Fundamentals of Satellite Communications
Part 2
Link Analysis, Transmission, Path Loss, & Reception

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Link Analysis, Transmission, Path Loss, & Reception

- Communications Link Objectives
- Design Factors to Consider in Signal Transmission
- Transmitter Sub-System
- Transmitted Power
- Common Digital Modulation Techniques
- Path Loss to the Satellite
- Atmospheric Effects
- Receiving System – Carrier to Noise
- Gain over Noise Temperature
- Satellite Link Example
- Bandwidth Economics
- Satellite Tracking
- Uplink Power Controller
- Summary -

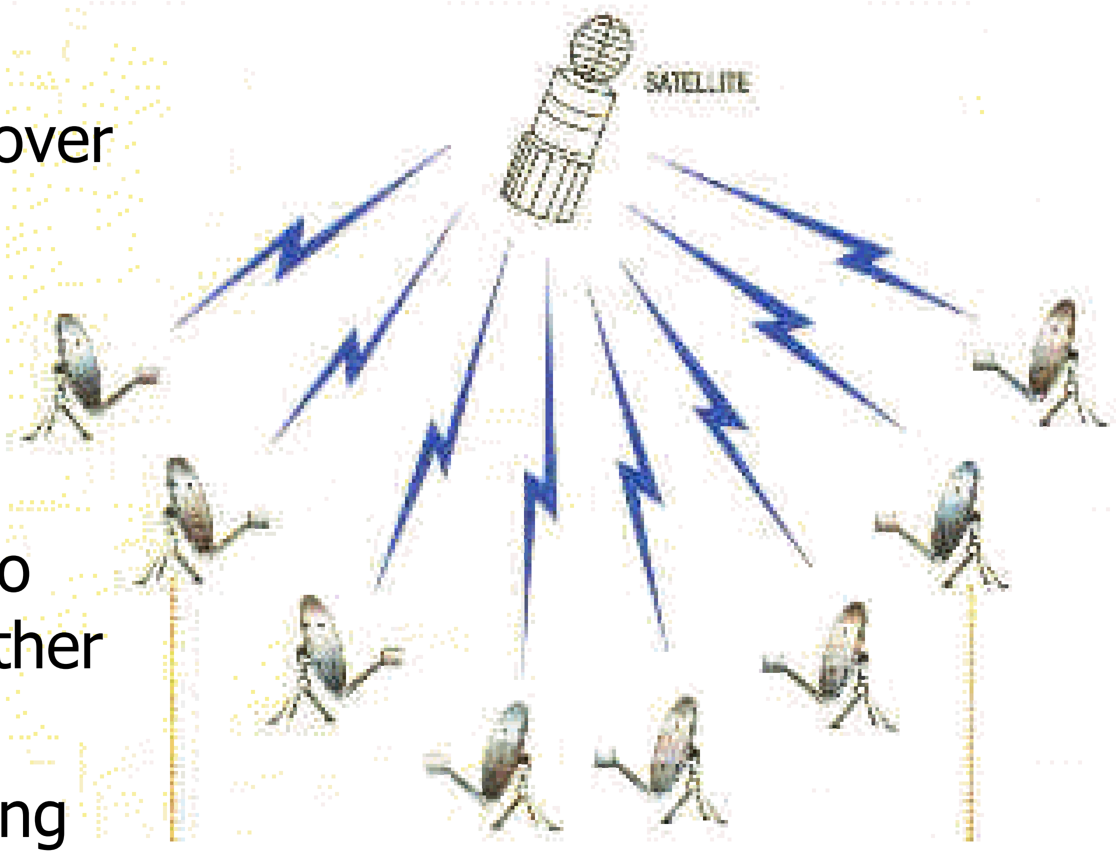
Communications Link Objectives

- Recover Information
  - Received Signal must be
    - Above noise
    - Above spurious signals
    - Undistorted
- Transmitters live in a community
  - Don’t interfere with your neighbor
- Cost effective so someone will use your link -

Design Factors to Consider in Signal Transmission

- Distance between users
  - Fixed Satellites are ≈ 25,000 miles above Earth
- Weather effects
  - Adjusting the Signal for Adverse Weather
- Availability of the communication link
  - Some Transmissions can wait for weather to clear
    - Internet users are use to waiting
  - Satellite TV needs a high level of availability
- Maintaining Signal Quality
- Using Minimum Bandwidth
- Antenna Tracking -

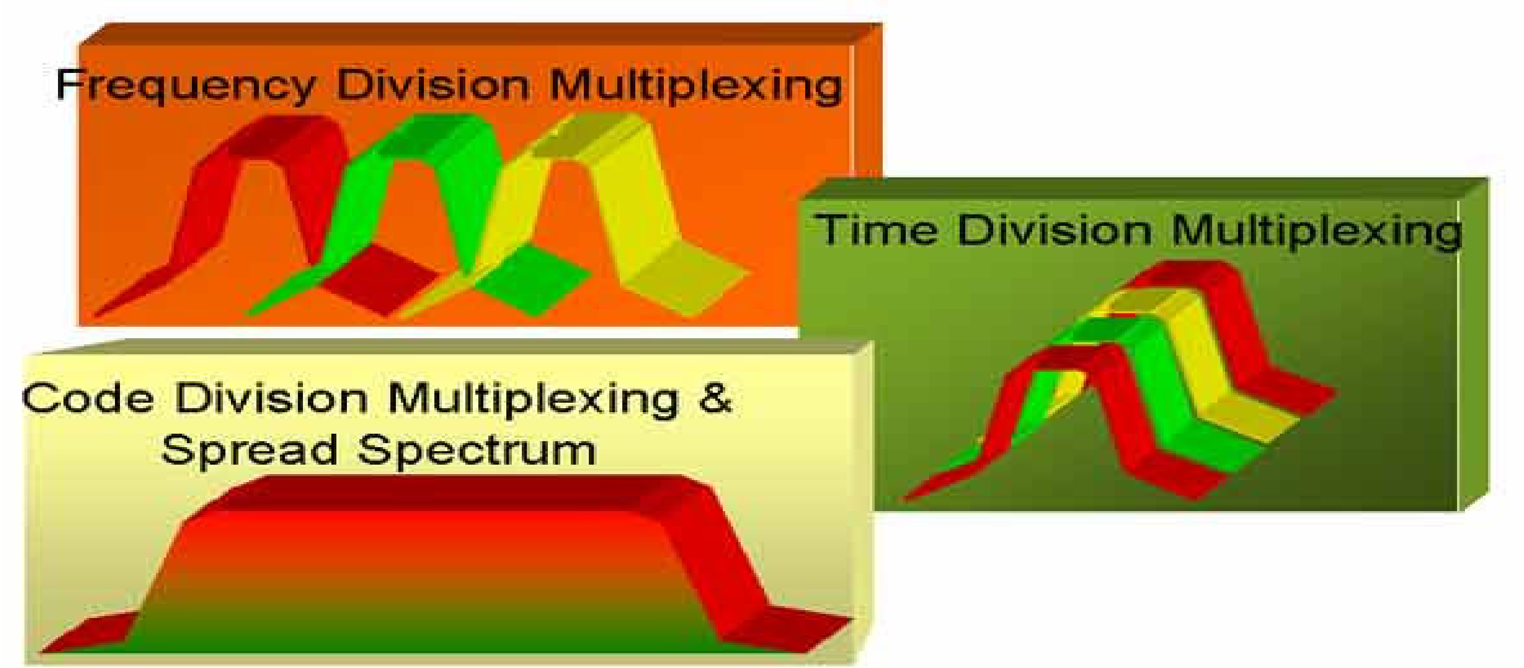
Satellite Communications Design Considerations



- Satellite signals cover a wide area
- Many users
- Independent Operations
  - One site has no idea what another site is doing
- Coexist by following the rules – Don't interfere with your neighbor -

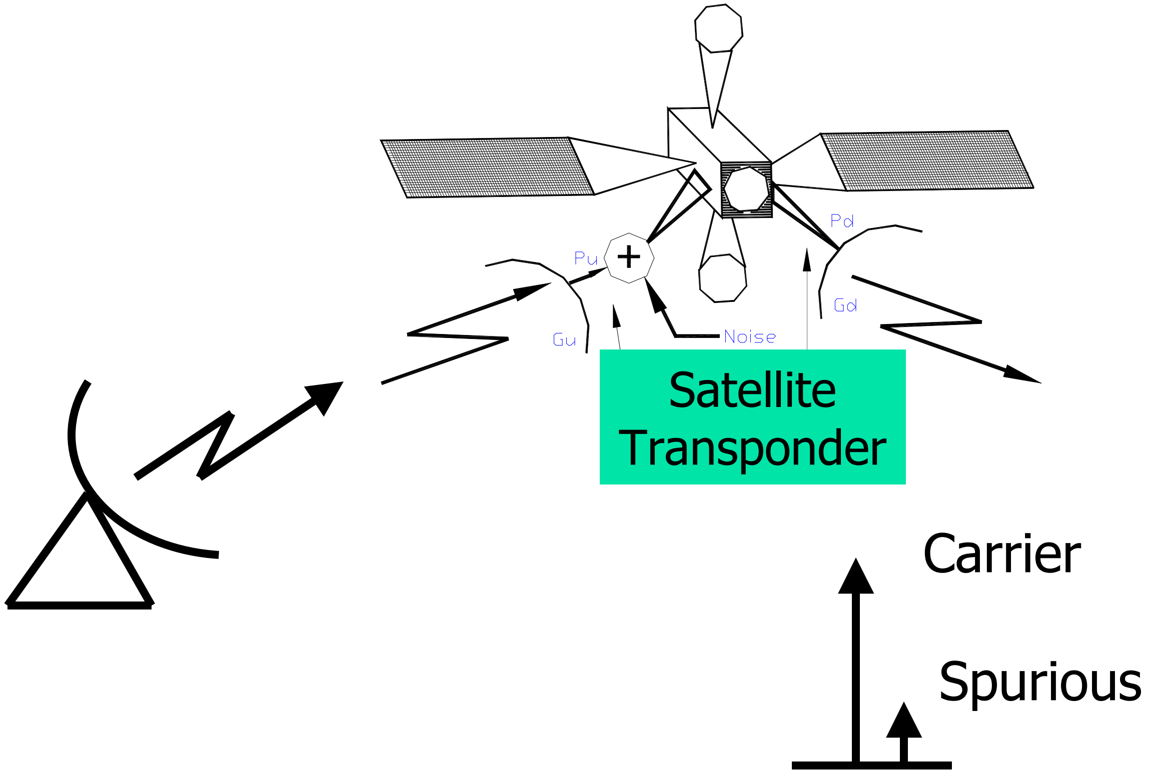
Multiple Carrier Transmission

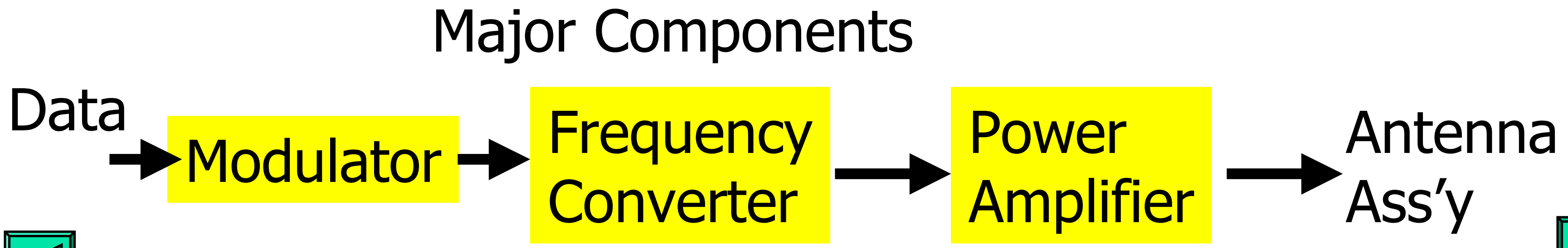
- ☐ Many Users - Multiple signals can be transmitted simultaneously or interleaved
- ☐ FDM - Each Carrier has an assigned Frequencies
- ☐ TDM - Each Carrier has an assigned Time to Transmit
- ☐ CDM - Each Carrier has an assigned Transmit Code
- ☐ Many systems use a combination of techniques
- ☐ Independent carriers to a satellite are assigned a center frequency and a bandwidth (FDM) -



Transmitter Sub-System

- Modulator
- Frequency Converter
- Power Amplifier
- Antenna -



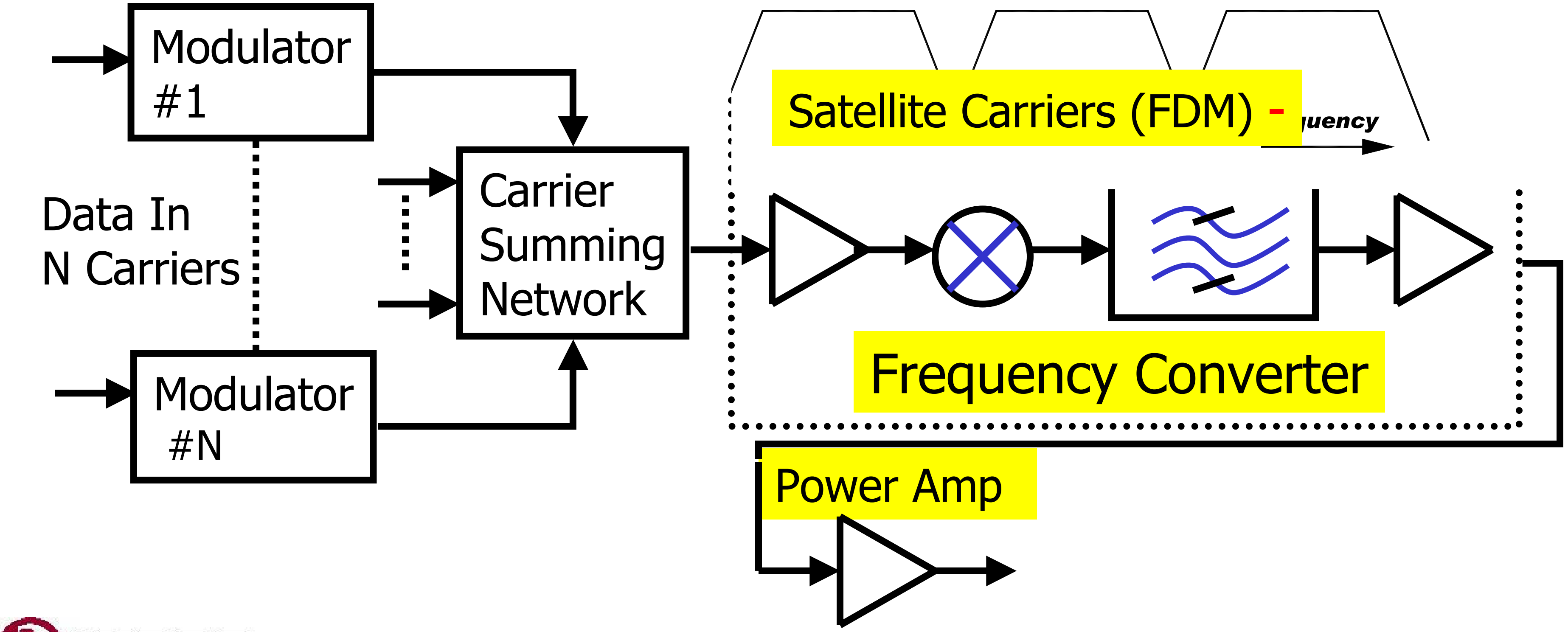


Major Components

Data → Modulator → Frequency Converter → Power Amplifier → Antenna Ass’y

Multiple Signal Transmission

- Two most expensive components in a Transmitter
  - Antenna & High Power Amplifier
  - Signals are combined prior to High Power Amplification
- Block Conversion
  - Multiple modulator outputs at their assigned frequencies are summed into a Block Up Converter (BUC)



Modulator #1

Data In
N Carriers

Modulator #N

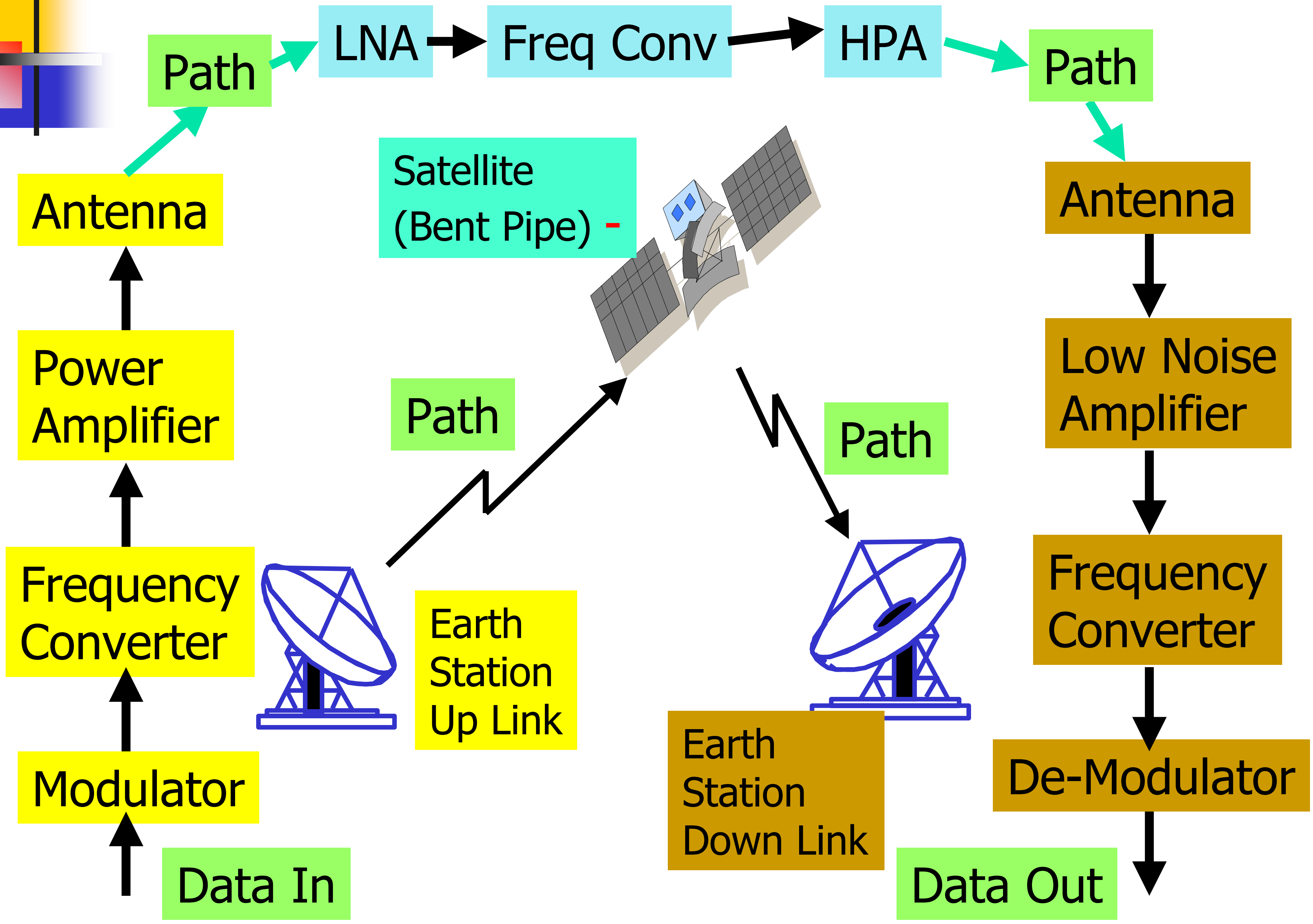
Carrier Summing Network

Satellite Carriers (FDM) - uency

Frequency Converter

Power Amp

Satellite Communications Signal Path



Data In

Modulator

Frequency Converter

Power Amplifier

Antenna

Earth Station Up Link

Path

Satellite (Bent Pipe) -

Path

LNA

Freq Conv

HPA

Path

Path

Earth Station Down Link

Antenna

Low Noise Amplifier

Frequency Converter

De-Modulator

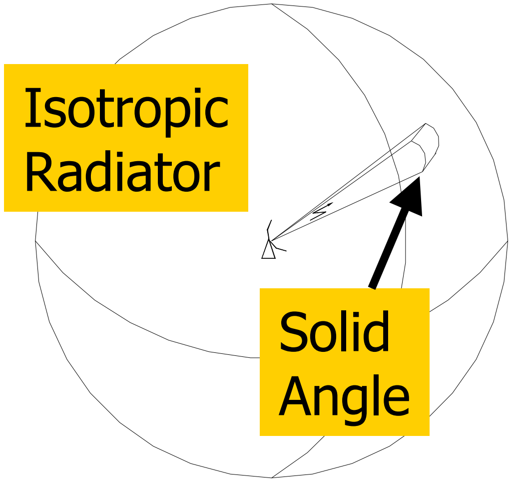
Data Out

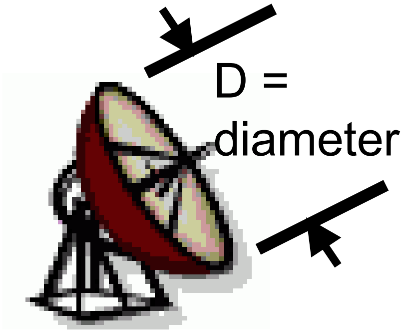
Transmitted Power

EIRP - Effective Isotropic Radiated Power

- Isotropic Radiated Power is the power emitted from a point source
  - Three dimensions
- Directional antenna emits radiation in a solid angle
- EIRP is the power radiated in the solid angle as if it were isotropic
  - EIRP = Power in Solid Angle x the number of solid angles in a sphere
- Antenna Gain (dB) = 10*Log_{10} (surface of the sphere/ surface of the solid angle)

Antenna Beam Width

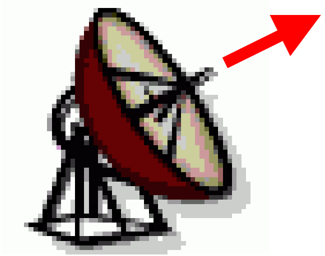




- $\mathrm{Gain}_{\mathrm{dB}} = 10*\mathrm{Log}_{10}(60*F^{2} * D^{2})$
- F = Frequency in GHz
- D = diameter of Parabolic dish in Meters -

EIRP - Effective Isotropic Radiated Power

- EIRP = Transmitter Output Power + Antenna Gain
- EIRP includes the effects of:
  - Antenna Gain
  - Antenna Efficiencies
  - Transmitter Output Power
  - Coupling and Wave guide Losses, Etc.



- Once the EIRP is known, no additional information about the transmitter is required.
  - **EIRP information assumes the transmitter is pointed directly at the receiver -**

Calculating Earth Station Transmitted Power

Typical Required EIRP = 42 dBW / 4kHz (Clear Sky)
  - Determined by the satellite operator
- Assume Signal Bandwidth = 8MHz ➔ + 33 dB (with respect to 4kHz) i.e 10Log(8MHz/4kHz)
- For 8MHz the required EIRP = + 75 dBW
  - +75 dBW ➔ 3 Billion Watts
- Antenna size
  - 10 Meter antenna @ 6 GHz ➔ 53.3 dB of Gain
- Misc Loss = 4 dB
- Pout= +75 dBW -53.3 dB + 4 dB = +25.7dBW
- Required transmitter Pout = 372 Watts -

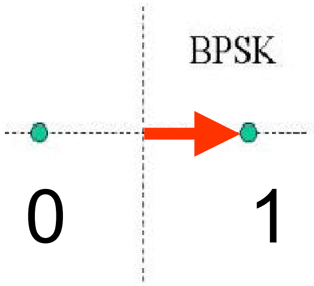
Analog vs Digital TV Transmission - Power Requirements

- Pout= 25.7 dBW in an 8 MHz BW (Digital TV Bandwidth)
  - Pout = 372 Watts
- Bandwidth of 36 MHz (Analog TV Bandwidth)
  - Pout = +25.7 dBW + 10*Log_{10} (36MHz/8MHz)
  - Pout= +25.7dBW + 6.5dB = 32.2 dBW = 1.66KW
- DTV has 4 to 8MHz BW
- HDTV 8 to 36 MHz BW
  - BW always improving
  - Better coding technology
    - Saves power
    - Increases the spectral efficiency -

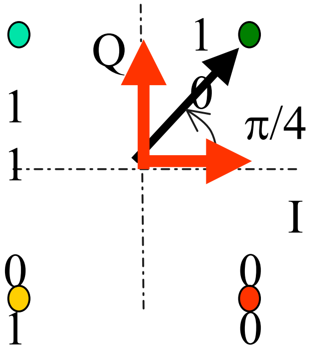
Common Digital Modulation Techniques

- Constant Envelope Modulation
  - BPSK – Bi-Phase Shift Keying
  - QPSK – Quadrature Phase Shift Keying
  - 8PSK – Phase Shift Keying with 8 phase states
- 16QAM –Quadrature Amplitude Modulation with 16 vector locations -

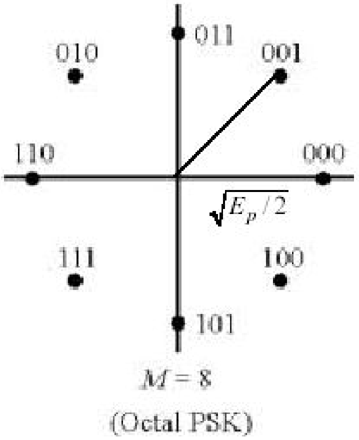
BPSK



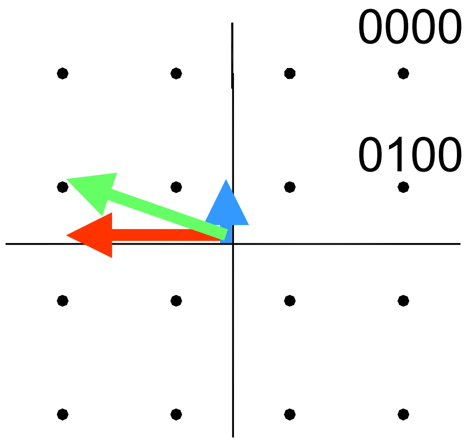
QPSK



8PSK



16-QAM



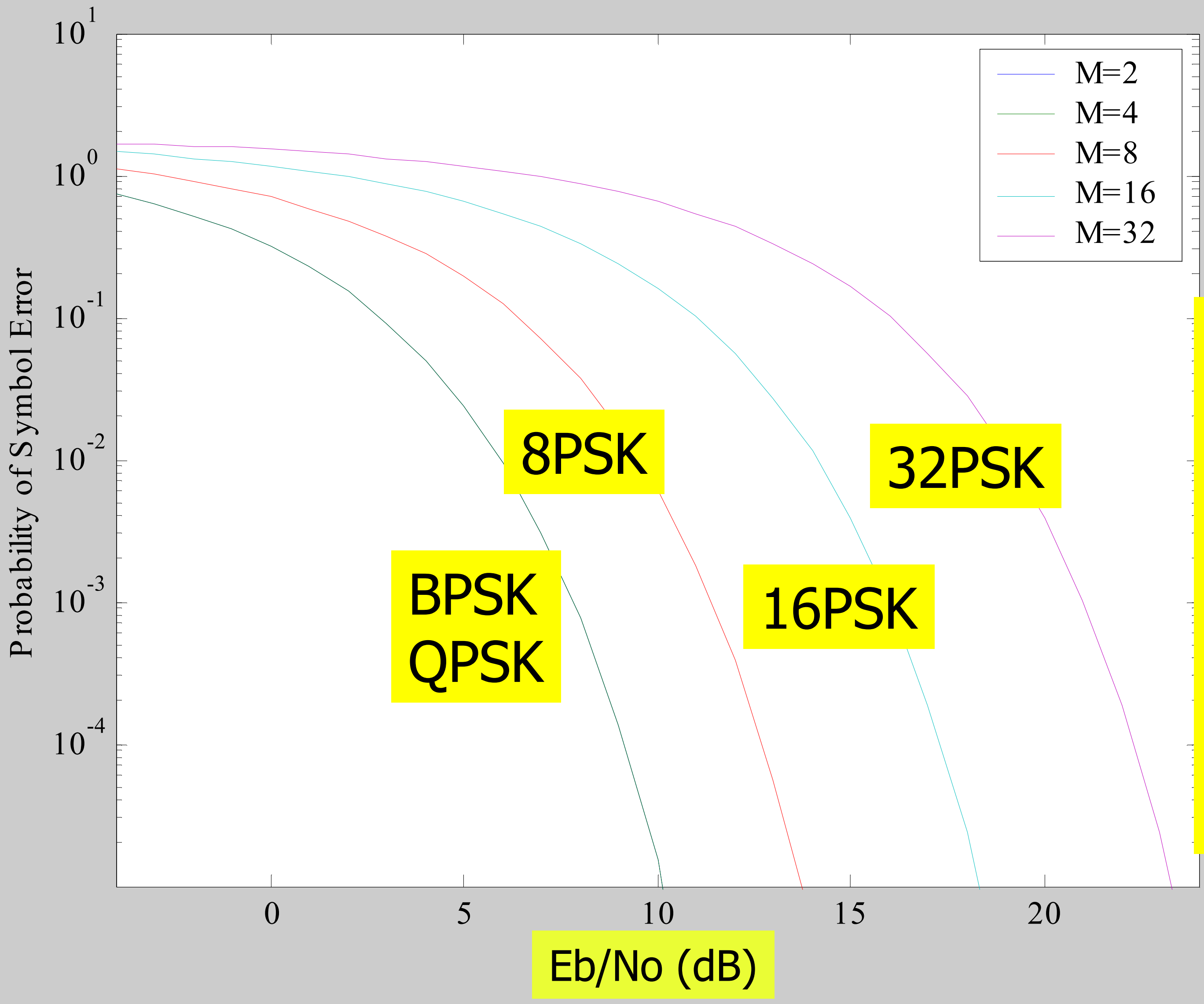
Digital Modulation: Design Trade Offs

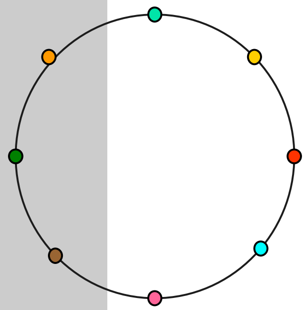
- Previously calculated Pout = 372W for an 8MHz BW
  - Required IF bandwidth (≈ 1.3 x Symbol Rate)
    - Housekeeping & Error Correcting Codes
- Bit Rate of 26MBits/Sec
  - BPSK Modulation (1 Bit/Symbol) ≈ 26MBits/Sec*1.3 ➔ 33.8 MHz
    - Pout= 1572 Watts
  - QPSK Modulation (2 Bit/Symbol) ≈ 16.9 MHz
    - Pout= 786 Watts
  - 8PSK Modulation (3 Bit/Symbol) ≈ 11.3 MHz
    - Pout= 524 Watts
- 16QAM Modulation (4 Bit/Symbol) ≈ 8.65 MHz
  - Pout does not correlate because of the AM Modulation
- More complex modulation requires less bandwidth & Less Power
  - Minumum S/N is increased to maintain an acceptable BER -

C/N vs. Eb/No

- Eb/No = C/N + 10Log(Symbol Rate/Bit Rate)
  - Eb is the Energy in a bit - Determines Bit Error Rate (BER)
  - Bit Rates >= Symbol Rates
  - Eb/No <= C/N
- For C/N = 14.49 dB
- BPSK Modulation (1 Bit/Symbol)
  - Eb/No ≈ C/N = 14.49 dB
  - Approximation is due different Forward Error Correcting (FEC) used to correct bit errors
- QPSK Modulation (2 Bit/Symbol)
  - Eb/No ≈ C/N – 3dB = 11.49dB
- 8PSK Modulation (3 Bit/Symbol)
  - Eb/No ≈ C/N – 5dB = 9.49 dB -

Symbol Error in M-ary PSK Systems





Note:
More
Complex
Modulations
Require
higher Eb/No
for the same
Error -

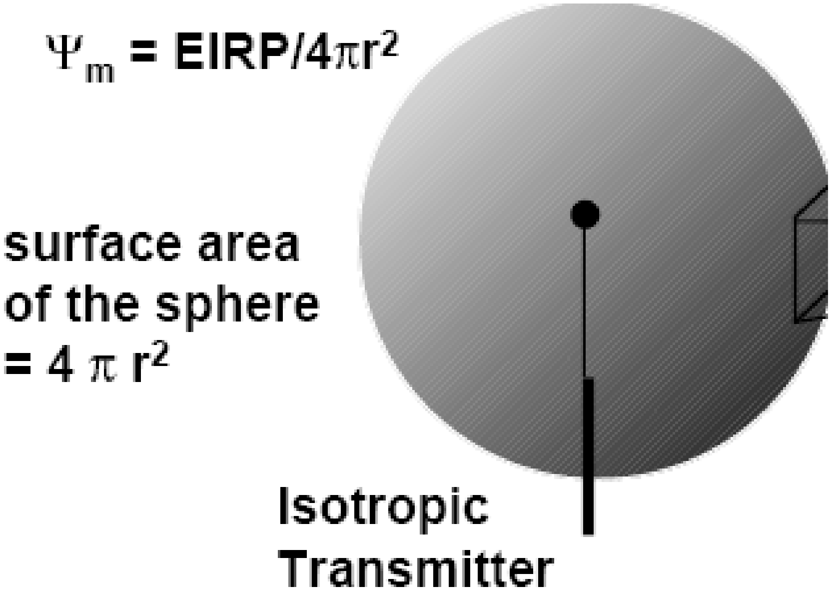
Higher Modulation Complexity ➔ Higher BER for same C/N

Limiting Factor in Digital Modulation

- Shannon's Theorem (1950's)
  - Relates Bit Rate, Bandwidth, & Signal to Noise
  - Bit Rate = BW * $\log_2(1 + SNR)$
    - Bit Rate (Bits/Sec.) = BR
    - Signal bandwidth = BW
    - SNR = Signal to Noise Ratio
- Bit Rate is limited by S/N
- Symbol rate is a function of Bandwidth
  - Bit Rate / Symbol Rate is a function of signal complexity
- Complex modulations optimize Bit Rates/BW
- Higher BR/BW requires higher Signal to Noise
- In a noiseless system
  - Infinite complexity and Bit Rate is theoretically attainable
- Shannon Theoretical limit has never been reached -

Path Loss to the Satellite

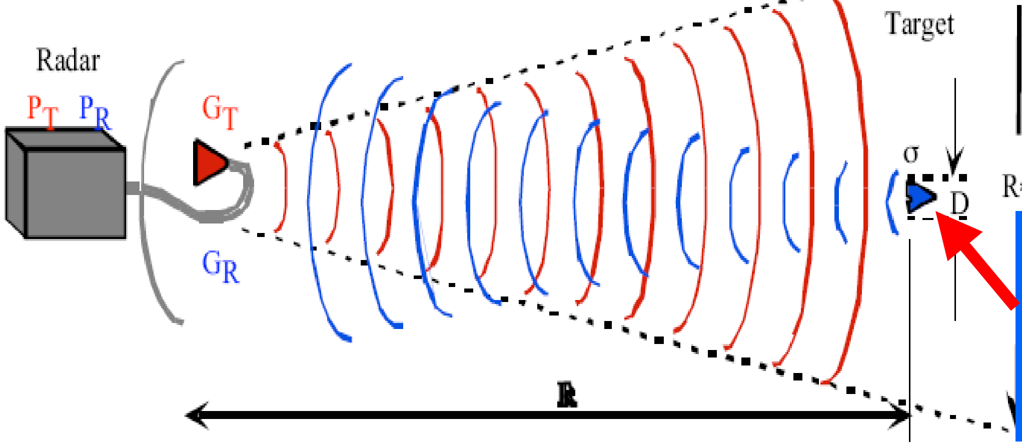
- Signal Radiates out from a point Source
- Flux Density is less at receiving antenna as the distance increases
- Path Loss is actually a dispersion of the transmitted signal



$\Psi_m = EIRP/4\pi r^2$

surface area of the sphere $= 4 \pi r^2$

Isotropic Transmitter



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

Path Loss Calculations

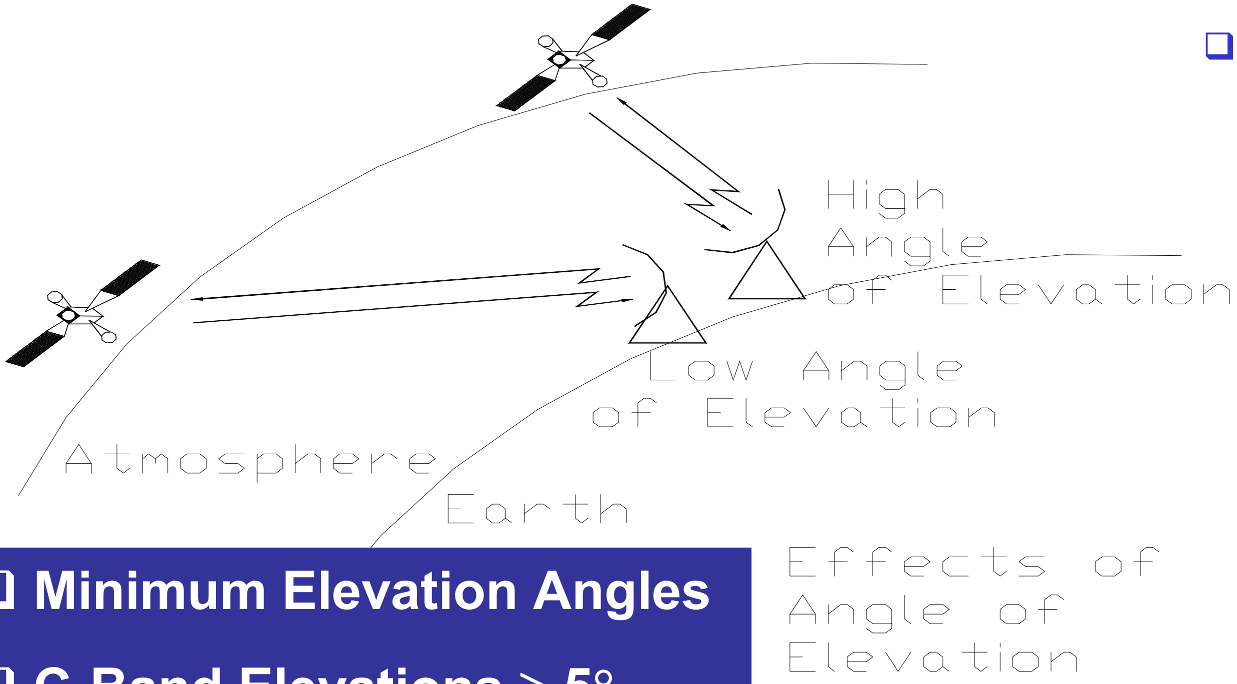
$$P_L = \left(\frac{4\pi D}{\lambda}\right)^2$$

Path Loss in dB = 10 Log(P_L)

- Note: Path Loss is related to Number of Wave Lengths Traversed:
  - Path Loss proportional to $(D / \lambda)^2$
- Example
  - Frequency: 14GHz
    - Lambda (λ) = 0.021429 Meters
  - Distance: 22,300 Miles (35,888 kM)
  - Path Loss: 206.46 dB
- This why EIRP is 3 Billion Watts -

Atmospheric Effects

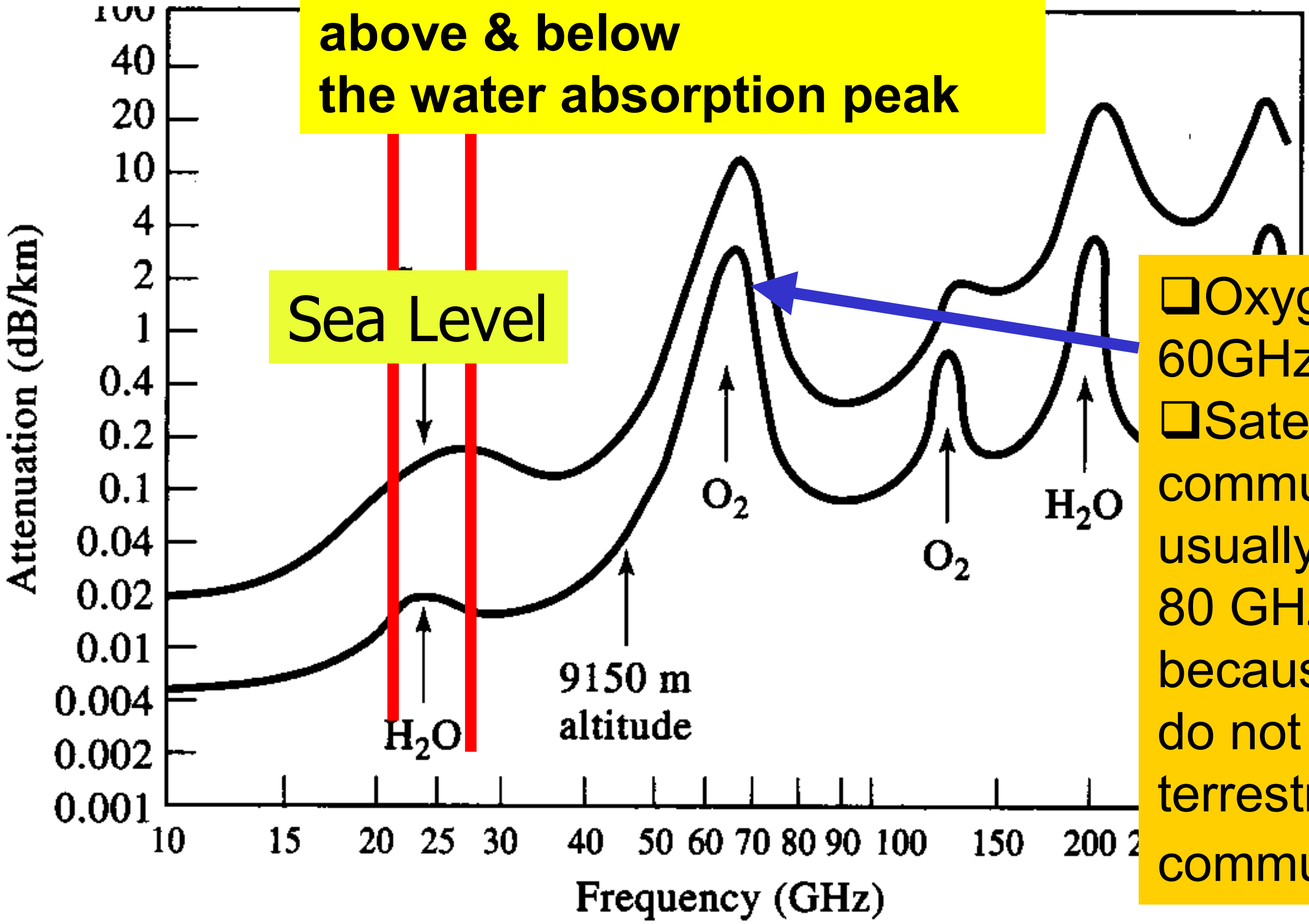
- 1st 5 miles of the 22,300 mile trip is the most detrimental
  - Potential interference from terrestrial sources
  - Increased atmospheric absorption
  - Partially depolarizes signal



- Low Elevation Angles traverse more atmosphere than high elevation angles

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

Atmospheric Attenuation vs. Frequency (Horizontal Polarization)



Ka Band Frequencies are above & below the water absorption peak

Sea Level

- Oxygen Peaks at 60GHz
- Satellite to Satellite communication is usually in the 50 to 80 GHz range, because the signals do not interfere with terrestrial communications. -

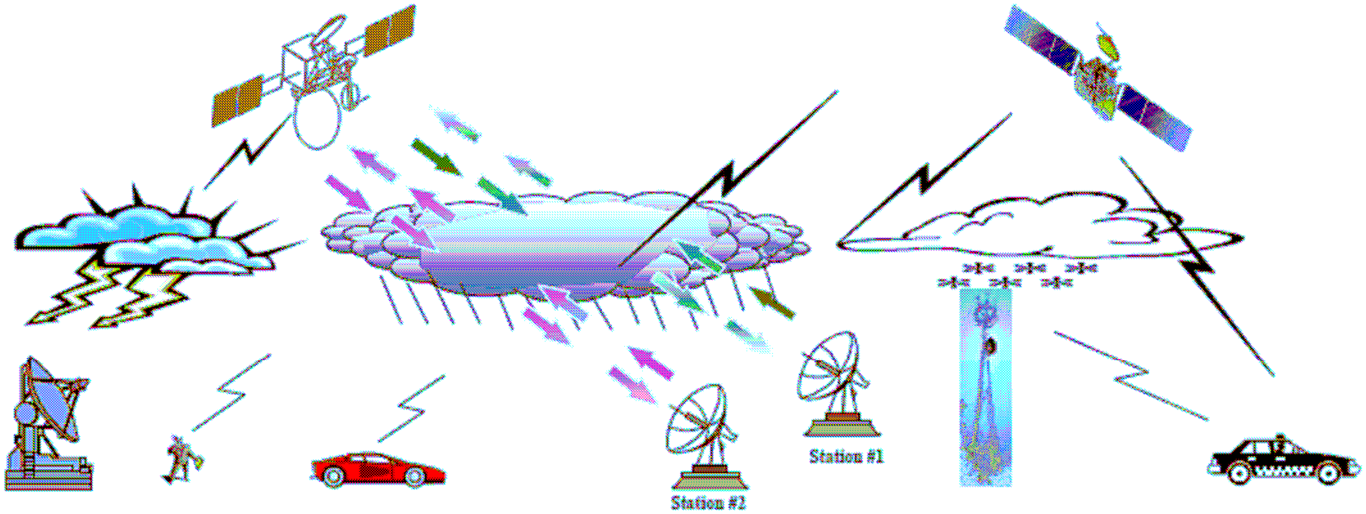
Adverse Weather

- Satellite operators demands that the signal entering the satellite have a fixed Power Spectral density
    - Prevents signals from interfering with each other
- Satellite users expectation of signal availability varies
    - Internet users have been conditioned to wait
    - Super bowl viewers must see pictures without a lapse
- Rain is the most common adverse effect on signal transmissions -

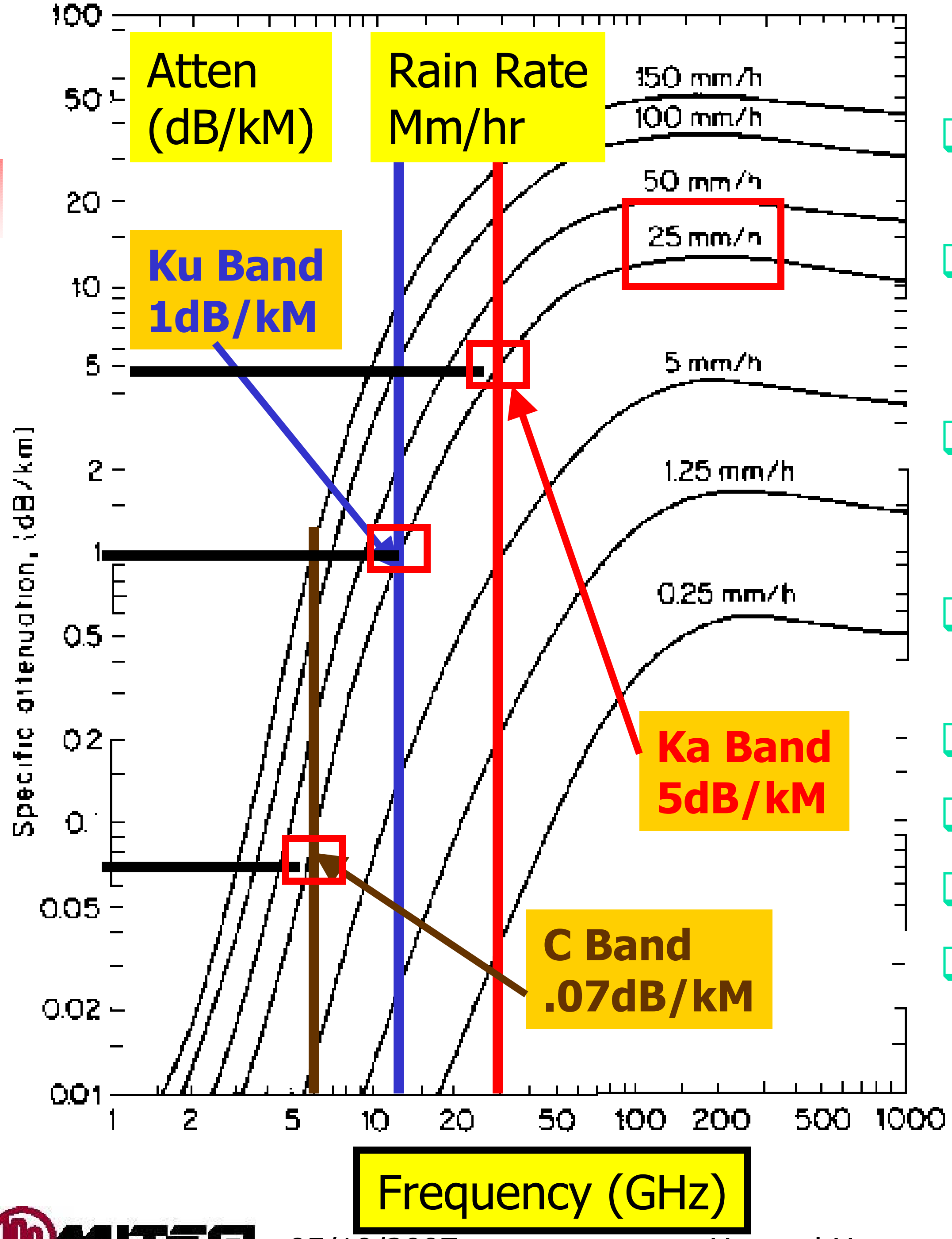
Rain Fade Margins

- Adverse weather is usually localized
- MUST have power to spare to burn through adverse weather
- C-Band: 2 to 3 dB
- Ku-Band: 5 to 15 dB
- Ka-Band: 20 to 50 dB

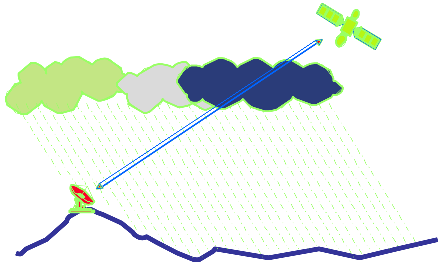
- Actual rain fade margins depend on
  - Location of the earth station
  - Rain fall model for the respective area
- Weather effects only the first 5 miles -



Rain Attenuation



- Droplets absorb and de-polarize the microwaves
- Rain effects depend on Rain Rates which are classified by region
- Note the significant difference in Ka Band Attenuation
- C-Band rain fade is a minor problem
- 5kM @ 25mm/Hr Rain
- C-Band Loss: .35dB
- Ku Band Loss: 5dB
- Ka Band Loss: 25dB -



Rain Rate Chart

CCIR Rain Zone Rain Rates in mm/h

% Time at Rate

Rain Rates

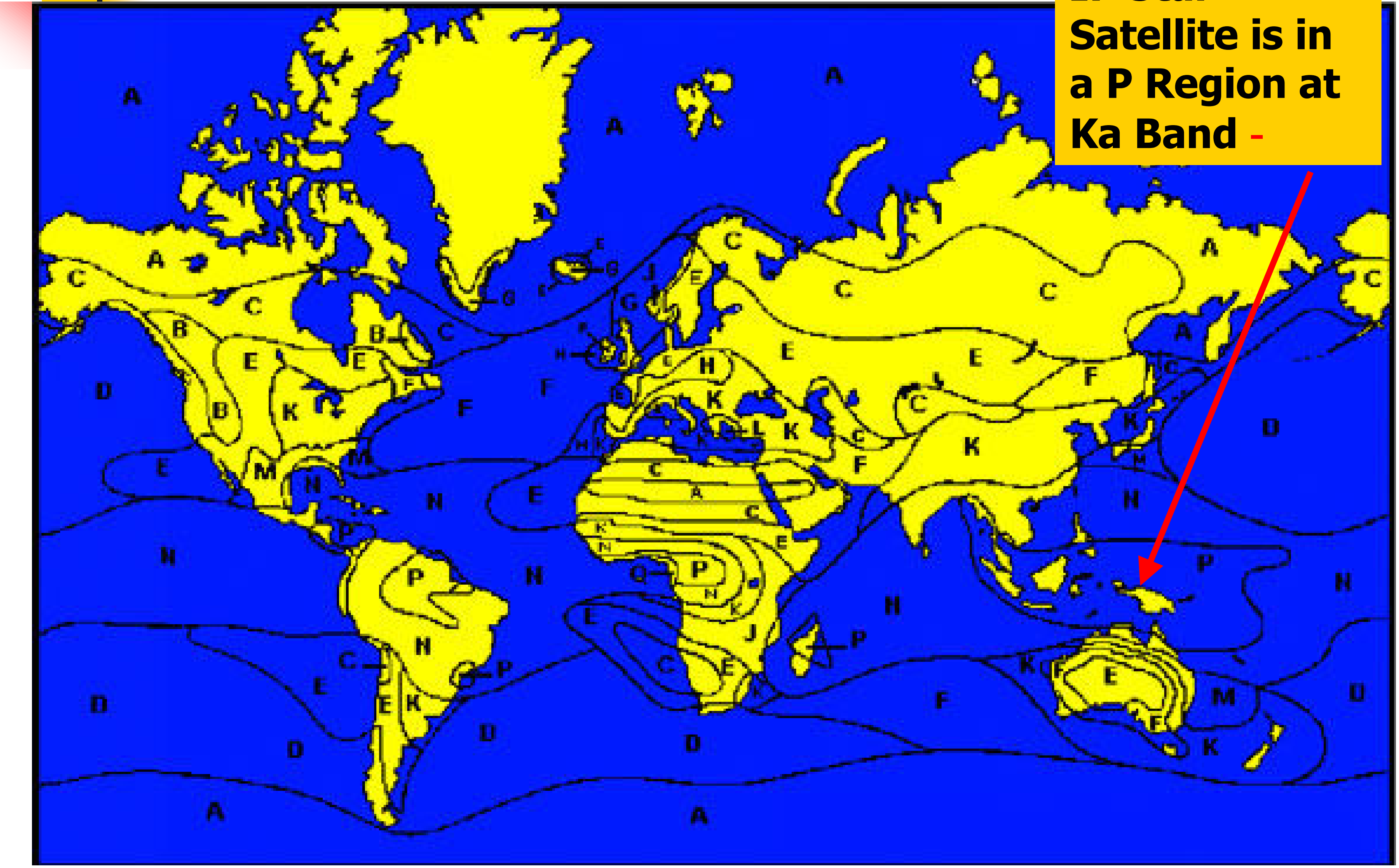
Rainzone	**1%**	**0.30%**	**0.10%**	**0.03%**	**0.01%**	**0.003%**	**0.001%**
A	0	1	2	5	8	14	22
B	1	2	3	6	12	21	32
C	0	3	5	9	15	26	42
D	3	5	8	13	19	29	42
E	1	3	6	12	22	41	70
F	2	4	8	15	28	54	78
G	0	7	12	20	30	45	65
H	0	4	10	18	32	55	83
J	0	13	20	28	35	45	55
K	2	6	12	23	42	70	100
L	0	7	15	33	60	105	150
M	4	11	22	40	63	95	120
N	5	15	35	65	95	140	180
P	12	34	65	105	145	200	250
Hr/Yr	**87.6**	**26.28**	**8.76**	**2.628**	**0.876**	**0.2628**	**0.0876**
Availability	**99%**	**99.7%**	**99.9%**	**99.97%**	**99.99%**	**99.997%**	**99.999%**
1 Year	**8760 Hours**						

mm/Hr

Problem Hr/Yr

99.9% availability in rain zone "P" requires sufficient dB margin to over come 65 mm/hr rain rates -

Rain Rates at Various Locations



IP Star Satellite is in a P Region at Ka Band -

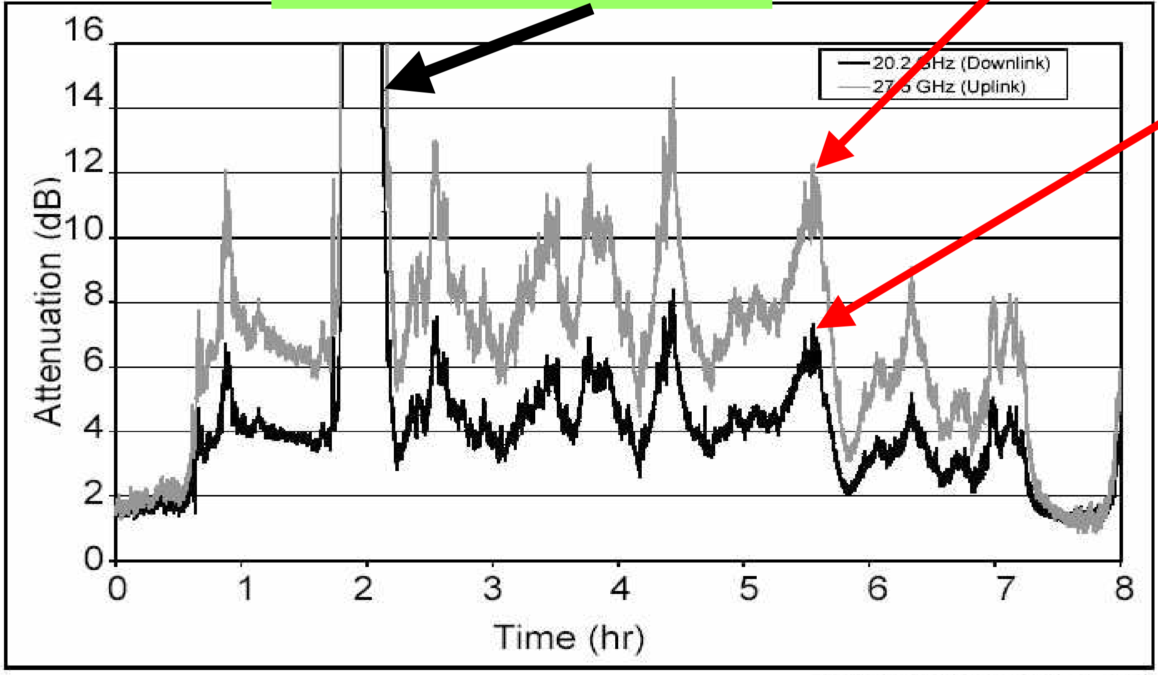
Approaches to Rain Fade

- Larger ground station antennas
  - Difficult to Point
- Higher available power
  - Up-Link Power Controller adjusts the transmitted power
  - average rain time is short (< 10%)
  - Added margin is wasted 90% of the time.
- Site diversity
  - Parallel operation several kilometers apart
  - “expensive”
- Adaptive Coding
  - Increase in Forward Error Correction Coding
  - Flexible Bandwidths maintain constant data rates
  - Difficult to Implement -

Atmospheric Attenuation Measured with the ACTS satellite systems over an 8 hour period in Tampa, FL. On Jan 1, 1996

Rain Fade at 27.5 GHz & 20.2 GHz

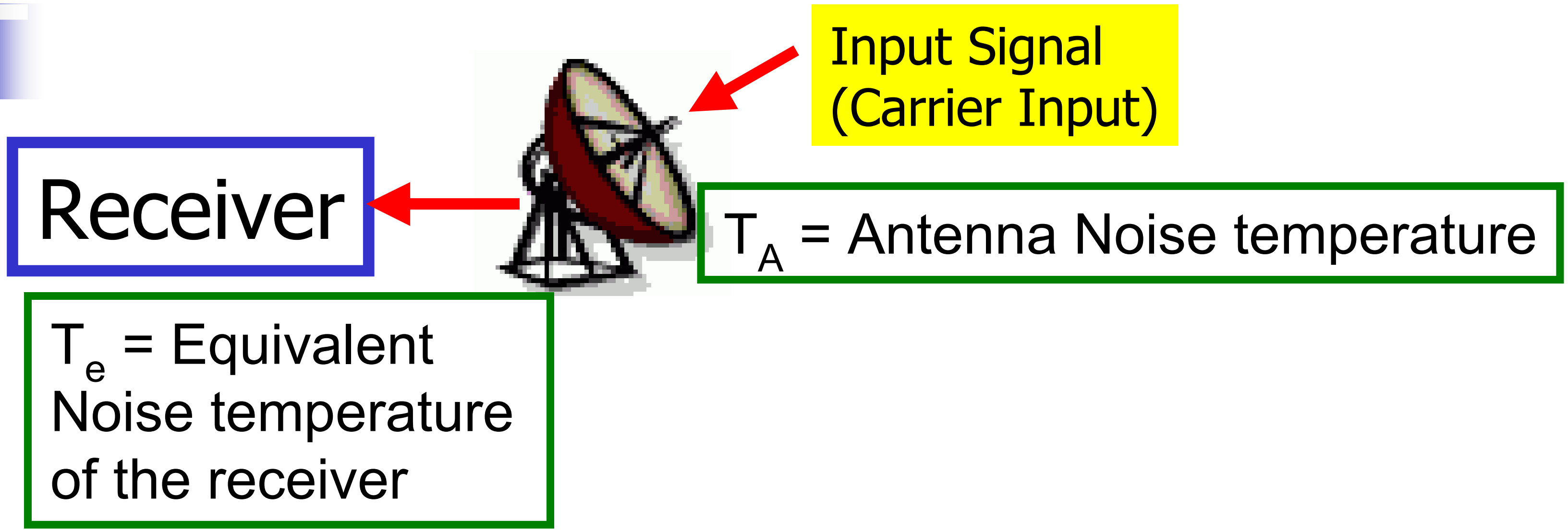
Transmission loss during the peak attenuations -



Rain Rate vs Time (Hours)

- Change in attenuation vs. time

Receiving System – Carrier to Noise



Input Signal (Carrier Input)

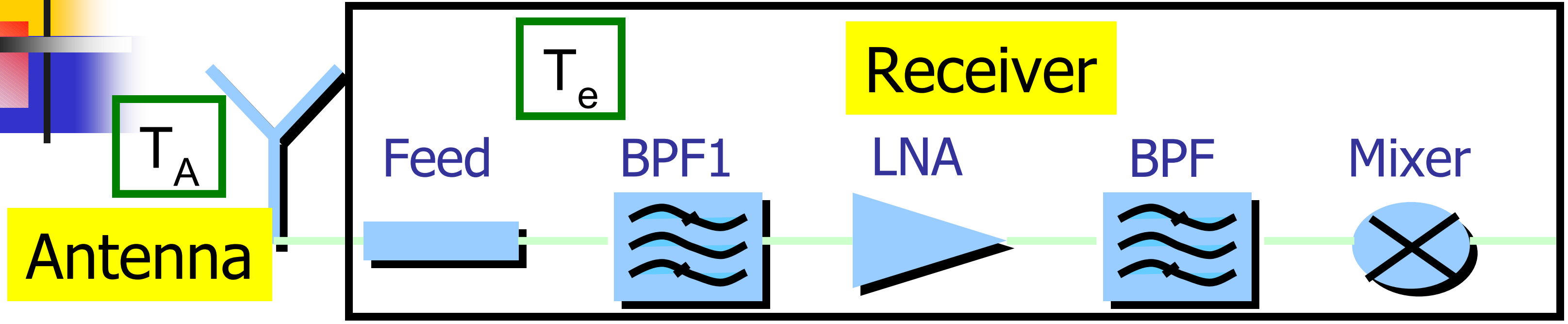
Receiver

T_A = Antenna Noise temperature

T_e = Equivalent Noise temperature of the receiver

- Noise is a random motion of electrons
- At 0 °K there is no electron motion
- Noise is referenced in terms of Noise Temperature (°K)
  - System Noise (T*sys)* is temperature above 0 °K
- Antenna & Receiving system adds noise to the input signal -

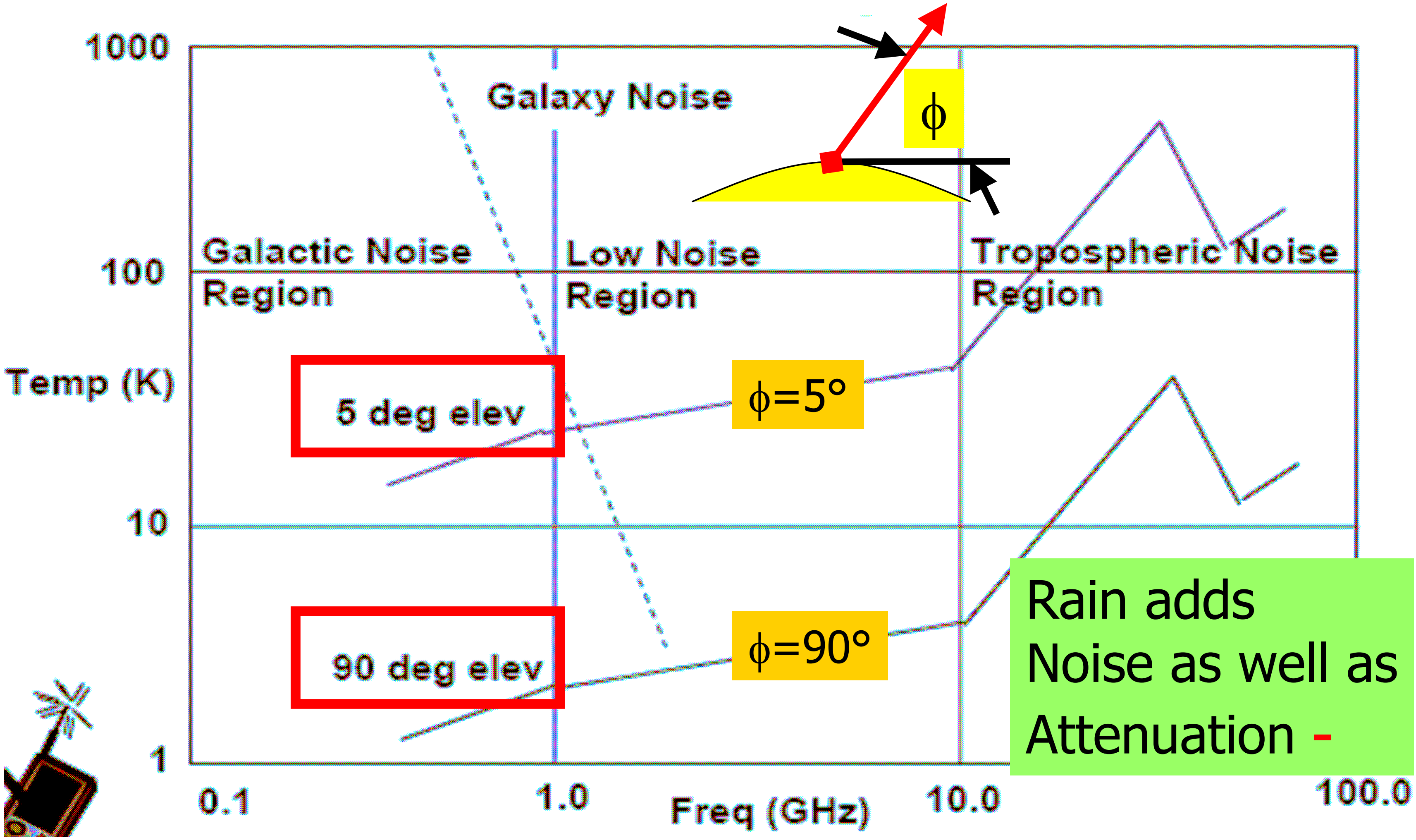
Antenna Noise & Noise Figure



- System noise temperature $T_{sys} = T_A + T_e$
- Antenna Noise Temperature = T_A
- T_A = sky noise + antenna losses
    - sky noise is background microwave radiation
- Receiver Noise (T_e) is the added to the signal
- Receiver Noise Temperature relates to Noise Figure
    - $T_e = (F_n - 1)\,T_o$ ($T_o = 290°K$)
    - Fn is the receiver noise factor
    - Noise Factor $F_n = 10^{NF/10}$
        - NF = Noise Figure in dB -

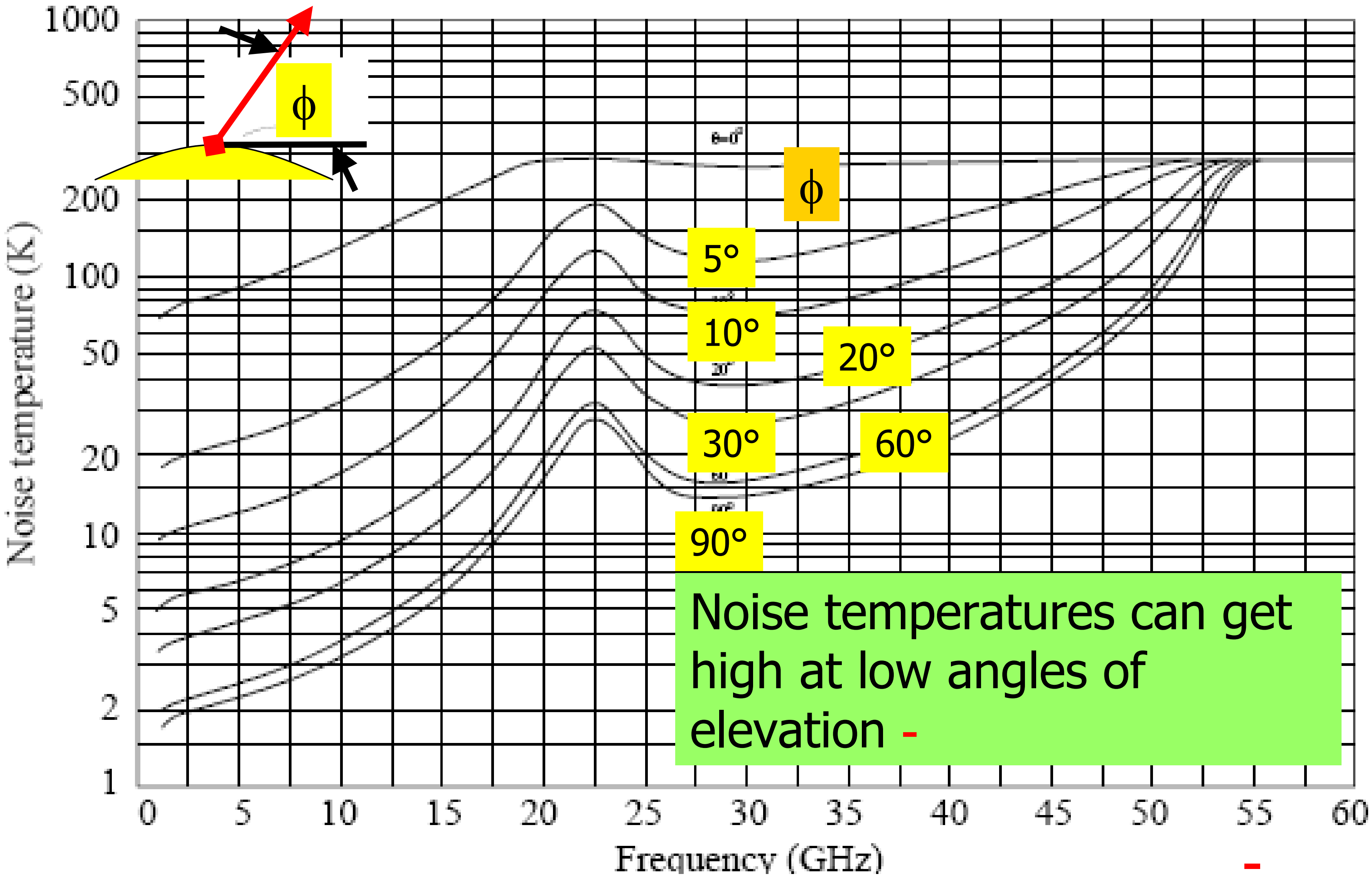
Antenna Noise

Antenna Noise is a function of Elevation Angle and Frequency



Rain adds Noise as well as Attenuation -

Antenna Noise vs. Angle off Perpendicular



Noise temperatures can get high at low angles of elevation -

Table of Noise Temperature (Te), Noise Factor (F) and Noise Figure (NF)

- Standard Temperature = To=290°K
- Noise Factor (Fn) = 1+ (T_{eff}/T_o)
- **NF is the noise Figure (dB)** -

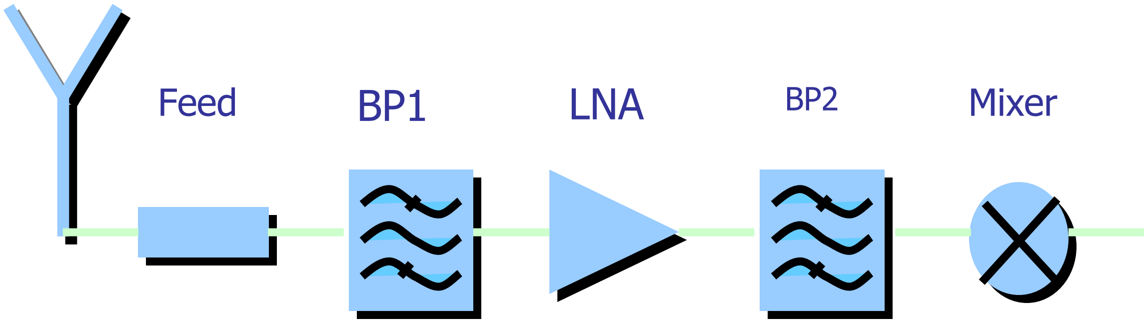
Te	F	NF
Deg K		dB
10	1.03	0.15
20	1.07	0.29
40	1.14	0.56
70	1.24	0.94
100	1.34	1.29
150	1.52	1.81
200	1.69	2.28
250	1.86	2.70
298	2.03	3.07
400	2.38	3.76
500	2.72	4.35
700	3.41	5.33

NF	F	Te
dB		Deg K
0.1	1.02	6.75
0.2	1.05	13.67
0.3	1.07	20.74
0.4	1.10	27.98
0.5	1.12	35.39
0.6	1.15	42.96
0.7	1.17	50.72
0.8	1.20	58.66
0.9	1.23	66.78
1	1.26	75.09
1.1	1.29	83.59
1.2	1.32	92.29

- NF = 10 * $\log_{10} [1+ (T_{eff}/T_o)]$ **= 10 Log (Fn)** -

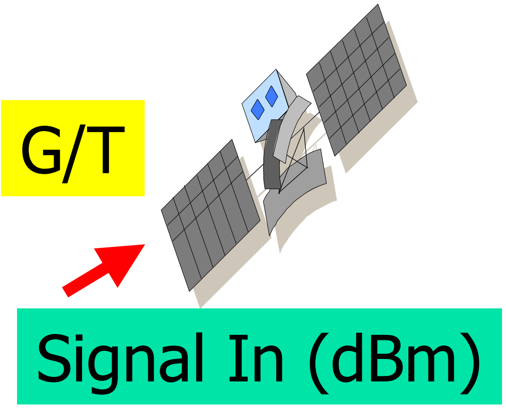
Calculating System Noise Temperature

- TSYS = TA + TLNA
  - TA is the antenna noise temperature
  - TLNA is the LNA noise temperature (Receiver Noise)
- Example:
  - Antenna Sky Noise : Tsky = 5° K
  - Losses: 0.5 dB ➔ Tloss = 38° K
  - TA = Tsky + Tloss = 43° K
- LNA: NF = 0.7dB ➔ TLNA = 51° K
- TSYS = 43 ° + 51 ° = 94 ° K -



Gain Over Noise Temperature (G/T)

- G/T is Gain / Noise Temperature
- G/T = Antenna Gain (dB) - System Noise Temperature (dB) [10 Log(Tsys/1°K)]
- Signal at the receiving antenna is increased by the antenna gain
- Subtract out the System Noise Temperature
- Result is signal level with respect to Thermal noise



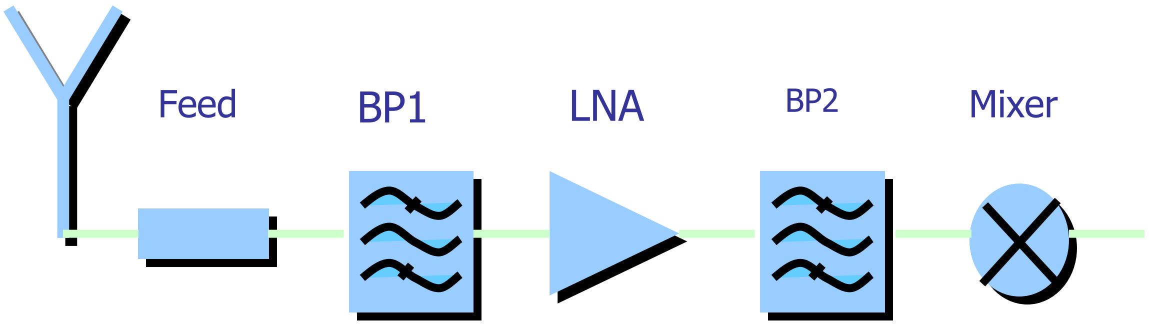
G/T

Signal In (dBm)

Signal In (dBm) + G/T (dB) = Signal with respect to Thermal Noise -

Calculating G/T

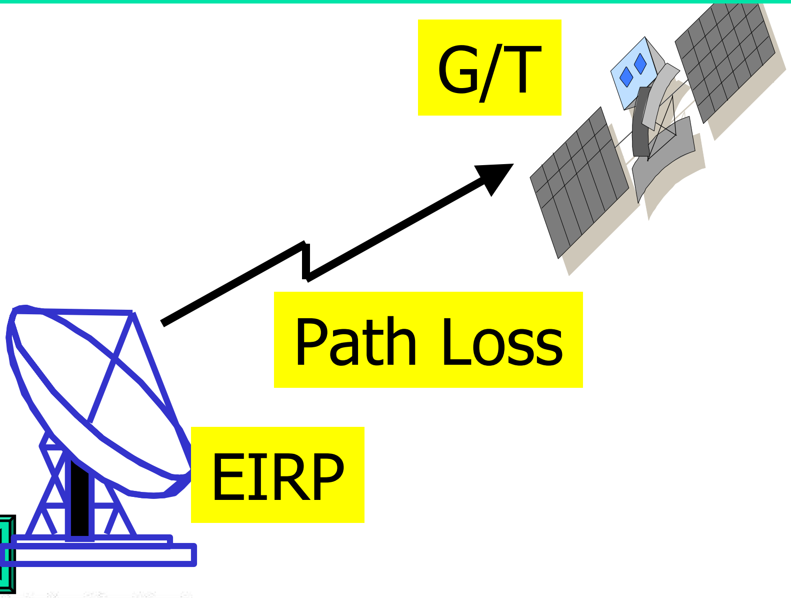
- TSYS = TA + TLNA
  - TA is the antenna noise temperature
  - TLNA is the LNA noise temperature (Receiver Noise)
- Antenna: TA = 43° K, Gain = 38 dB
- LNA: TLNA = 51° K
- TSYS = 43 ° + 51 ° = 94 ° K
- G/T = Antenna Gain (dB) - 10 Log(Tsys/1°K)
- G/T = 38dB –19.7dB = 18.3 dB -



Importance of G/T Parameter

- Signal into the antenna is increased by G/T (dB) = S_A(dBm)
  - C/N = S_A(dBm) / Thermal Noise (dBm)
- C/N = Carrier at the Antenna (dBm) + G/T(dB) – (-174dBm/Hz) - 10Log(BW(Hz))
- Signal Level at the Antenna & G/T of a receiver is all the information necessary to determine the C/N
- Communication Link C/N can be determined knowing only EIRP, Path Loss, G/T, & Bandwidth

C/N = EIRP(dBm) - Path Loss(dB) + G/T(dB) - 10Log$_{10}$(kTB) -



- k=Boltzman’s Constant
- T=Temperature (°K)
- B=Bandwidth in Hz
- Bit Error Rate is a function of C/N

Satellite Link Example

Transmission System Antenna Gain & EIRP

Antenna Gain

Diameter	2.5	Meters
Frequency	14	GHz
Lambda	0.021429	Meters
Ideal Gain	48.66	dB
Ant Effic.	2	dB
Ant Gain	46.66	dB

EIRP Analysis

Antenna Gain	46.7	dBi		
HPA Output	24.77	dBW	300	Watts
Feed Loss	0.4	dB		
Xmit Path Loss	0.6	dB		
System EIRP	70.47	dBW		

- EIRP is 70.47 dBW
- Total Necessary information about the Transmit system -

Path Loss & Received Signal Level

System EIRP:70.47 dBW → +100.47 dBm

Path Loss		
Distance	**22300**	Miles
	35888.37	kM
Path Loss	206.46	dB
Fade Margin	10	dB
Worst Path Loss	216.46	dB

- Path Loss is under Clear Sky Conditions
- Worst Path Loss is during adverse weather conditions

Received Signal Level

Clear Sky	-105.99 dBm
Adverse Weather	-115.99 dBm -

Receiver (G/T)

Antenna Gain

Diameter	1.5	Meters
Frequency	14	GHz
Ideal Gain	44.23	dB
Ant Effic.	2	dB
Ant Gain	42.23	dB

G/T Analysis

Antenna Noise at 20 Deg Elevation Angle	11	Deg K
W/G Loss	14	Deg K
LNA Noise Temp	50	Deg K
System Noise Temp	75	Deg K
Antenna Gain	42.23	dBi
G/T	23.48	dB/°K

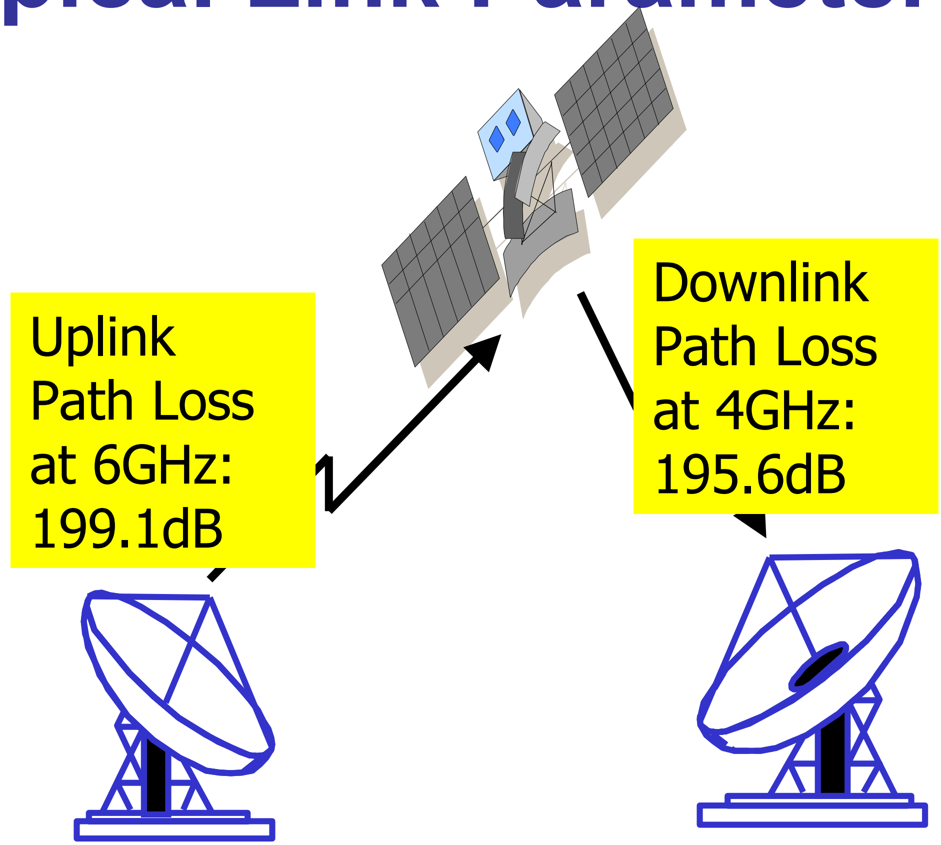
- Loss in a passive device is the devices noise figure
- Waveguide loss is converted to Noise Temperature -

Link Analysis

Link Analysis	Clear Sky	Adverse Weather
Max. EIRP	70.47 dBW	70.47 dBW
Power Back-Off	10.00 dB	0.00 dB
EIRP	60.47 dBW	70.47 dBW
Path Loss	206.46 dB	216.46 dB
Signal at Receiver	-115.99 dBm	-115.99 dBm
G/T	23.48 dB	23.48 dB
Effective Signal at RCVR	-92.52 dBm	-92.52 dBm
Thermal Noise	-174 dm/Hz	-174 dm/Hz
C/N (1Hz)	81.48 dB/Hz	81.48 dB/Hz
Bandwidth	5.00 MHz	5.00 MHz
C/N	14.49 dB	14.49 dB

- Note the back-Off under clear sky conditions -

Typical Link Parameters



Uplink Path Loss at 6GHz: 199.1dB

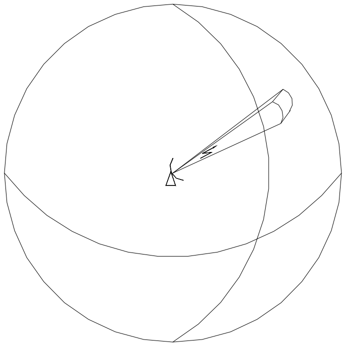
Downlink Path Loss at 4GHz: 195.6dB

- Uplink Frequency: 5.925 to 6.425GHz
- Down Link Frequency: 3.7 to 4.2 GHz
- Up Link is always the higher Frequency (Higher Path Loss)
- Higher Power Amplifiers and lower noise amplifiers are more available on the Ground Segment ---

Bandwidth Economics

- Bandwidth is expensive
  - Bandwidth is a Limited Natural Resource
  - There is a limited bandwidth availability
- More Bandwidth requires greater EIRP
- Power Amplifiers are expensive
- Larger Antennas are expensive
  - Pointing Large Antennas can be a problem
    - A 3 Meter Antenna at 14 GHz has a 1.5° Beam width -

Antenna Beam Width



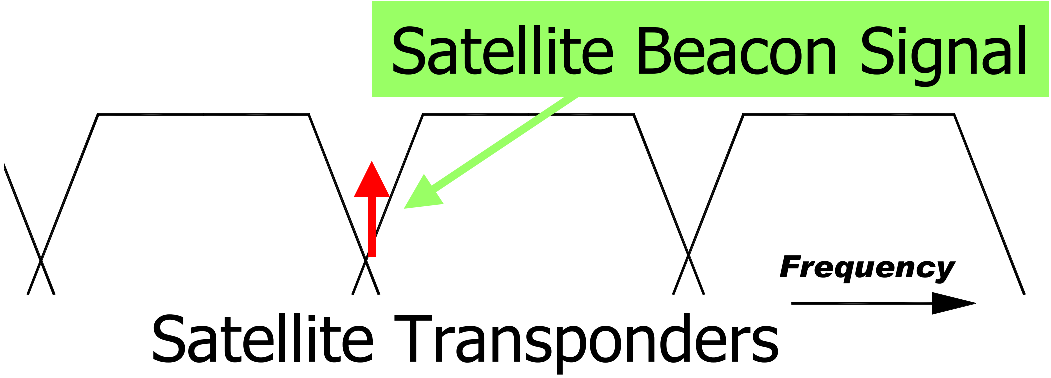
Beam width is a solid angle
• Beam width ≈ 21 / (F*D) in degrees (Parabolic dish)
F = Frequency in GHz
D = diameter of the dish in Meters

Satellite Tracking
Antenna Pointing

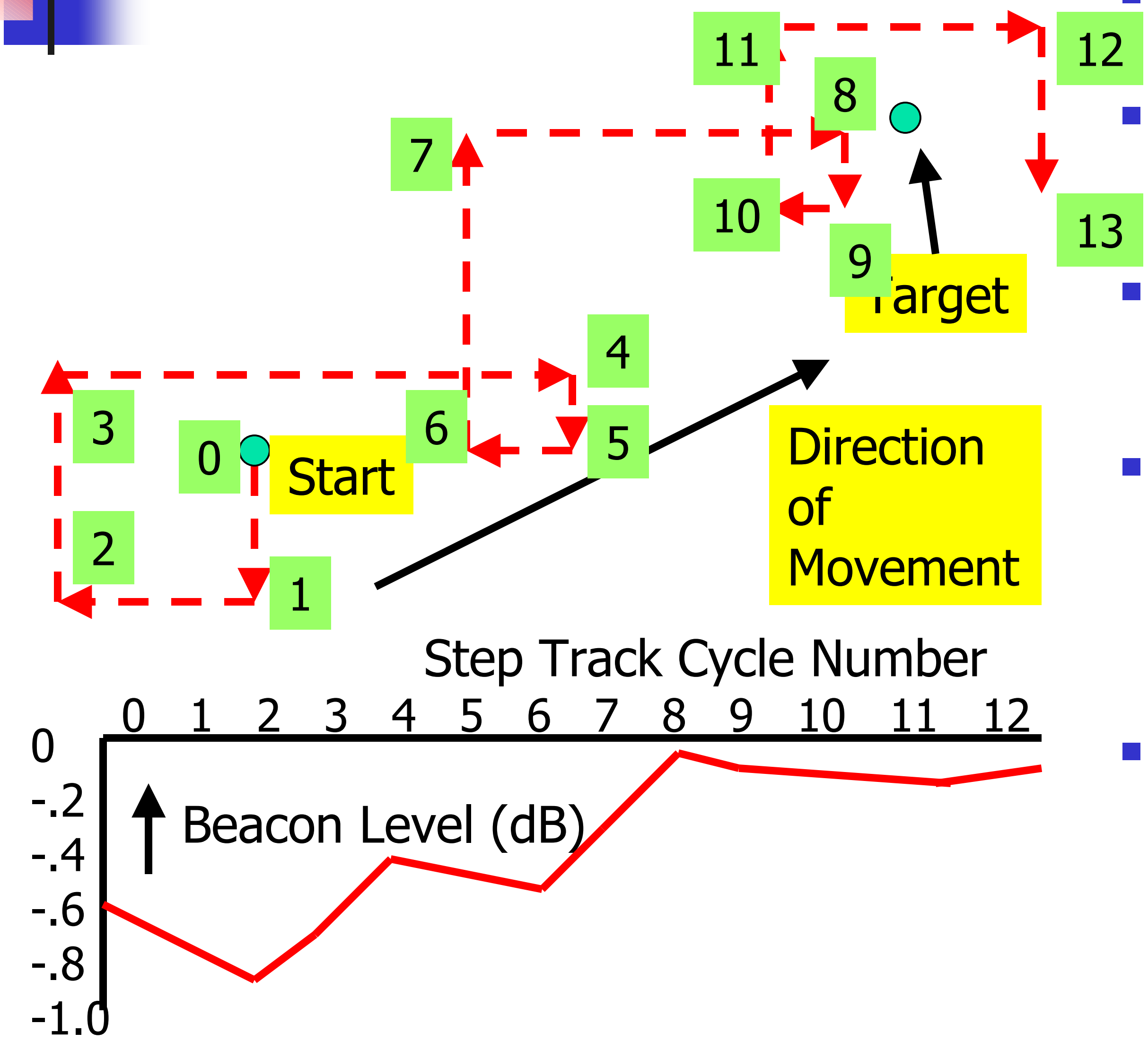
- Satellite locations are relatively fixed in the sky
- Small antenna can be set manually
- Large Antenna require some satellite tracking mechanism
- A sensitive receiver locks on to a satellite beacon
- Earth Station antenna searches for maximum beacon power to focus the antenna on the satellite -

Beacon Receiver

- Beacon Signals are buried between the data transponders
- Beacon can be as much as 50dB below the composite carriers
- Beacon Receiver must locate the beacon and measure its power level
- Beacon Signals change from CW to Spread Spectrum Telemetry Data Carriers
- Locking on a Beacon Signal is difficult -



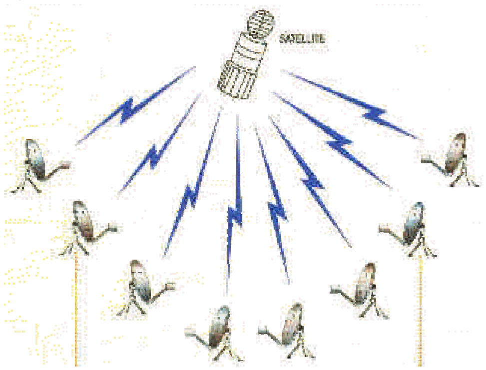
Antenna Step Tracking



- Used for Low Relative Motion
- Beacon Receiver Monitors Signal Strength
- Moves Antenna in Small Az/El Increments
- Compares Signal Strength with Previous Values to Determine Direction & Size of Next Step
- Once Signal Strength is “Peaked” Waits for Next Scheduled Step Track Cycle -

Uplink Power Control

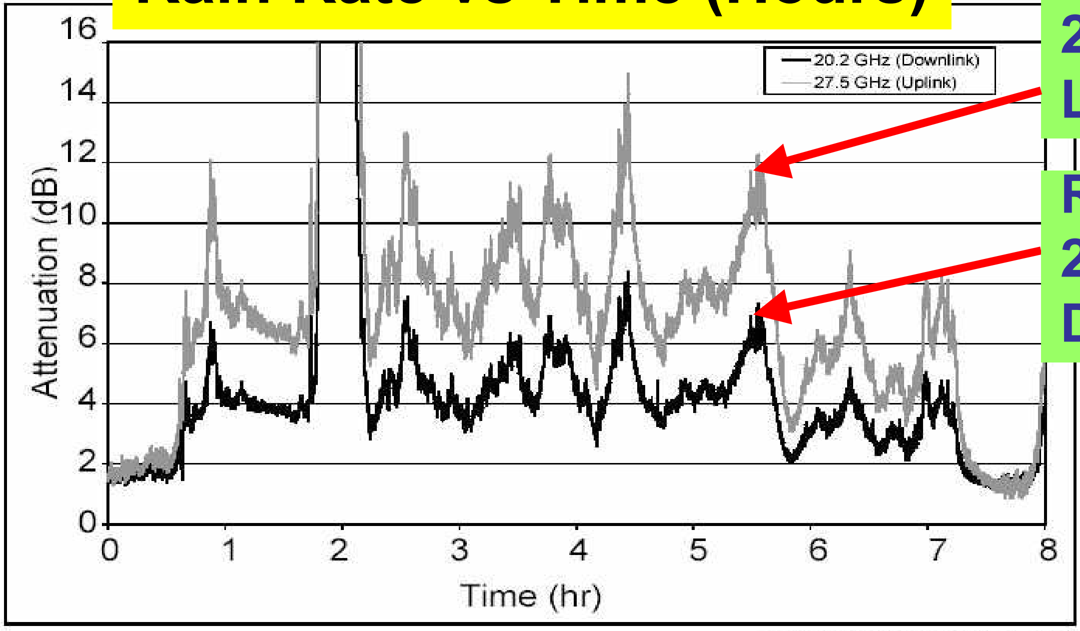
- Spectral Densities at the satellite MUST be constant (dBm/Hz)
  - Prevent adjacent channel interference
  - Constant within 0.5 dB under clear sky conditions
  - Within 1dB under adverse weather conditions
- Beacon Receiver monitors down link signal strength
- Algorithm converters down link signal strength to expected uplink path loss
- Up Link Power Controller adjusts transmitter power to compensate for path loss variations -



Up & Down Link Correlation

- Note the correlation of down link and up link attenuation
- Uplink controller corrects uplink power
  - Uses down link beacon power and a correlation algorithm -

Rain Rate vs Time (Hours)



Rain Fade at 27.5 GHz Up Link

Rain Fade at 20.2 GHz Down Link

Summary

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- A Satellite Communication system was used as a example
  - Principals hold for all communication systems
- Terrestrial Communications Systems other issues:
  - Shorter paths
  - Multi-paths
  - Terrestrial interference
- Fundamentals of Satellite Communications
  - Part 3 Modulation Techniques
  - Part 4 Effect of Sub-System Specifications on Signal Recovery -