular rotation
- Elevation is the Angle with respect to the horizon -





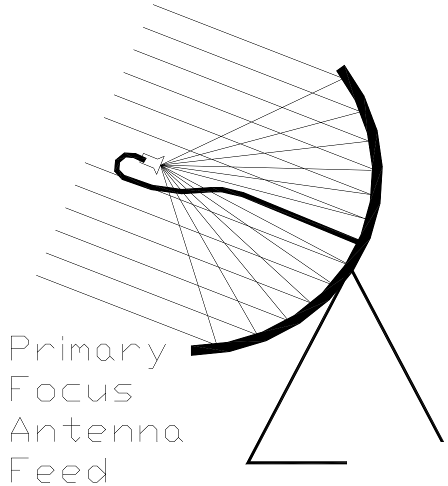
Parabolic Reflector Geometry

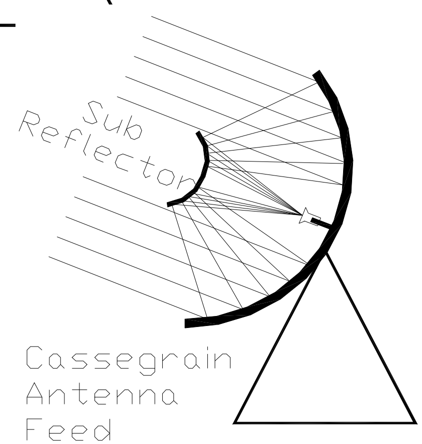


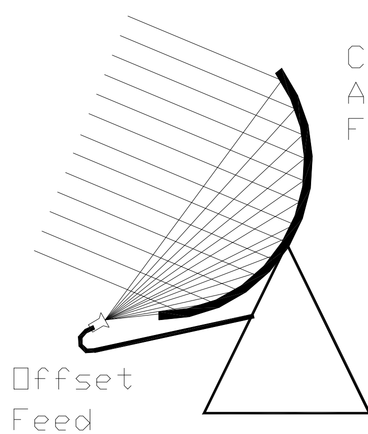
- Signals are fed from a point source
- Feed Horn is the antenna
- Dish is a Reflector
- Geometry is such that all signals are reflected in parallel

Parabolic Antenna Types

- Prime Focus Feed
  - Simplest Antenna Design
- Cassegrain Feed
  - Allows for Shorter Feedlines
- Offset Feed
  - Minimizes Feed Blockage -

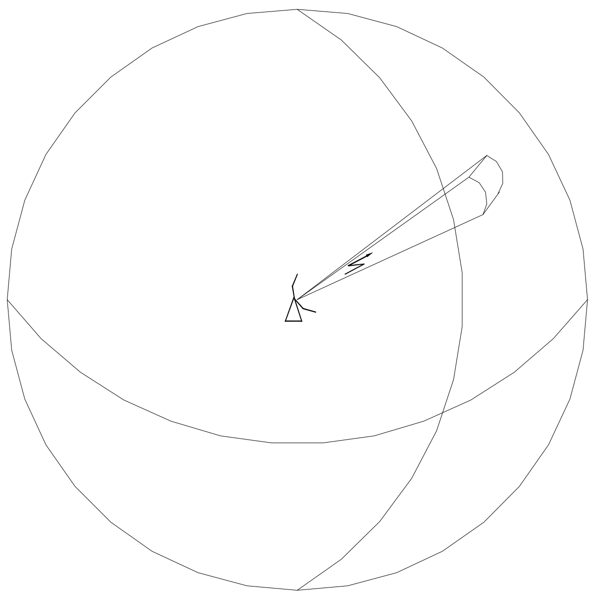






Antenna Beam-Width

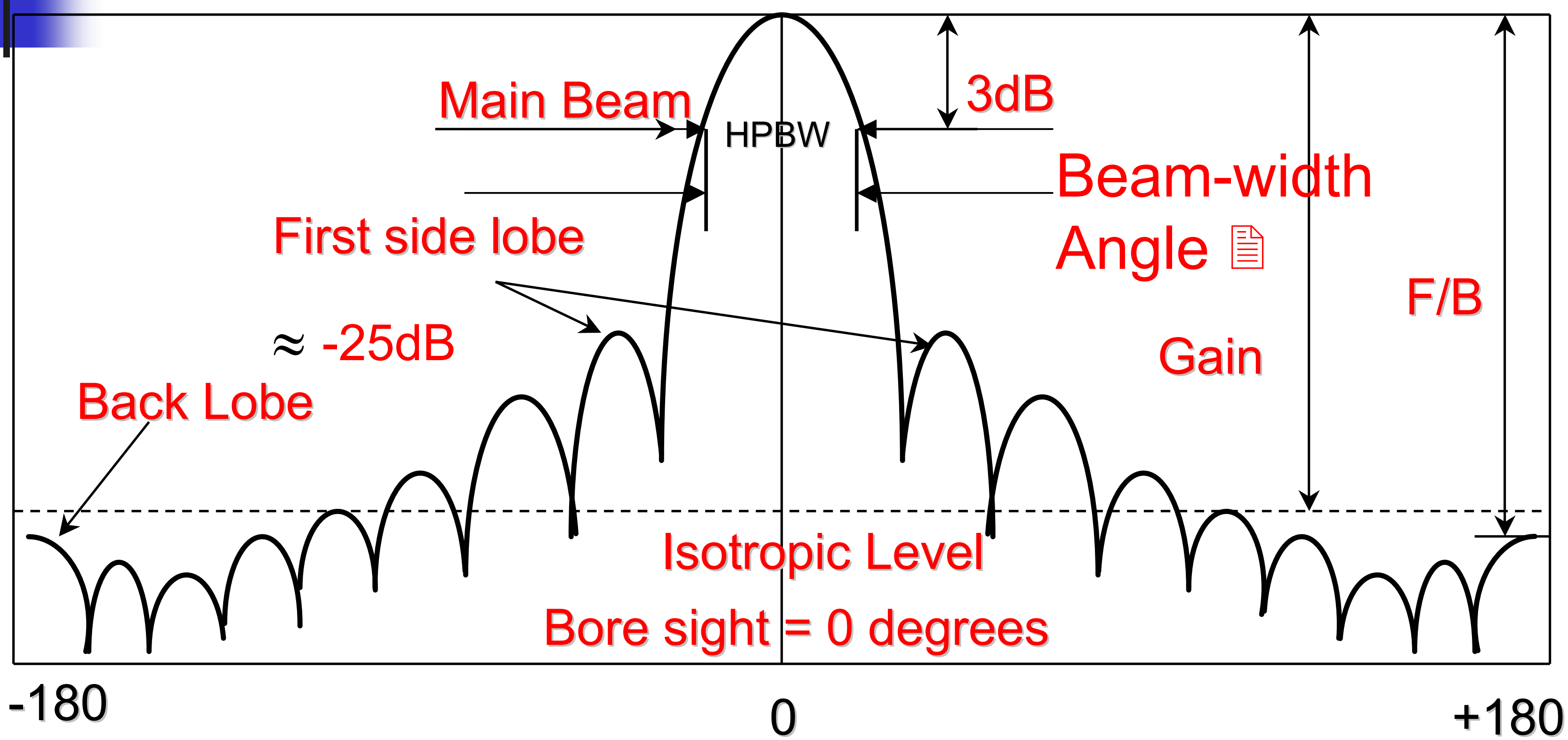
Antenna Beam Width



- Example: 3 Meter Antenna @ 4 GHz has a 1.75° Beam width (-3 dB) -

- Beam width is the angle where the antenna power is within 3 dB of the peak
  - Beam Mid-Point: Boresight
- Beam width is a solid angle
- Beam width ≈ 21 / (F*D) in degrees (Parabolic dish)
  - F = Frequency in GHz
  - D = diameter of the dish in Meters
- For a parabolic dish D is the same in all directions

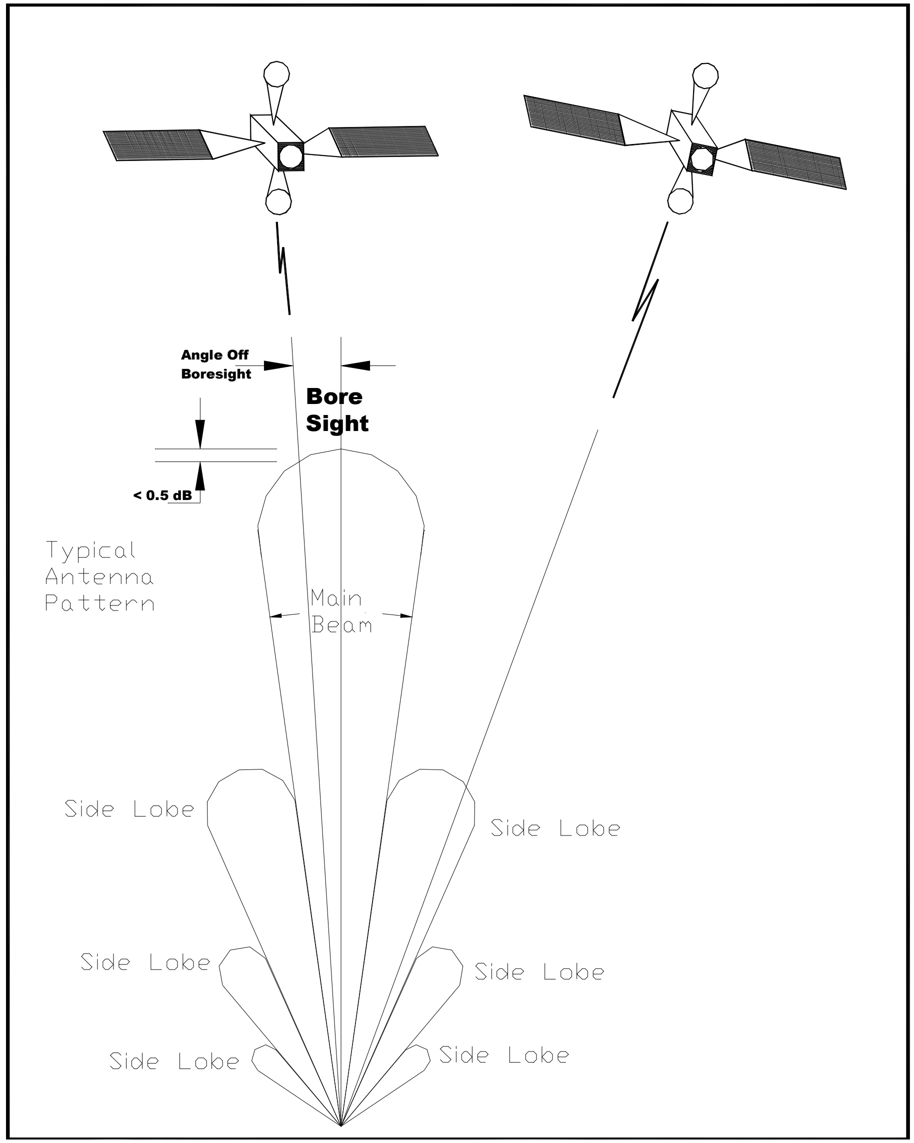
Antenna Radiation Pattern



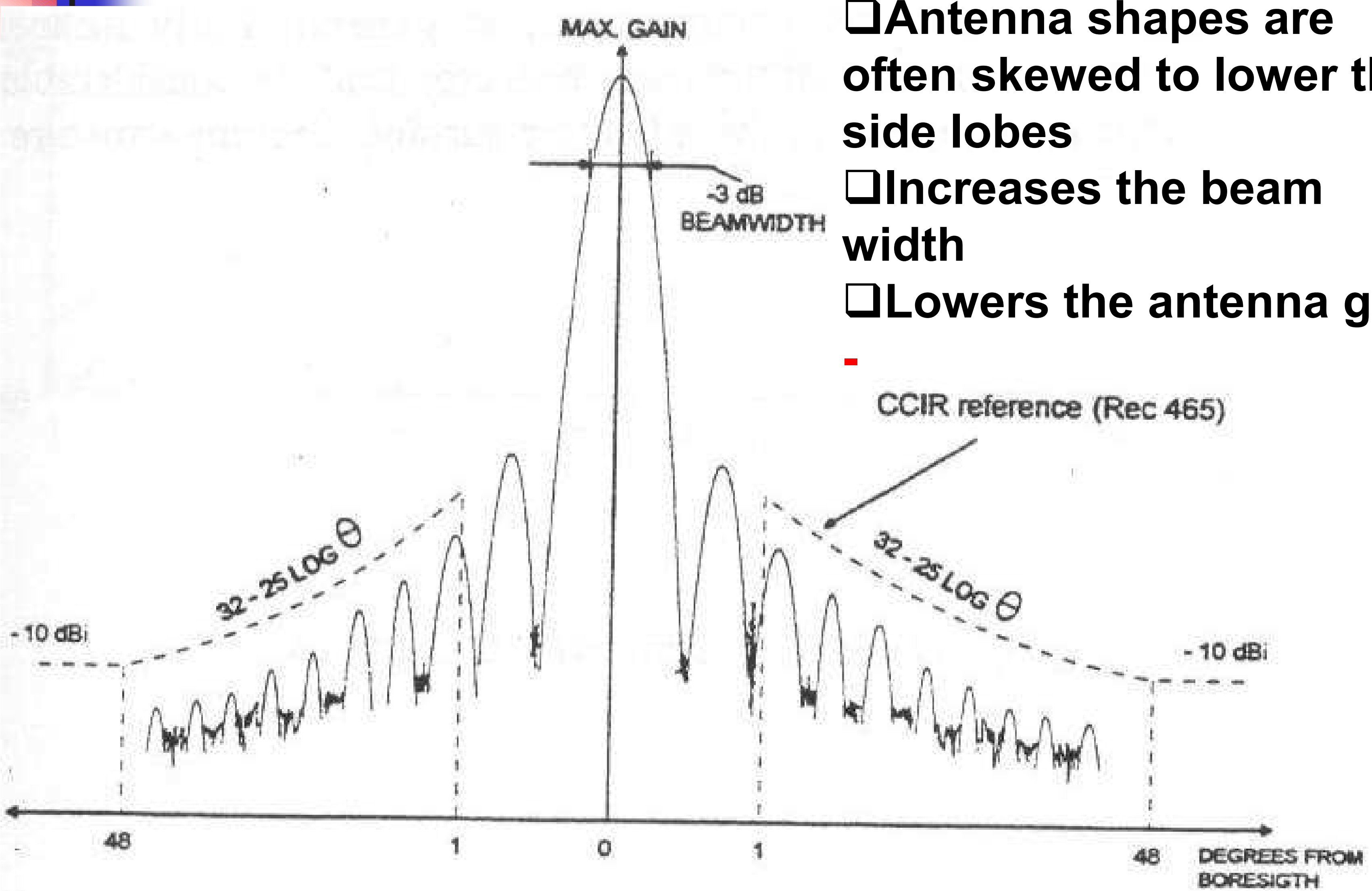
- All angles are referenced to Bore-sight
- is the ½ Power (3dB) Beam Width
- Side Lobes: **The antenna patterns are repeated at lower gains on either side of the main beam -**

Side Lobe Radiation Problem

- **<u>Side Lobe Energy Limits:</u> Limit interference to nearby satellites**
- **<u>IESS Spec: Side Lobe Max:</u> $\leq$ 29 - 25* Log $_{10}$ (A) in dB**
  A = the angle off boresight. -

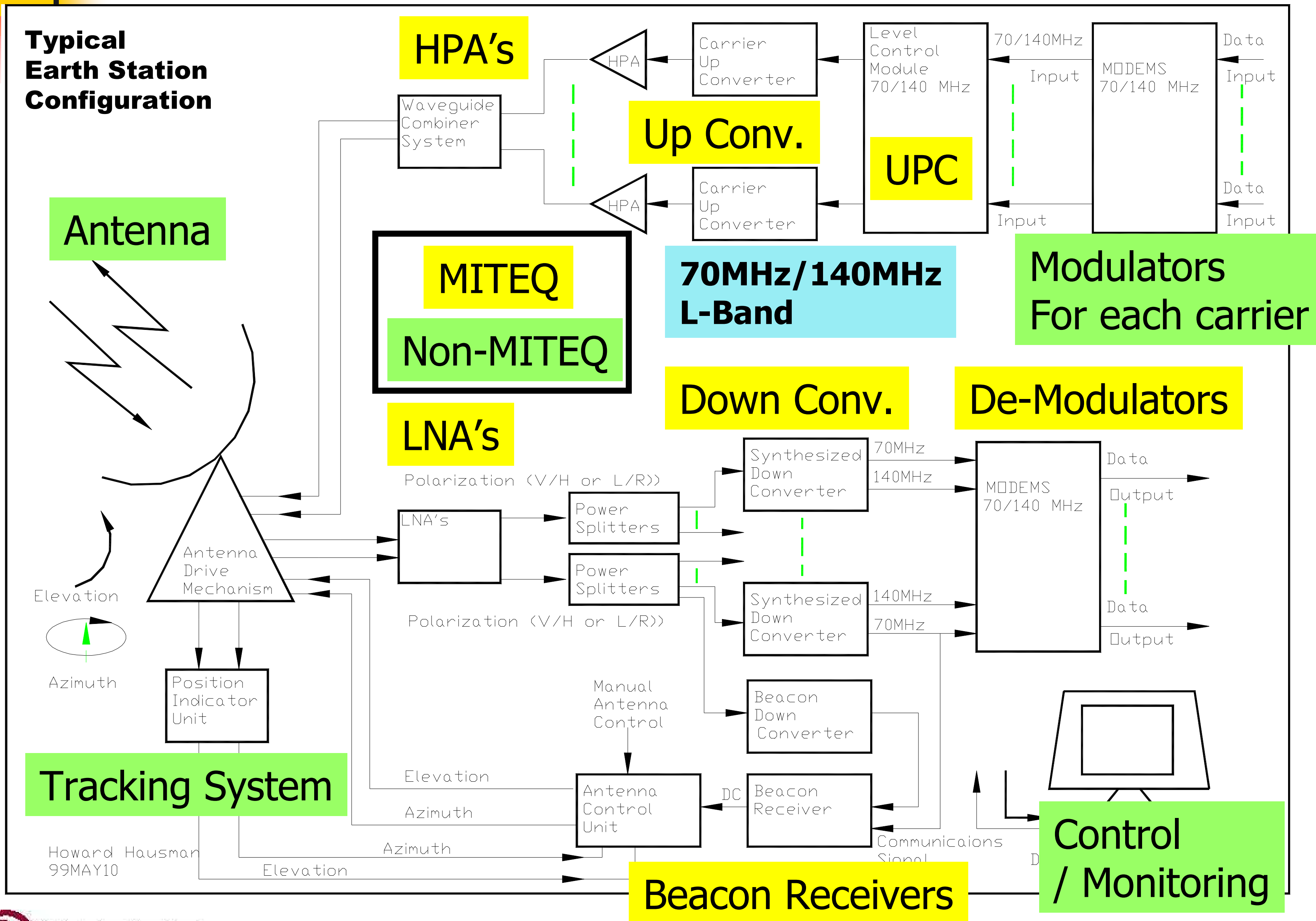


Antenna Side Lobes Limits



- ❑Antenna shapes are often skewed to lower the side lobes
- ❑Increases the beam width
- ❑Lowers the antenna gain

Major Earth Stations Components



Satellite Communications Summary

- Broadcasting
  - One Transmitter to millions of receivers
- Voice, Data, Internet, etc. access everywhere
  - On the move
  - In the Air
  - Isolated locations
- Communications with minimal infrastructure
- Satellite Communications is versatile enough to let your imagination runaway with ideas