Overview of Satellite Communications

Dick McClure

Agenda

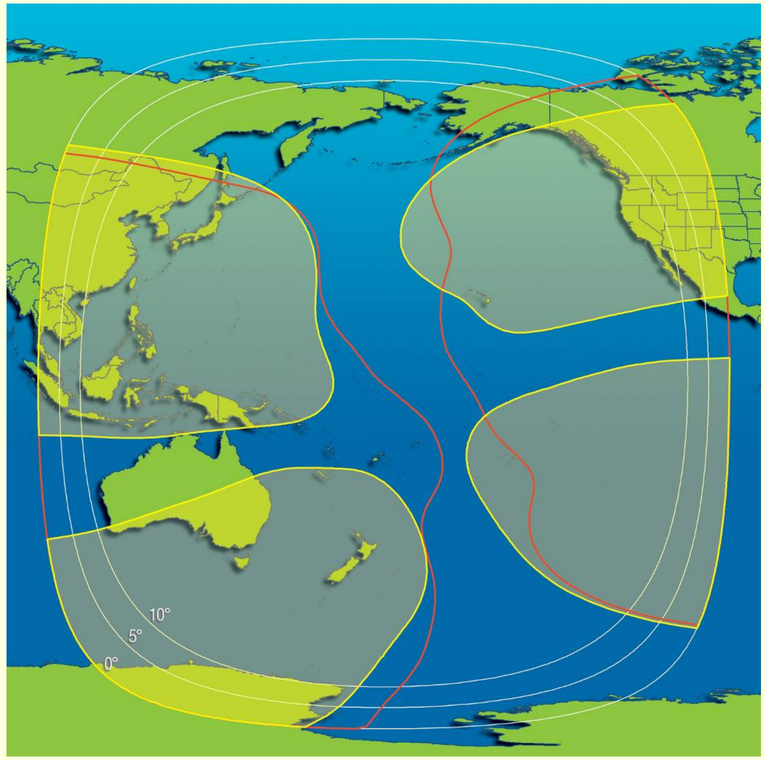
- Background
- History
- Introduction to Satcom Technology
- Ground System
- Antennas
- Satellite technology
- Geosynchronous orbit
- Antenna coverage patterns

COMMUNICATION SATELLITES

- Uses
- Example satellite systems

Why Satellite Communications?

- Satellite coverage spans great distances
- A satellite can directly connect points separated by 1000's of miles
- A satellite can broadcast to 1000's of homes/businesses/military installations simultaneously
- A satellite can be reached from ground facilities that move
- Satellites can connect to locations with no infrastructure
- Satellites adapt easily to changing requirements



Some Common SATCOM Systems

- The INTELSAT system
  - provides globe-spanning TV coverage
- The Thuraya satellite-based phone system
  - covers all of Saudi Arabia and Egypt
- DoD Military Communications Satellite System
  - Links field sites with Pentagon and US command centers
- DirecTV, Echostar
  - Direct-to-home TV
- XM Radio, Sirius
  - Satellite radio-to-car/home
- Hughes VSAT (Very Small Aperture Terminal) systems
  - Links GM car dealers, Walmart, Costco, J C Penney, etc. to their accounting centers

Common Satellite Orbits

- LEO (Low Earth Orbit)
  - Close to Earth
    - Photo satellites – 250 miles
    - Iridium – 490 miles
- Polar Orbit
  - Provides coverage to polar regions (used by Russian satellites)
- GEO (Geosynchronous Earth Orbit)
  - Angular velocity of the satellite = angular velocity of earth → satellite appears to be fixed in space
  - Most widely used since ground antennas need not move
  - Circular orbit
  - Altitude: 22,236 miles
  - Can't "see" the poles

HISTORICAL BACKGROUND

- People
- Early satellites
- Evolution

Historical Background: People

- **Arthur C. Clarke**
  - Highly successful science fiction author
  - First to define geosynchronous communications satellite concept
    - Published paper in *Wireless World*, October 1945
  - Suggested terrestrial point-to-point relays would be made obsolete by satellites
  - Unsure about how satellites would be powered
- **John R. Pierce** – Bell Telephone Laboratories
  - Directed seminal work in the '50's on communications satellites at Bell Labs
- **Harold C. Rosen** - Hughes Aircraft Company
  - Led team that developed practical geosynchronous communications satellite
  - Key contribution: spin stabilization
    - Rotational inertia maintains pointing with small fuel requirement
  - First geosynchronous satellite: Syncom II – July 26, 1963

Historical Background: Early Communications Satellites

- **Echo** – NASA
  - First communications satellite (passive)
  - 100 foot diameter metallized balloon – 12.7 mil Mylar polyester film
  - Echo 1A launched August 12, 1960
- **Telstar** – built entirely by Bell Telephone Laboratories; funded by AT&T
  - First active communications satellite
  - Launched July 10, 1962 by NASA
  - Low elliptical orbit (not geosynchronous)
- **Relay** – built by RCA; funded by NASA
  - First NASA communications satellite; experimental
  - Launched December 16, 1962
  - First to use Traveling Wave Tube in its transponder
    - Relay TWT.gif
- **Syncom** – built by Hughes; funded by NASA and DoD
  - First geosynchronous communications satellite; experimental
  - Launched July 26, 1963
- **Early Bird** – built by Hughes; funded by Communications Satellite Corporation
  - First *commercial* geosynchronous communications satellite
  - Launched April 6, 1965
  - "Live via Early Bird"

Satcom Timeline

- 1950's: Navy: D.C.⇔Hawaii Teletype Link via the Moon
- 1957: Sputnik
- 1958: SCORE
- 1960: Project Westford a.k.a. "Project Needles"
- 1961: Echo
- 1962: Telstar (spinning satellite)
- 1962: Relay "
- 1963: Syncom "
- 1965: Early Bird/Intelsat I "
- 1974: Intelsat IV (spinning body, 'de-spun' antennas)

INTRODUCTION TO SATCOM TECHNOLOGY

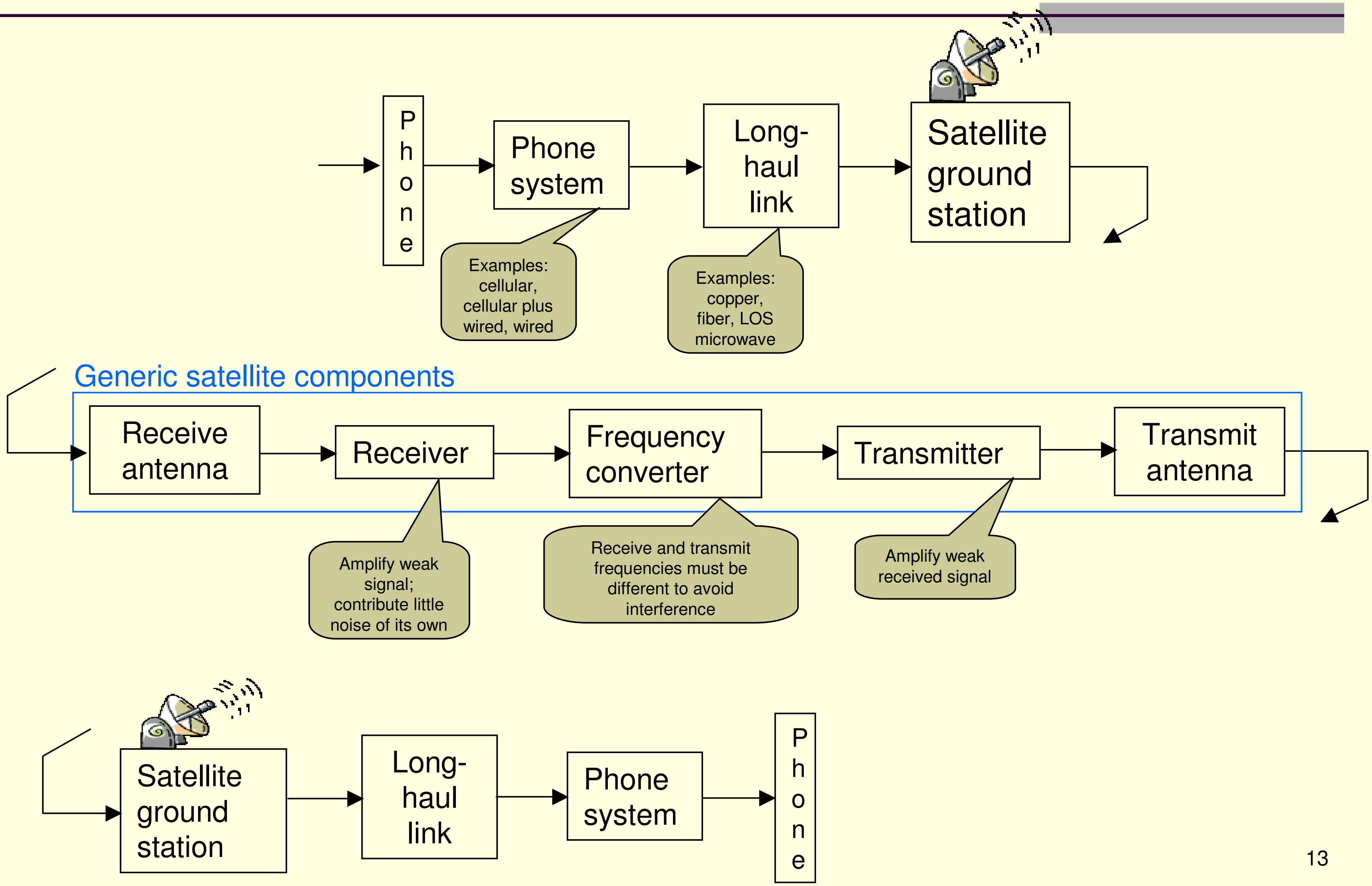
Cellular-to-Satellite Comparison

- User
- Cell site
- Central office
- Cell site
- User

⇔

- User
- Ground Terminal
- Satellite
- Ground Terminal
- User

End-to-end Satcom Picture



Satellite Communications Terminology

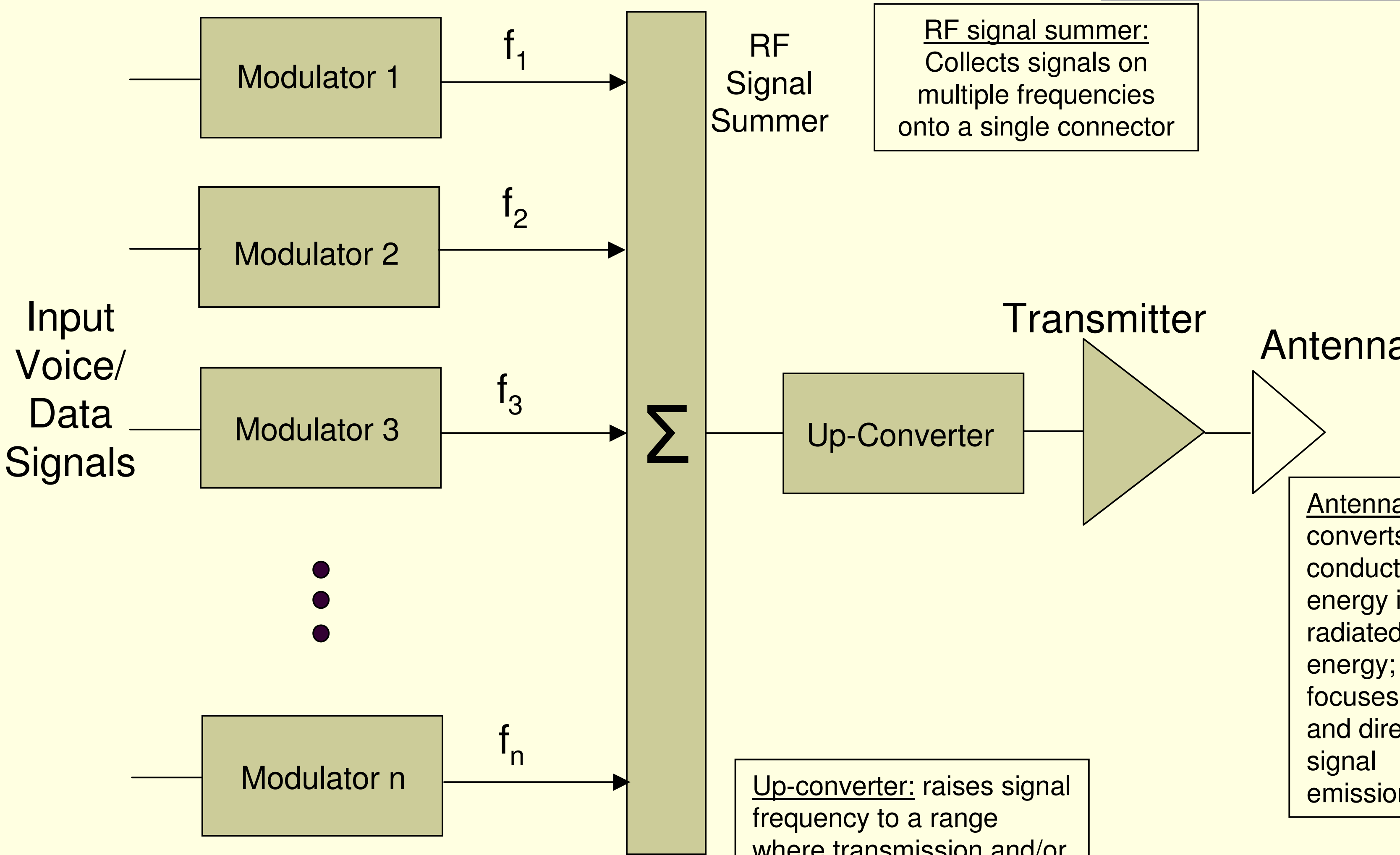
1. **Ground station** (also "ground terminal")
   - sends signals to/receives signals from a satellite
2. **Modulator, demodulator** (modulator + demodulator = modem)
   - Ground station component: **modulator** converts digital "1"s and "0"s to a radio frequency signal (**modulated carrier**) that can be transmitted
   - Demodulator recovers digital "1"s and "0"s from the modullated carrier
3. **Carrier frequency**
   - The center frequency of a modulated carrier
4. **Frequency band**
   - The frequency range containing the carrier frequency
   - Satellite communications frequency bands are standardized
   - Within the US, the FCC defines frequency bands for satcom; coordinates specific frequency assignments;
   - Outside the US, the International Telecommunications Union has the same role
5. **Frequency conversion** (up-conversion, down-conversion)
   - The process by which the carrier frequency is changed to accommodate standards or hardware limitations
6. **Up-link** – the link from the ground terminal to the satellite
7. **Down-link** – the link from the satellite to the ground terminal

Satellite Communications Process

1. Digital information from user arrives at a *“**ground station**”.*
2. Digital signal goes into a *modulator*, converting digital information into a ***modulated carrier**.*
3. **Carrier frequency** is changed (***up-converted***) to place it in the desired frequency range (***up-link frequency band***) for transmission to the satellite
4. Carrier is amplified
5. The ground station **antenna** radiates the carrier toward the satellite
6. The signal passes through earth’s atmosphere (~10 miles thick) and continues on to satellite ~22,300 miles away
7. The satellite receives signal and changes (**down-converts**) the carrier frequency to the ***down-link frequency band**.*
8. The satellite amplifies the carrier
9. Amplified carrier is re-radiated toward earth through the satellite antenna.
10. Received carrier is picked up by earth station antenna, amplified, and changed to a frequency that the ***demodulator*** can process.
11. Demodulator recovers original digital information from carrier, though not perfectly; errors are always present!

SATCOM GROUND TERMINALS

Ground Terminal Transmitting Subsystem

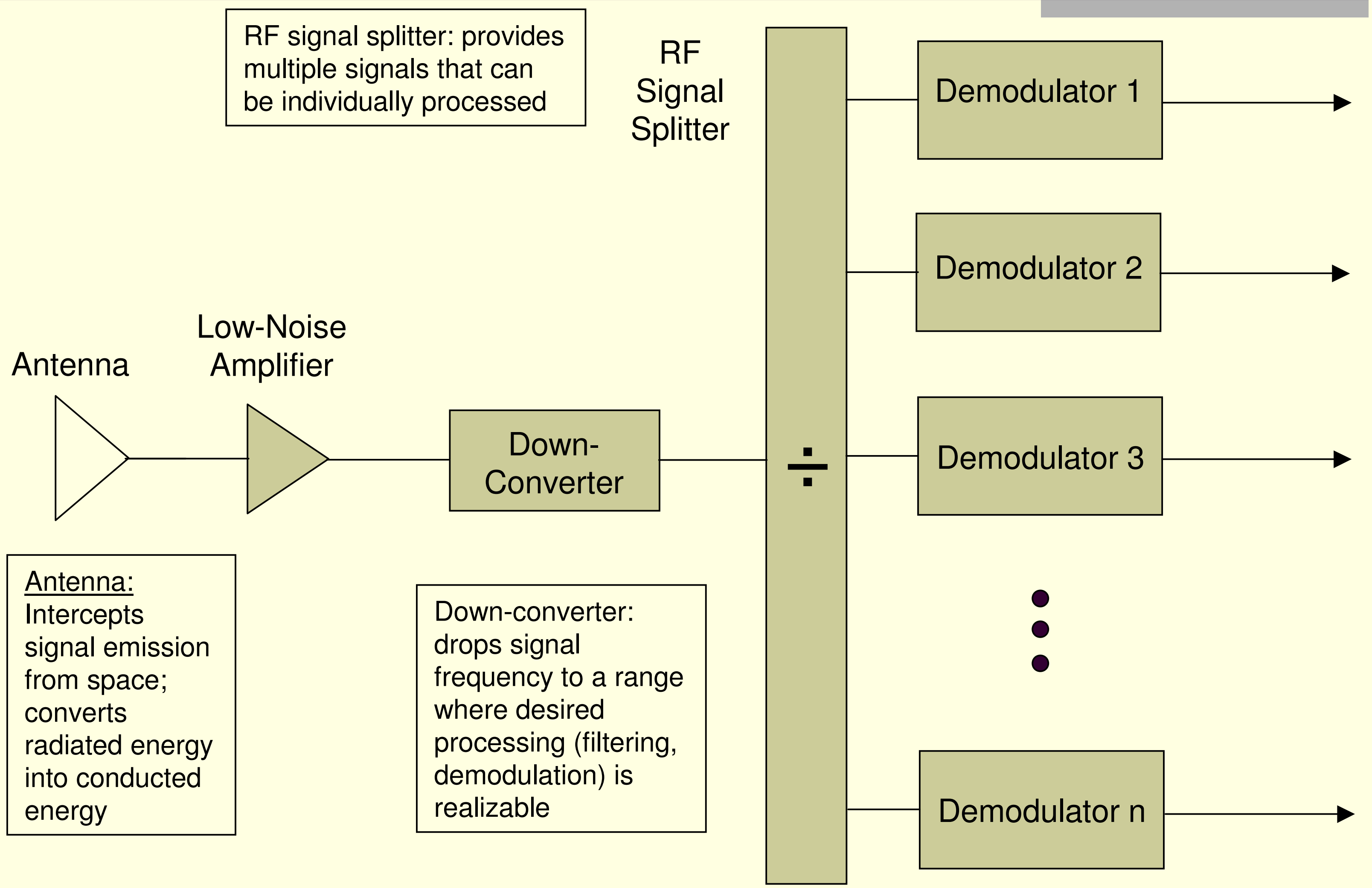


RF signal summer: Collects signals on multiple frequencies onto a single connector

Up-converter: raises signal frequency to a range where transmission and/or filtering is realizable

Antenna: converts conducted energy into radiated energy; focuses and directs signal emission

Ground Terminal Receiving Subsystem

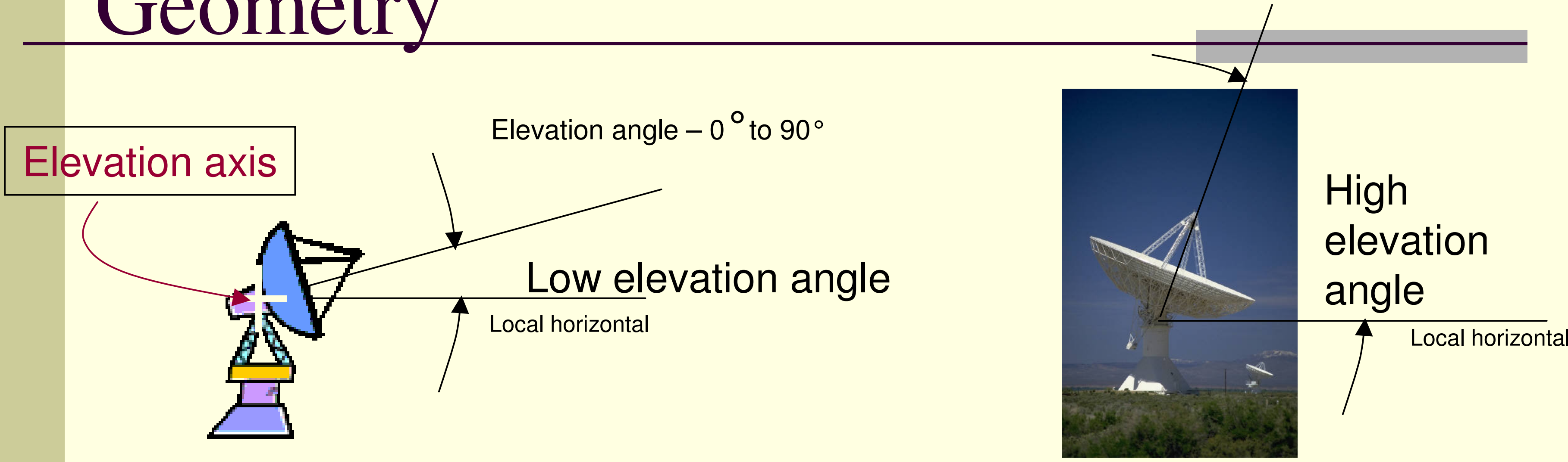


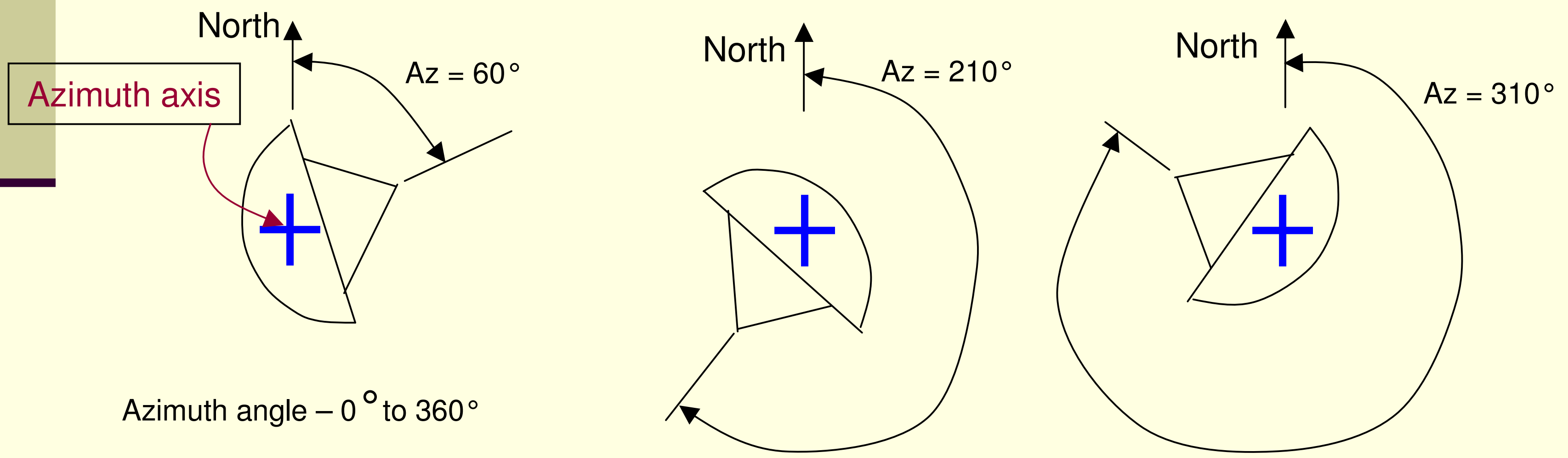
SATCOM ANTENNAS

Antenna Key Points

- One antenna talks to only one satellite!
- Antenna-satellite association must be unique to avoid interference
  - Small antennas have advantage of compactness, but
  - Communications design for ground terminals with small antennas requires care to avoid interference

Earth Station Antenna Pointing Geometry



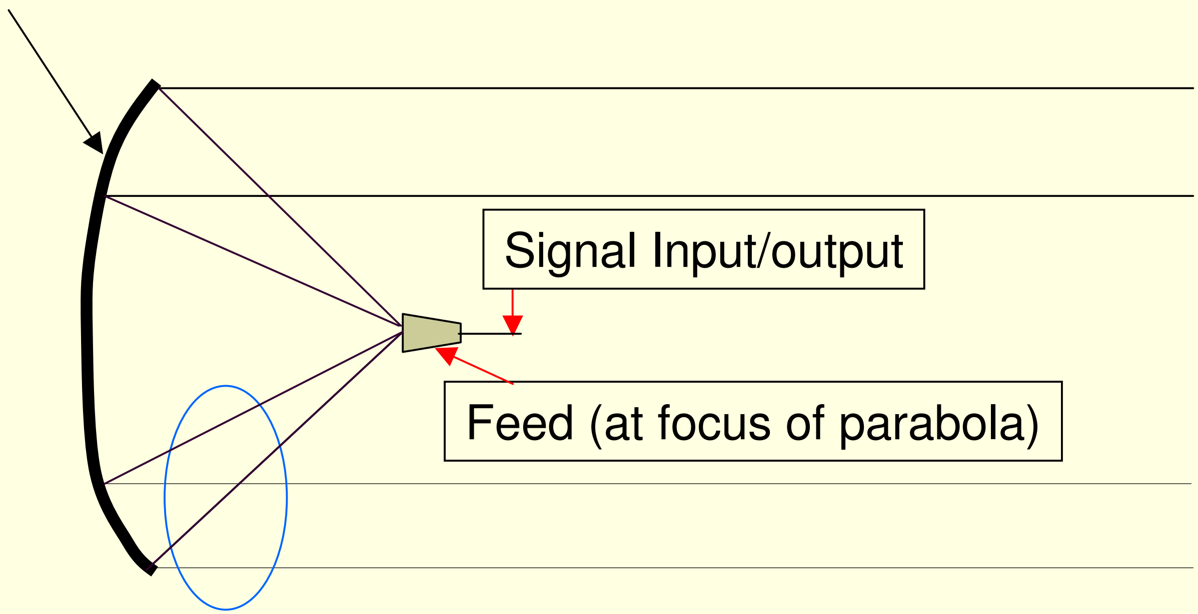


Antenna Geometry
Focus-fed Design

Advantage: simple design;

Disadvantage: distance to feed from electronics

Circular Parabolic Reflector (surface accuracy related to signal wavelength)

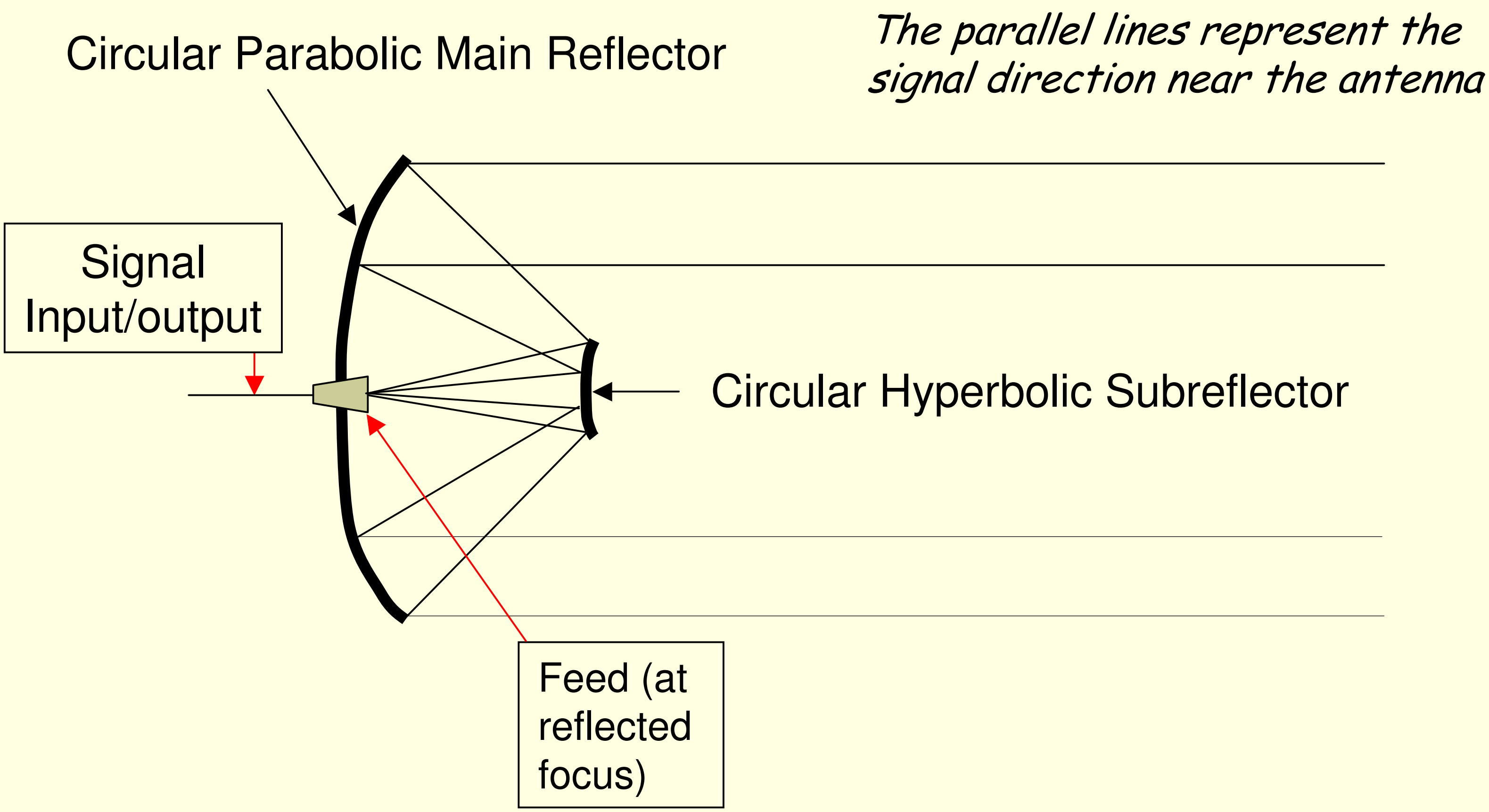


Lines indicate ray-paths traversed by radio-frequency energy passing to or from the antenna feed (similar to light rays)

One antenna talks to only one satellite!

Antenna Geometry
Cassegrain Design

Advantage: feed can be close to electronics, minimizing losses;
Disadvantage: more expensive - requires subreflector

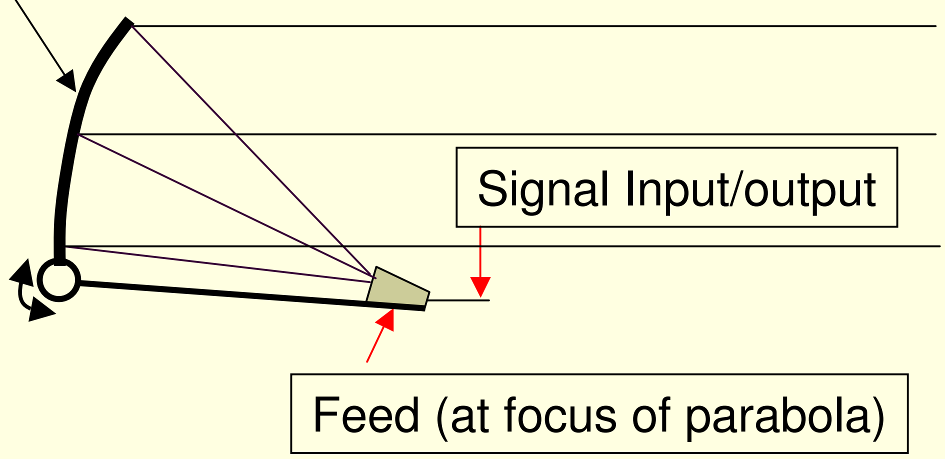


Antenna Geometry
Offset-fed Design

Advantage: Easily adaptable to roof-top mounting for mobile (truck-mounted) applications;

Disadvantage: distance to feed from electronics

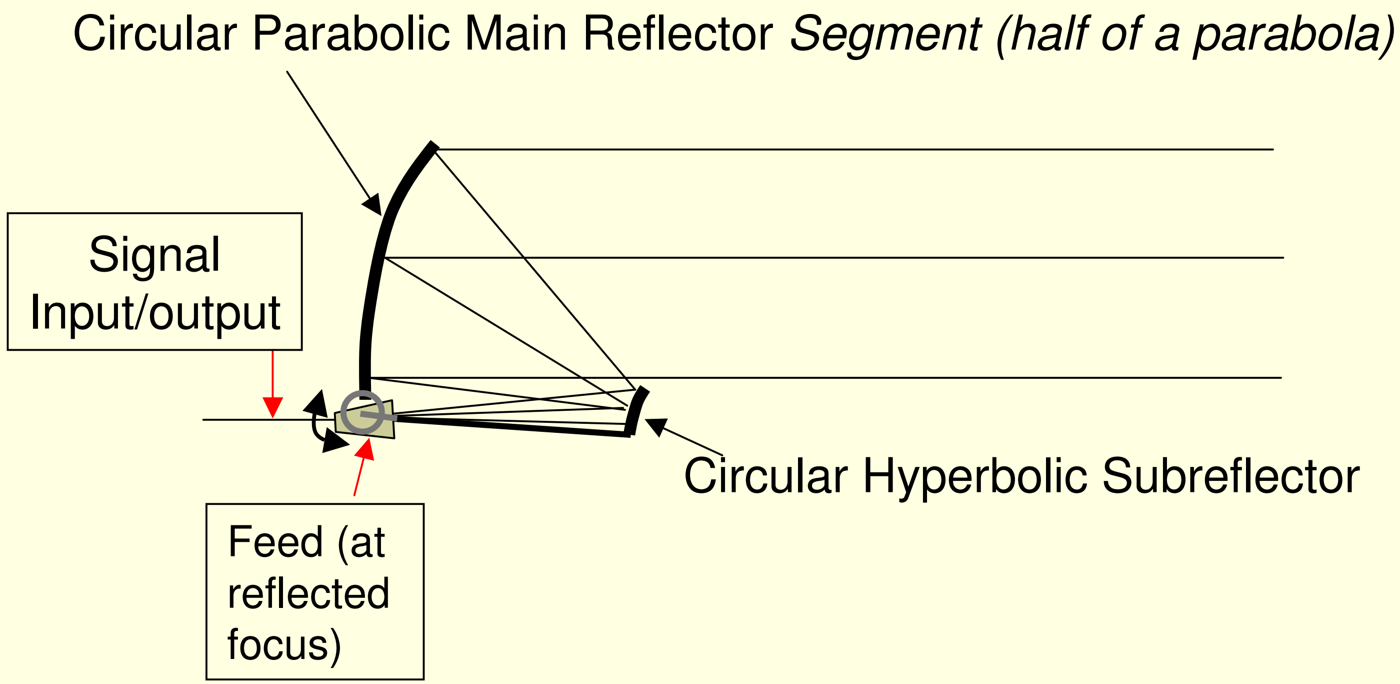
Circular Parabolic Reflector *Segment (half of a parabola)*



Antenna Geometry
Gregorian Design

Advantages: Compact; easily adaptable to roof-top mounting for mobile (truck-mounted) applications; feed can be close to electronics

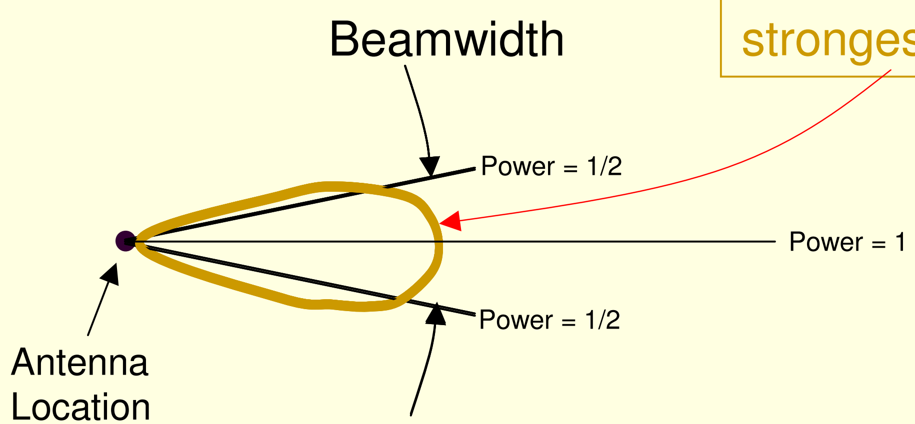
Disadvantages: distance to feed from electronics; expensive to manufacture



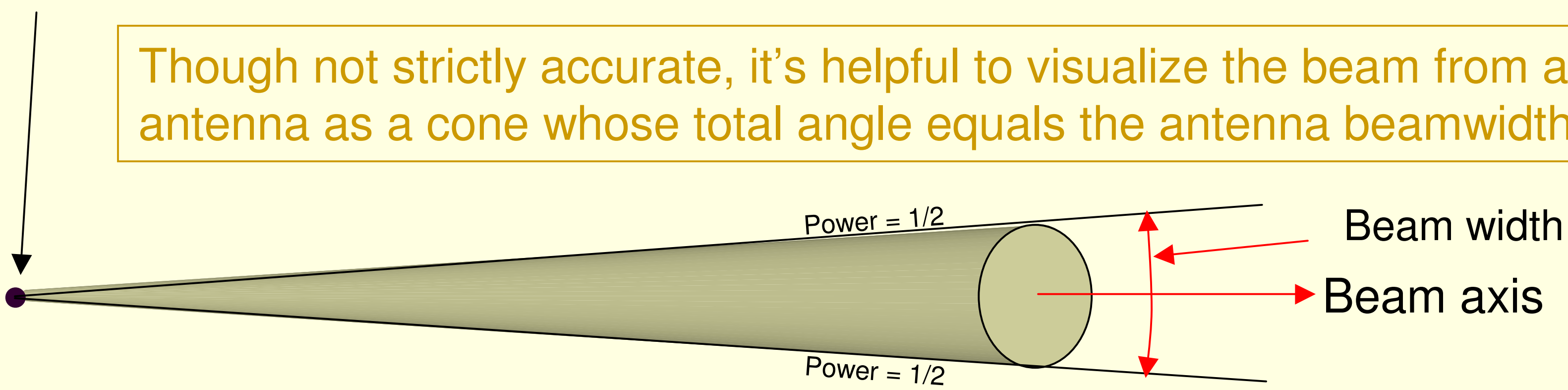
Antenna Beamwidth: Two Views

Beamwidth: the angle off the axis of the beam where the emitted power is half that at the on-axis peak of the beam. Beamwidth is expressed in degrees.

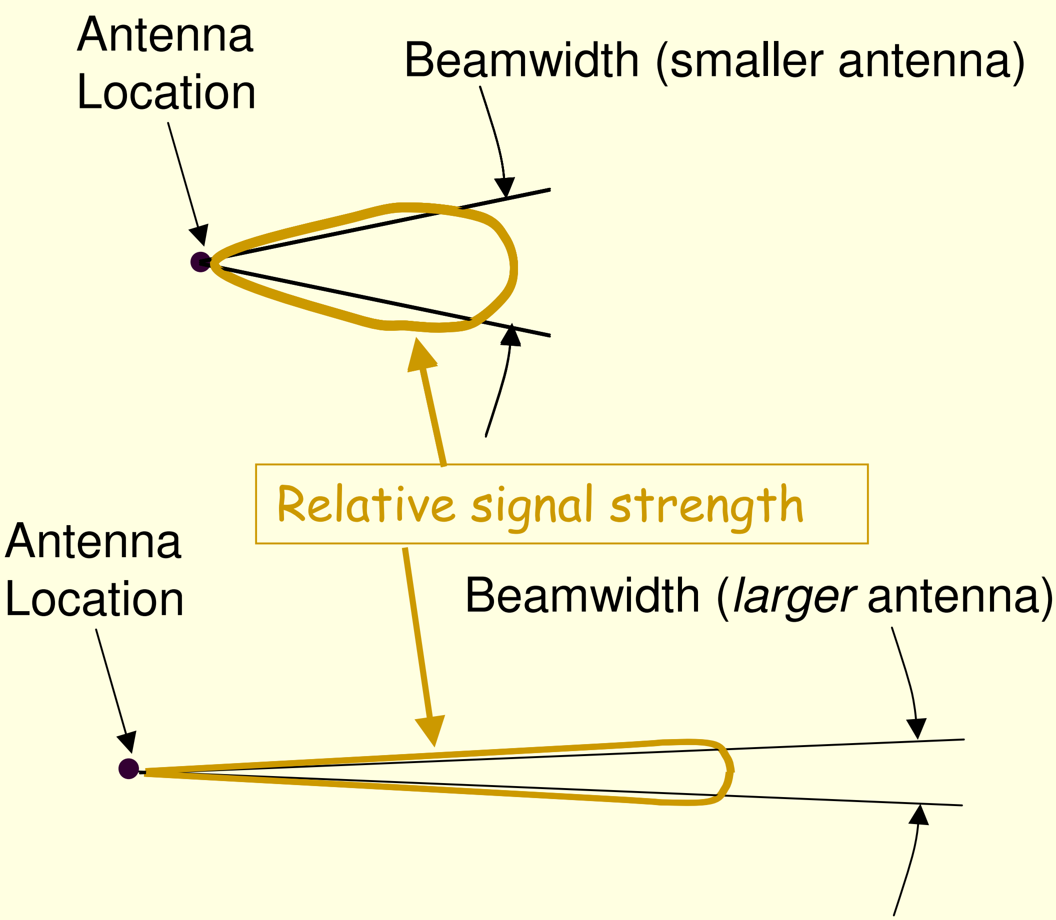
Contour indicates relative signal strength; strongest on axis, weaker to the sides



Though not strictly accurate, it's helpful to visualize the beam from an antenna as a cone whose total angle equals the antenna beamwidth:



Antenna Size vs. Beamwidth



Smaller Antenna →
- Wider beamwidth
- Lower gain
- Less precise pointing requirement

Larger antenna →
- Narrower beamwidth
- Higher gain
- More precise pointing requirement

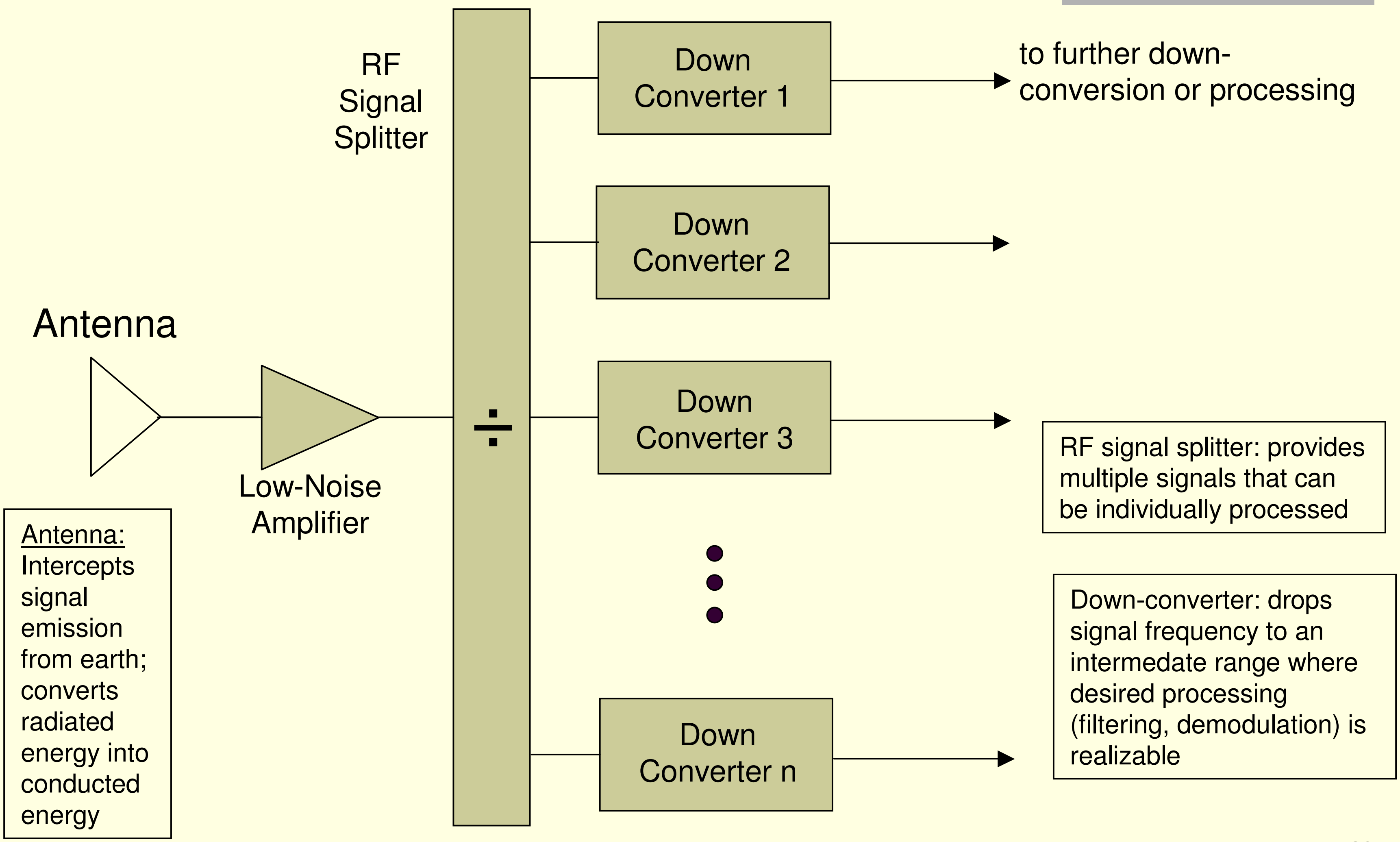
COMMUNICATIONS SATELLITES

- Types
- Electronics
- Orbits
- Launch Sequence

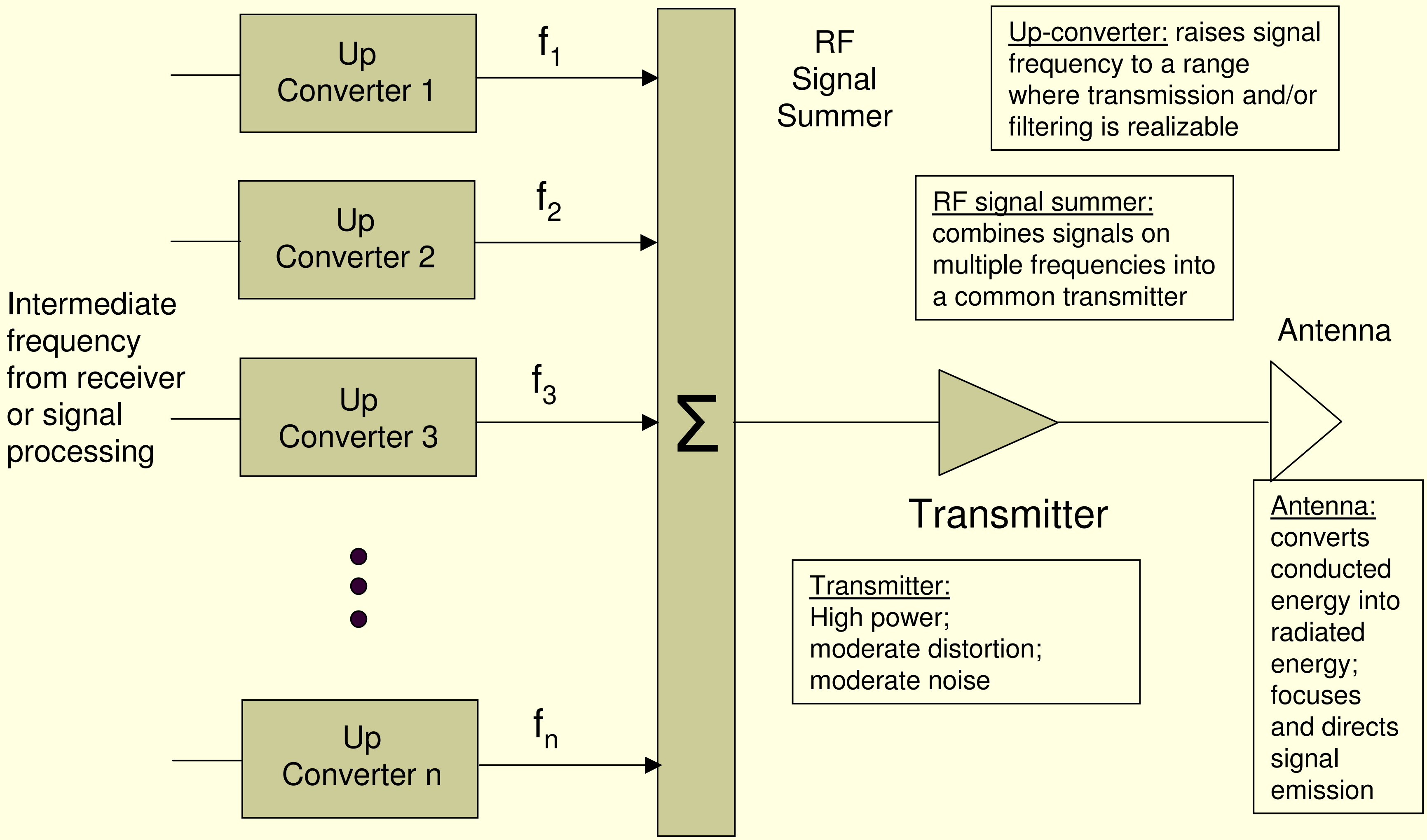
Types of Communications Satellites

- “Bent-pipe” satellites (“repeater in the sky”)
  - What comes down = what goes up
  - Example satellites: US domestic, Intelsat, Panamsat
- Processing satellites
  - What comes down may be (slightly) different from what has gone up
    - With demodulation
      - Iridium
        - Routing determined from message headers
    - Without demodulation
      - Thuraya
      - Spaceway
      - WGS
        - Up-loadable stored-program switching
        - Digital signal processing used to route traffic of varying bandwidths between/within beams

Typical Satellite Receiver Section



Typical Satellite Transmitter Subsystem



Communications Satellite Components

- Bus
  - Power System
  - Command and Telemetry System
  - Propulsion System
- Communications Payload
  - Antennas
  - Receiver
  - Processor
  - Transmitter

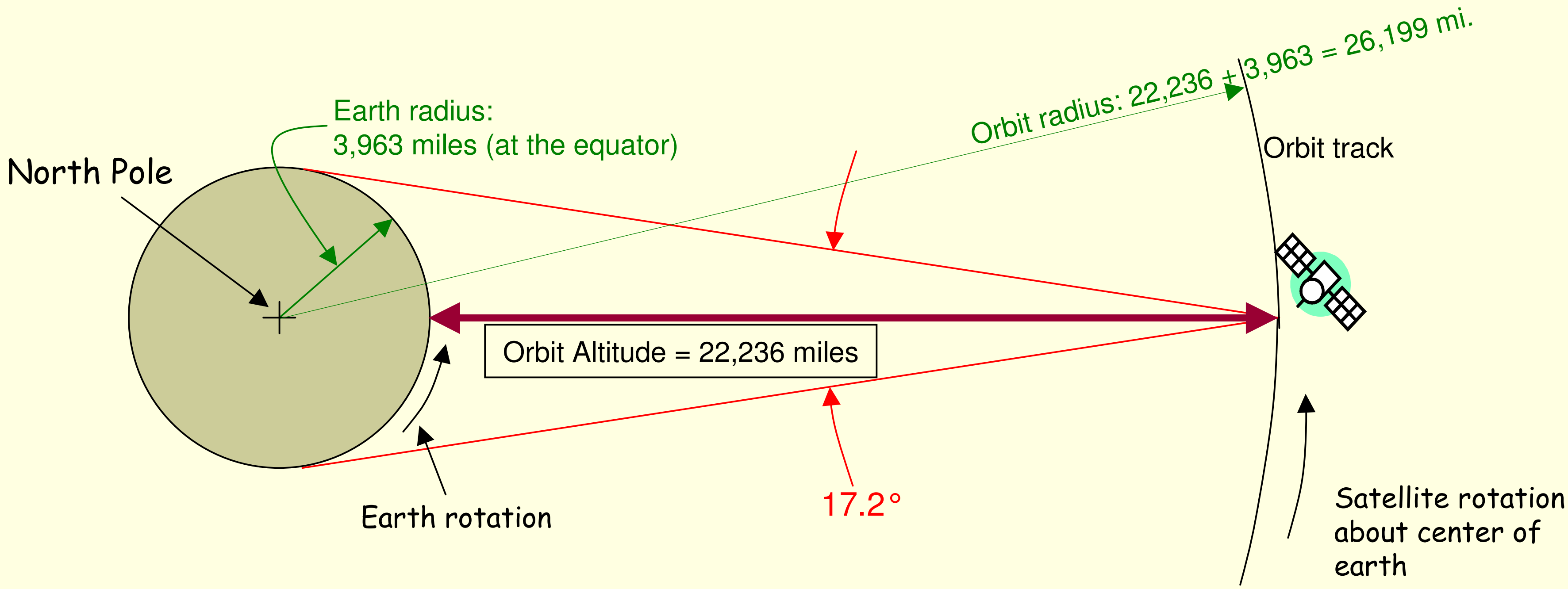
Satellite Power System

- Solar cells are power source
- Solar cell array length: 5 – 100 feet
- Primary power: up to 18,000 watts
- Arrays fold to fit in booster “fairing”; unfurl following launch
- Batteries maintain constant power levels during eclipse
- Power is regulated for electronics

GEOSYNCHRONOUS ORBIT

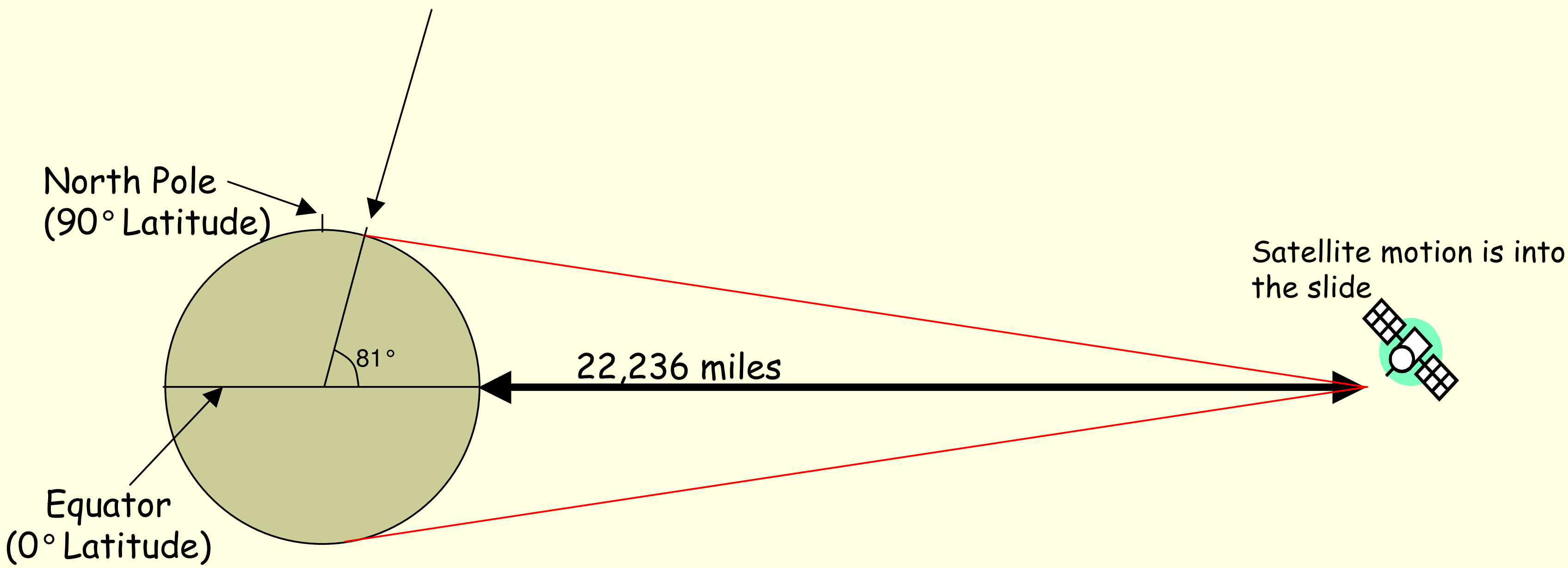
Geosynchronous Orbit Geometry (View from the North Pole)

- Key point: in geosynchronous orbit, satellite rotates at precisely the same angular velocity as does the earth; from earth, satellite appears to remain motionless
- Geosynchronous orbit altitude above earth: 22,236 statute miles
- Earth radius: 3,963 statute miles
- Angle subtended by earth from satellite: 17.2°



Geosynchronous Orbit Geometry (View at the Equator)

- Highest latitude at which satellite can be seen = 81°



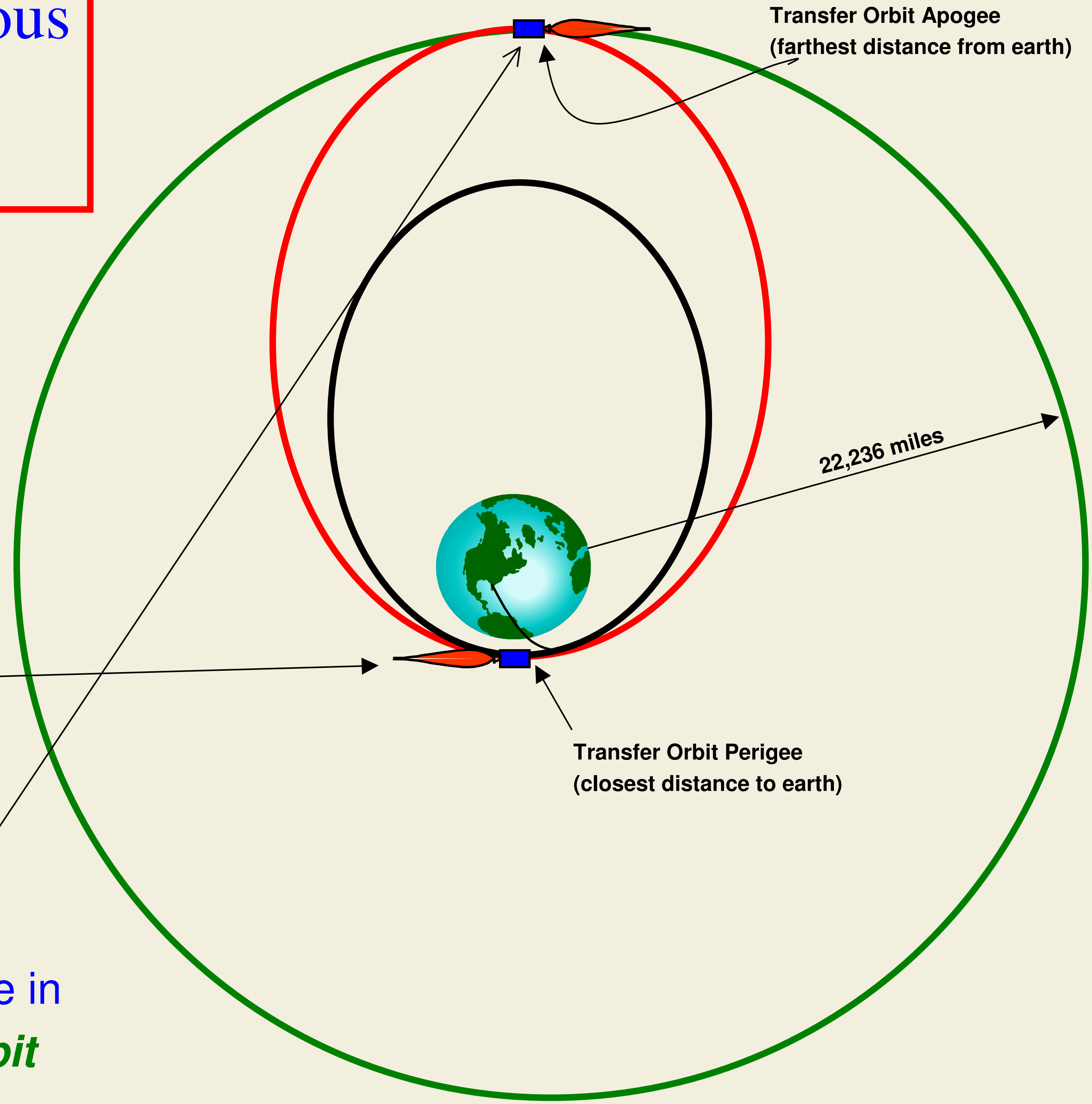
Geosynchronous Launch Orbit Sequence

1. Launch from Cape Kennedy

2. Satellite is launched Into ***Parking Orbit***

3. Rocket is fired to boost satellite into ***Transfer Orbit***

4. Apogee Kick Motor Is fired to place satellite in ***Geosynchronous Orbit***

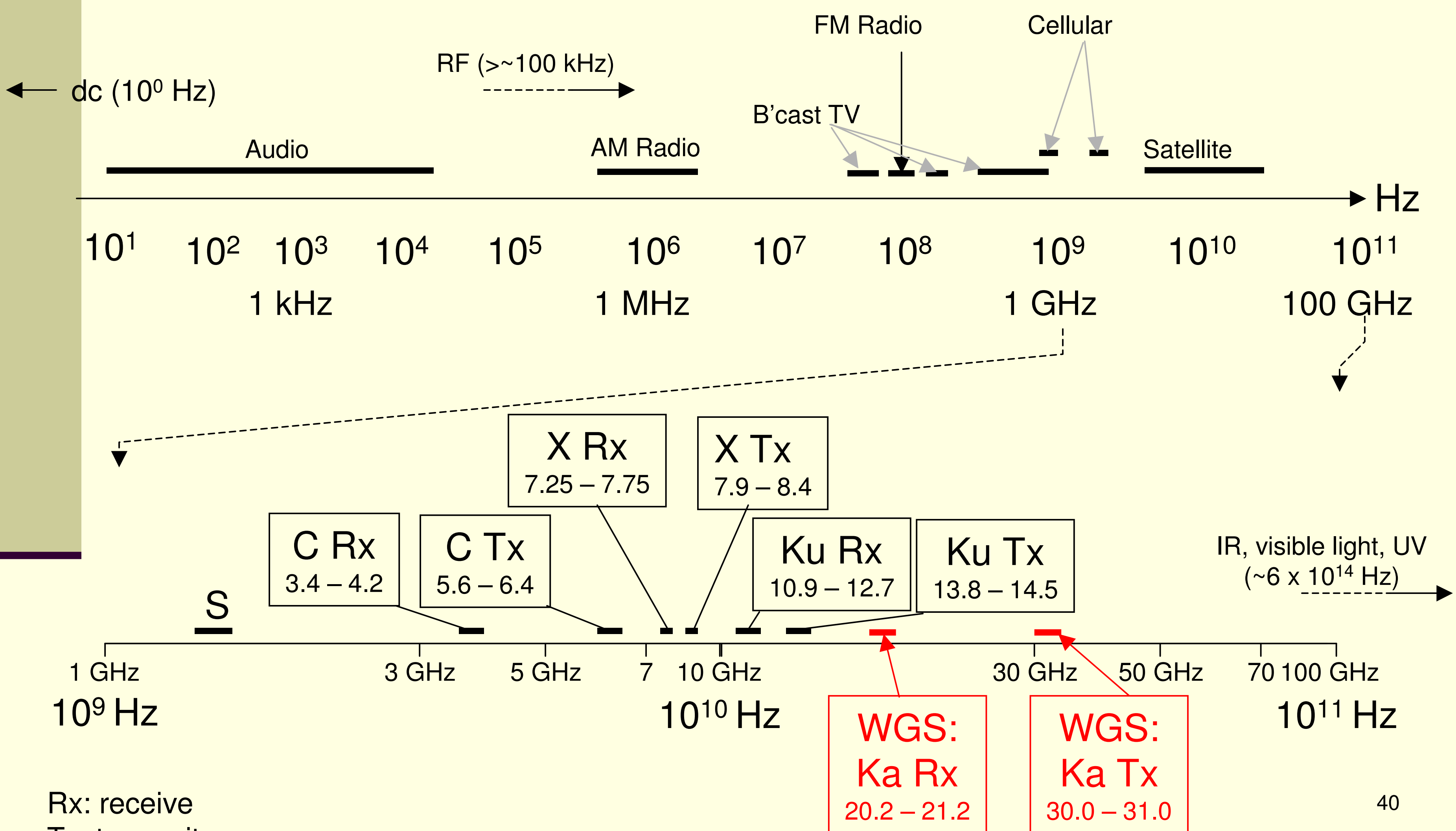


FREQUENCIES FOR SATELLITE COMMUNICATIONS

Frequency Usage

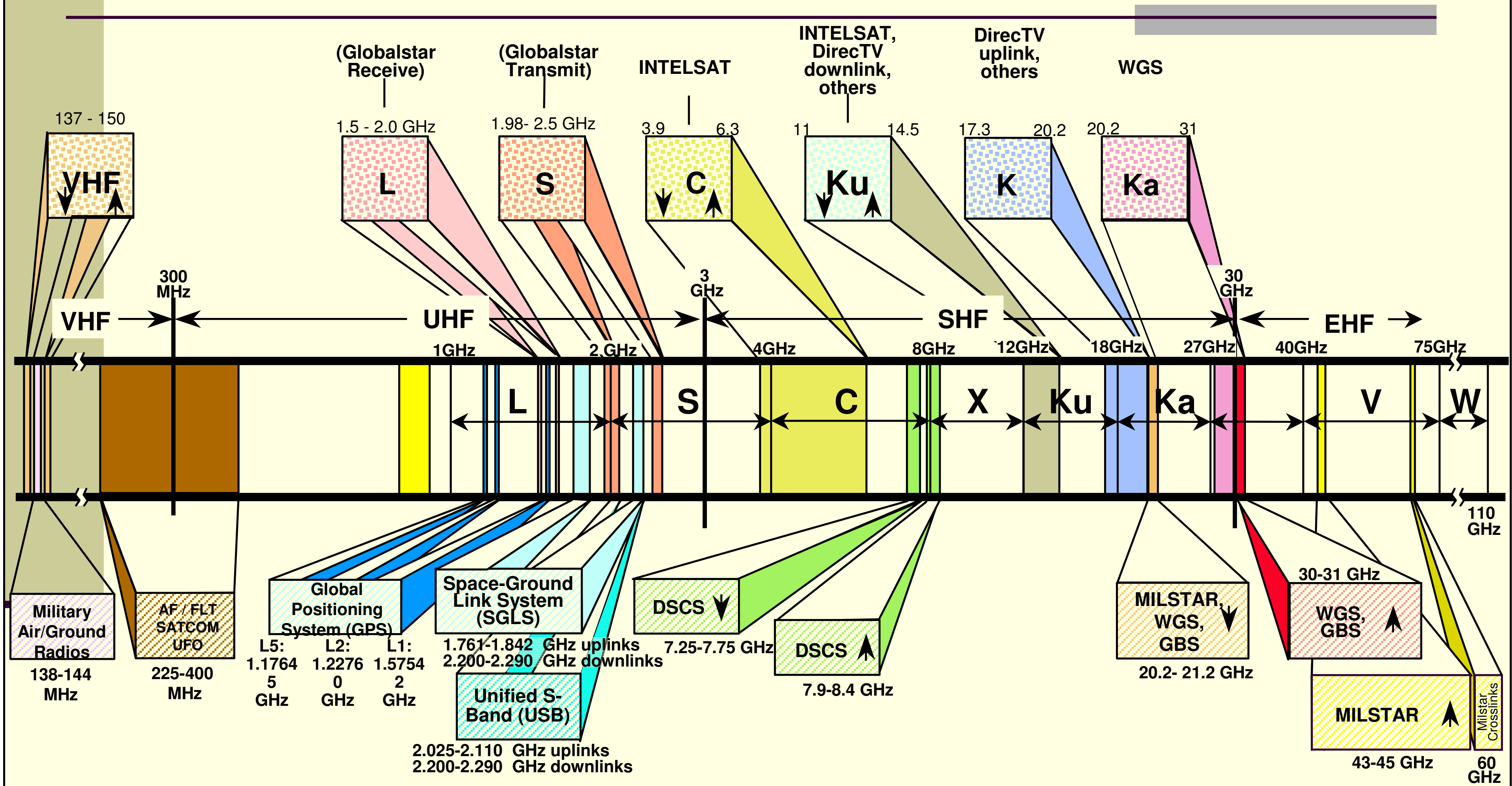
- Key point: uplink and down link signals *always* on different frequencies
  - Reason: interference control on ground and at satellite
- Band and frequency assignments authorized by FCC (US domestic) and ITU (International Telecommunications Union; non-US)
  - frequencies used by US military/DoD outside US selected to meet ITU recommendations
  - FCC and ITU promote regulations on ground terminals to control interference between users

Electromagnetic Frequency Spectrum with Satcom Band Designations



Rx: receive
Tx: transmit

Satcom Frequency Usage



Adapted from chart published by ITAC

Frequency Domain Terminology

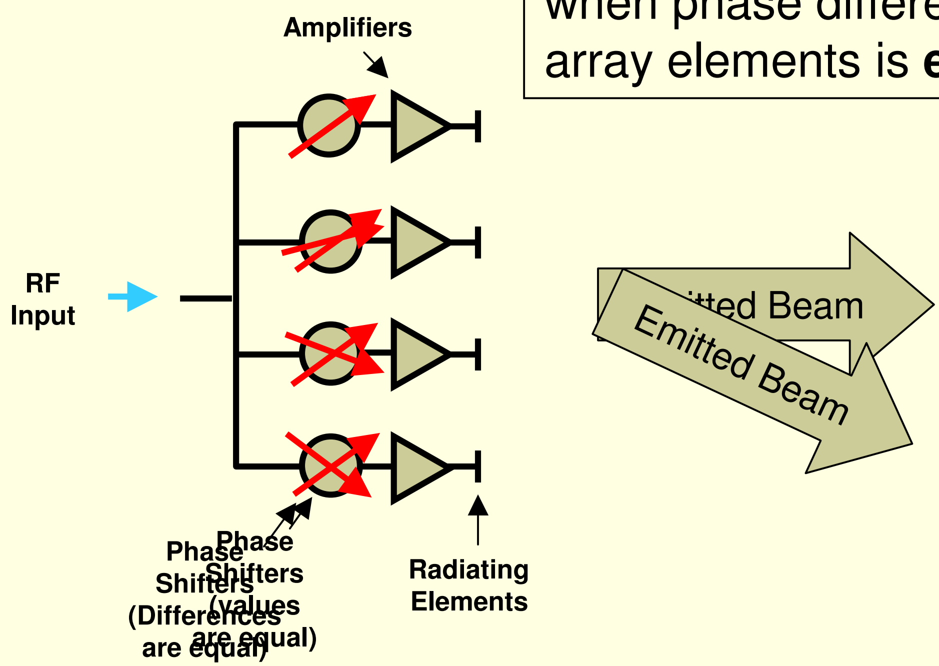
- Baseband:
  - the signal that is received from the user(s) – may be digital or analog;
  - the input to the modulator;
  - the output from the demodulator
- IF (Intermediate Frequency)
  - a (relatively) low frequency which the modulator emits or the demodulator accepts; the frequency of the carrier from the modulator;
  - typical IF frequencies: 70 MHz, 140 MHz
- RF (Radio Frequency)
  - a (relatively) high frequency at which a transmitter or receiver operates;
  - typical frequency ranges: X-band (7.25 – 7.75 GHz ground receive; 7.9 – 8.4 GHz ground transmit);
  - Ka-band: 30-31 GHz ground transmit; 20.2 – 21.2 GHz ground receive

- Note: these definitions are only samples; all baseband signals don't go into a modulator; IF frequencies may be other than 70/140 MHz, etc.

PHASED ARRAY SATELLITE ANTENNA CONCEPTS

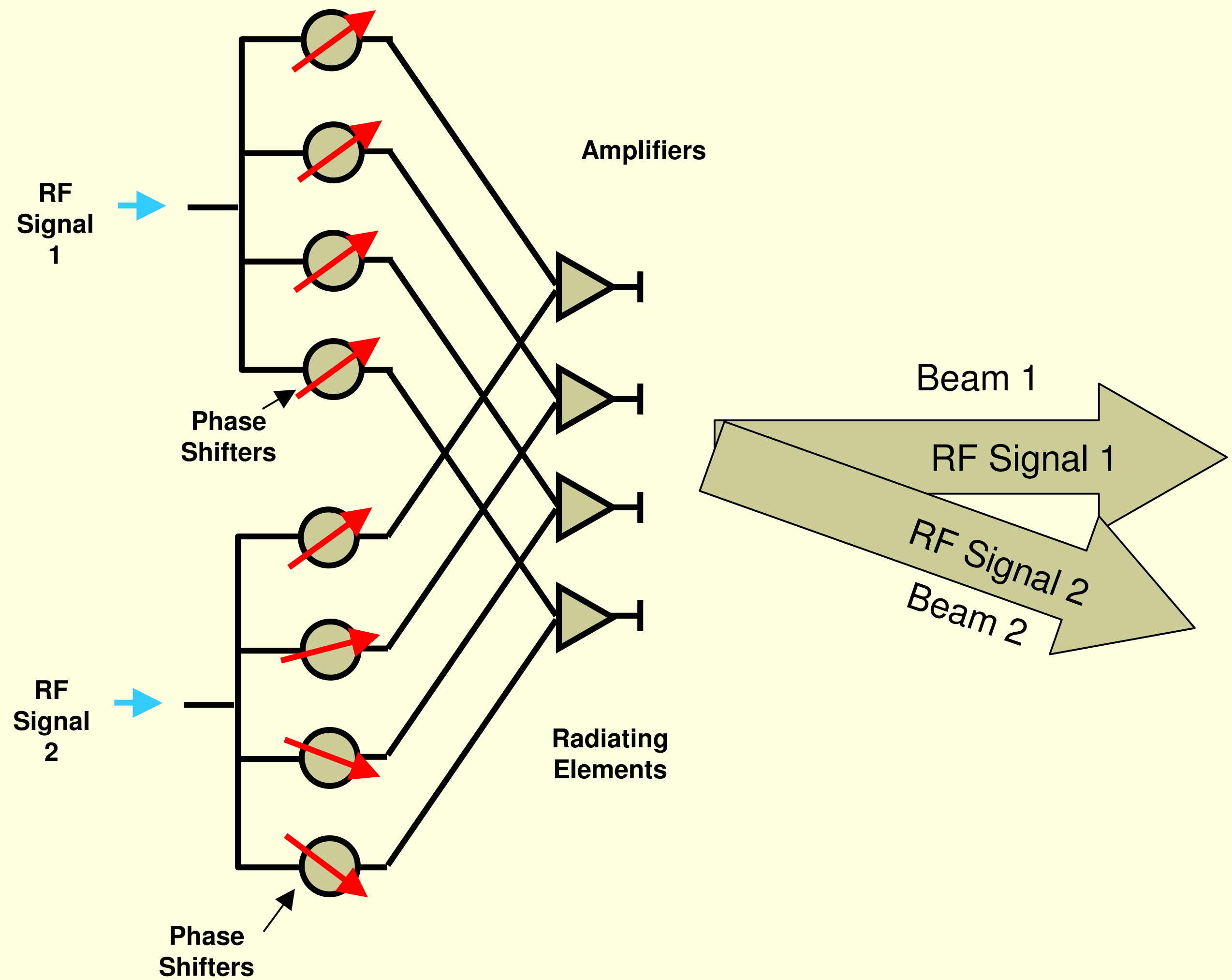
Phased Array Concept:
Transmission with variable aiming

Wavefront is perpendicular to array when phase difference between array elements is **equal to zero**



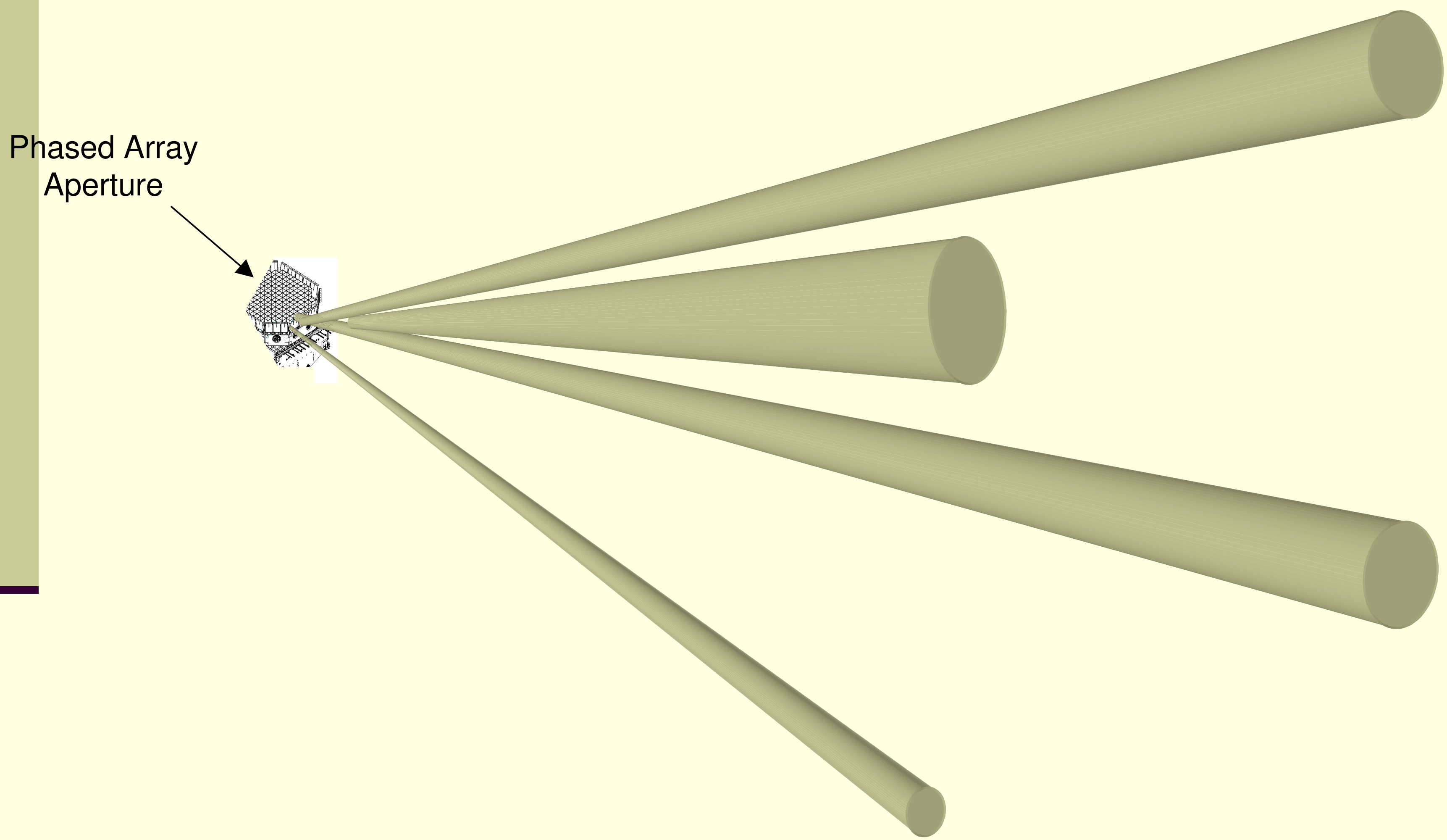
Wavefront is at a slant to array when phase difference between array elements is **equal and non-zero**

Phased Array Concept: Two Signals; Two Beams



Note: Signals 1 and 2 must be on different frequencies

Phased Array Cartoon: One array – four beams



THE GROUND-TO-SATELLITE LINK

Link Analysis

- Goal: determine the conditions under which an adequate signal-to-noise ratio is available
- Link budget: an analysis of losses between transmitter and receiver, and noise sources impacting the receiver

Link Analysis

- Uplink:
  - Carrier power: $P_r = P_t + G_t - FSL - L_a + G_r$
    - P_r : satellite received carrier power
    - P_t : ground transmitted power (into antenna)
    - G_t : ground transmit antenna gain
    - FSL: Free Space Loss
    - L_a : atmospheric losses
    - G_r : spacecraft receive antenna gain
  - Noise Power: $N_r = kT_rB + kT_uB + N_i$
    - N_r : satellite received noise power
    - T_r: receiver noise temperature
    - T_u: uplink noise (earth thermal noise, sky noise "seen" by antenna)
    - T_i : interference noise temperature
    - B: noise bandwidth
  - $C/N_u = P_r – N_r$

    $= P_t + G_t – FSL – L_a + G_r – (k\,T_r\,B + kT_uB + kT_iB)$

    $= e.i.r.p._u – FSL – L_a + G_r – [k + 10\log(T_{r\,sat} + T_u + T_i) + B]$

Link Analysis

- Downlink:
  - Carrier power: $P_r = P_t + G_t - FSL - L_a + G_r$
    - P_r : ground received carrier power
    - P_t : satellite transmitted power (into antenna)
    - G_t : satellite transmit antenna gain
    - FSL: Free Space Loss
    - L_a : atmospheric losses
    - G_r : ground receive antenna gain
  - Noise Power: $Nr = kT_rB + kT_eB$
    - N_r: ground receiver noise power
    - T_r: ground receiver noise temperature
    - T_e: atmospheric noise (sky thermal noise)
    - B: noise bandwidth
  - $C/N_d = P_r - Nr = P_t + G_t - FSL - L_a + G_r - (kT_rB + kT_eB)$

    $= e.i.r.p._d - FSL - L_a + (G_r / T_r)_{es}(1/kB) - kT_eB$

Sample 8 GHz Uplink Calculation

C/N_u = e.i.r.p.$_u$ – FSL – L_a + $G_{r\,sat}$ – [k + 10 log($T_{r\,sat}$ +T_u + T_i) + B]

e.i.r.p.$_u$ = 10 log (6 watts) + (antenna gain of) 28.2 dB = 36 dBW

FSL = 201.7 dB

L_a = 0.5 dB

$G_{r\,sat}$ = 34.1 dB

$T_{r\,sat}$ = 512 K

T_u = 290 K

T_i = 60 K

k = -228.6 dBW/K-Hz

B = 100 kHz = 50 dB-Hz

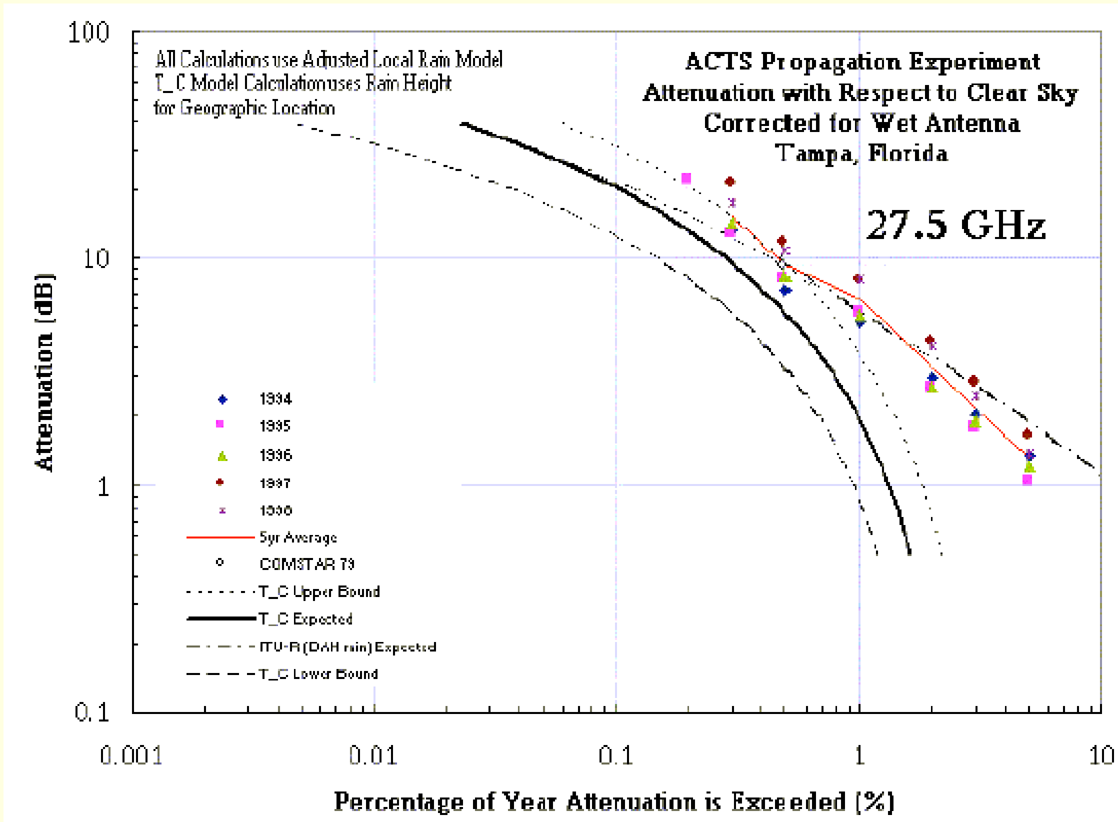
C/N_u = 36 – 201.7 - 0.5 + 34.1 – [-228.6 + 10 log (512 + 290 + 60) + 50]

= 17.2 dB

Rain

- Introduces attenuation by absorption and scattering
- Increases noise through absorption
- At either 20 or 30 GHz, attenuations of more than 30 dB may occur 0.1% of the time

- Techniques to counter rain fade include dropping bit rate and changing to different error-correction codes



Sample 8 GHz Downlink Calculation

C/N_d = e.i.r.p.$_d$ – FSL – L_a + $(G_r/T_r)_{es}$(1/kB) – kT_eB

e.i.r.p.$_d$ = RF power of 28 dBW + antenna gain of 33 dB = 61 dBW

BUT e.i.r.p.$_d$ is total for all eight beams, and is spread over ~1766 MHz (though not equally)

10 log 1766 = 32.5 dB-MHz

Average e.i.r.p.$_d$ is 61 – 32.5 = 28.5 dBW/MHz (an approximate value)

FSL = 201.0 dB

L_a = 0.5 dB

$G_{r\ gnd}$ = 24 dB

$T_{r\ gnd}$ = 150 K

k = -228.6 dBW/K-Hz

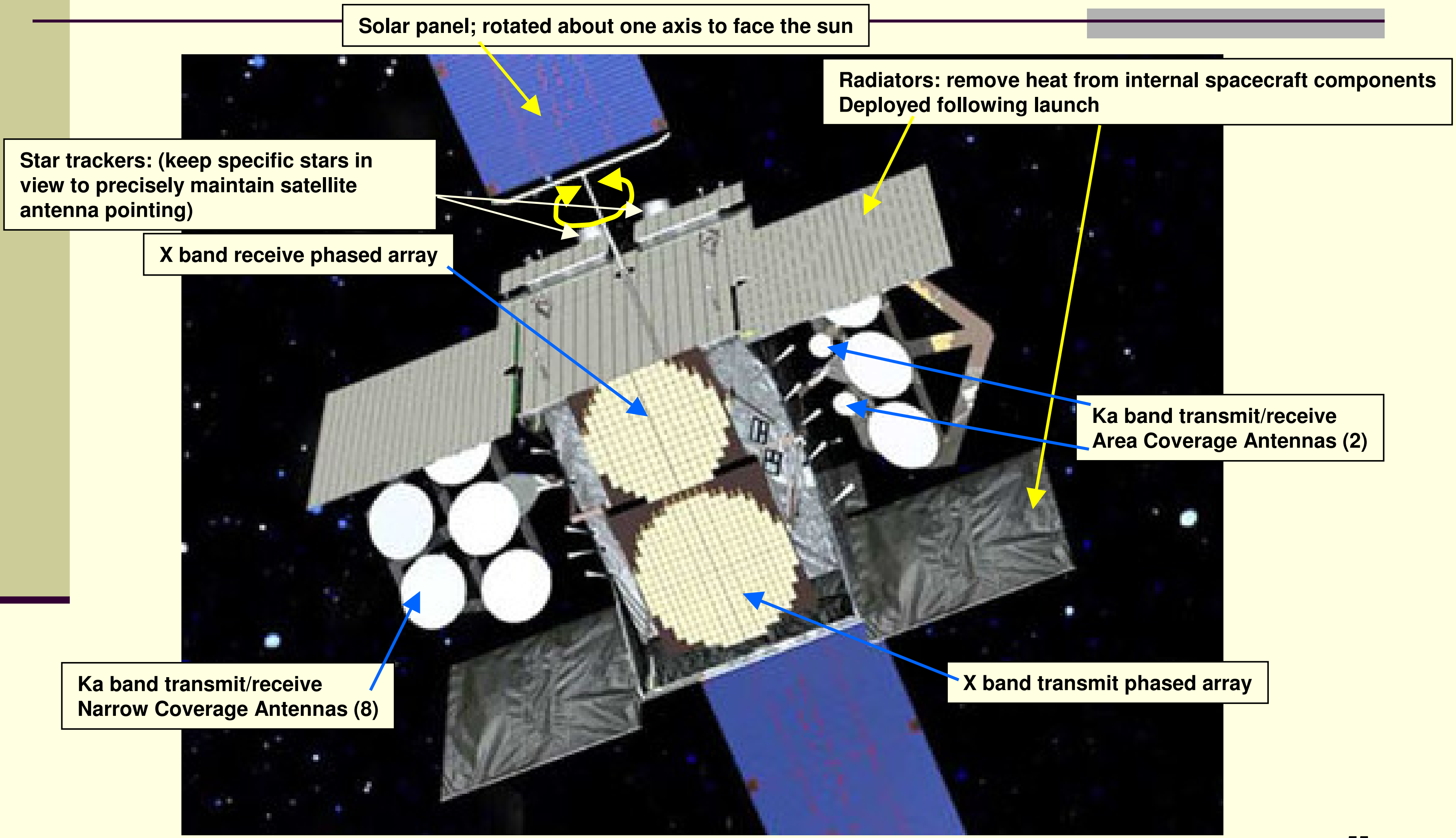
B = 1 MHz = 60 dB-Hz

C/N_d = 28.5 – 201.0 - 0.5 + 54 – [-228.6 + 10 log (150) + 60]

= 27.8 dB

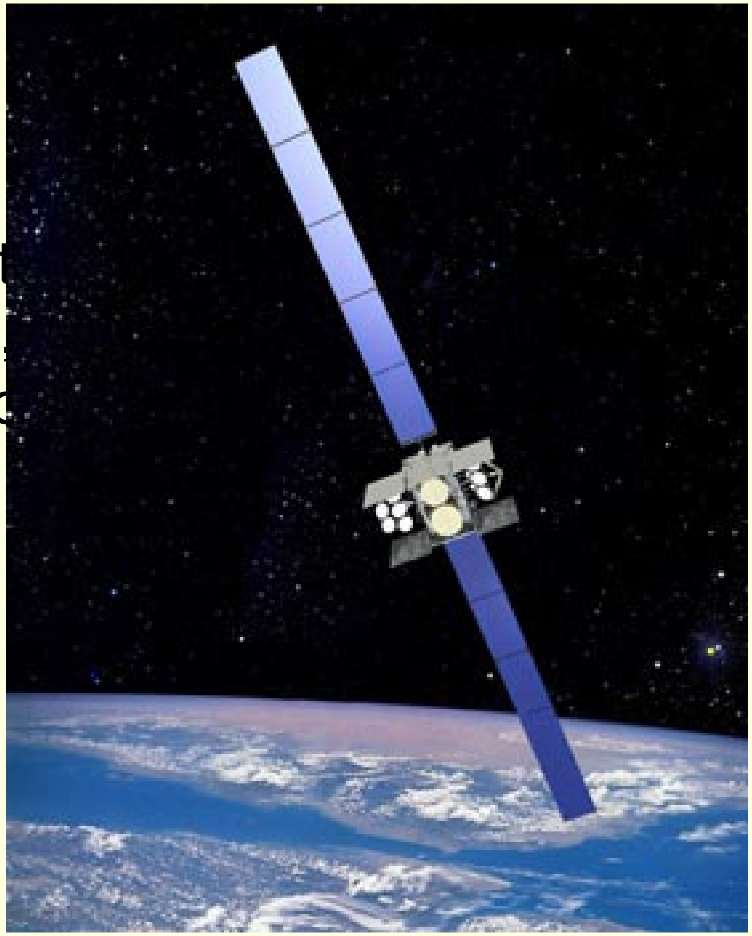
WGS COMMUNICATIONS SATELLITE

WGS Close-up View



Wideband Gapfiller Satellite

- Based on Boeing 702 design
  - First 702 launch 1999
  - Used on Anik F, Panamsat 1R, Galaxy IIIC, Galaxy XI, Spaceway 1/2/3, XM Radio 1/2/3
  - Modular payload bay
  - 18 kW power available

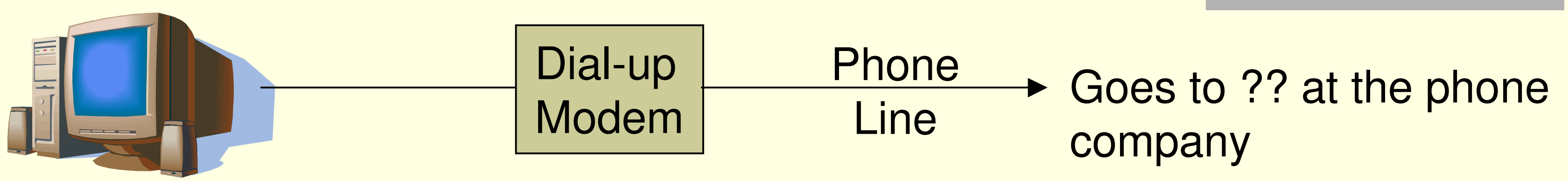


Satcom Technology Evolution

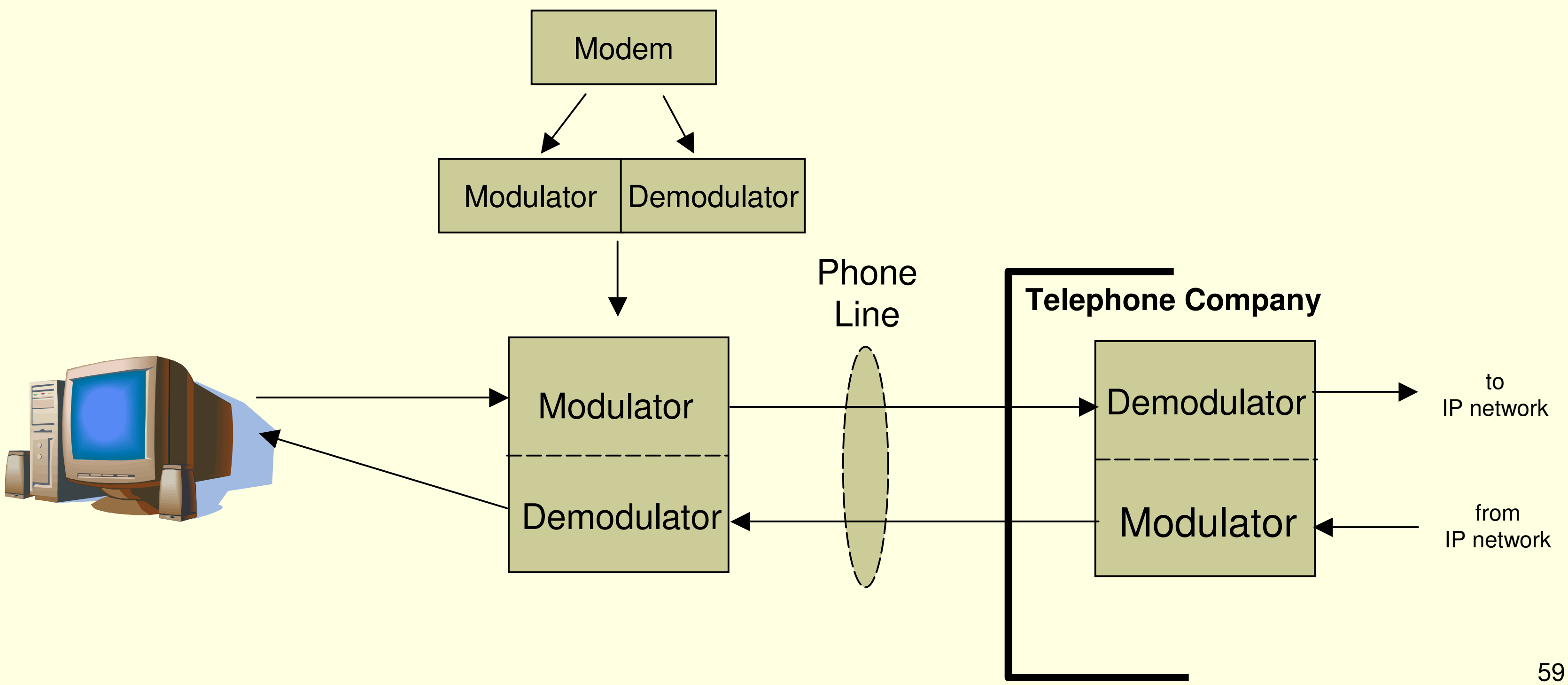
- First satellites – single channel, low power (400 watts)
- Evolution path:
  - more channels (48 now not uncommon)
  - higher power (WGS can provide up to 18,000 watts of primary power)
- Frequency utilization:
  - Initial: satellites shared frequencies with terrestrial microwave long-haul communications systems → interference problems
  - Now: terrestrial long-haul microwave largely extinct, replaced by fiber; satellites generally use frequency bands set aside for satellite use only
- Non-processing satellite
  - Signals received by satellite are returned to earth without modification except for operating frequency
- Processing satellite
  - Signals received by the satellite are switched to different destinations in the satellite:
  - Examples:
    - Iridium: routes messages based on info in message headers
    - Thuraya/WGS: routes signals to different destinations based on the frequency of the received signal

DIGITAL MODULATION

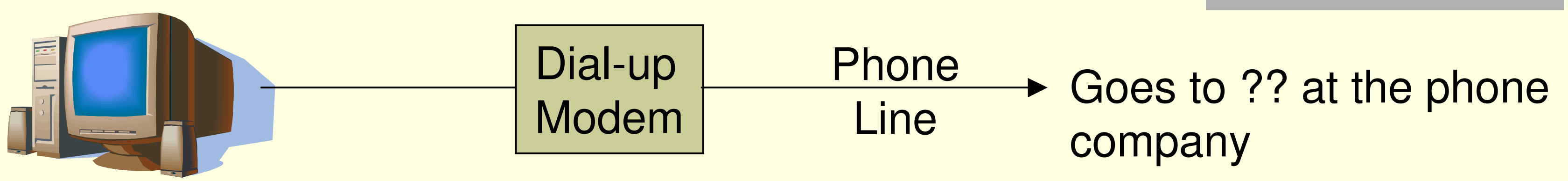
Digital Communications: Modems (1)



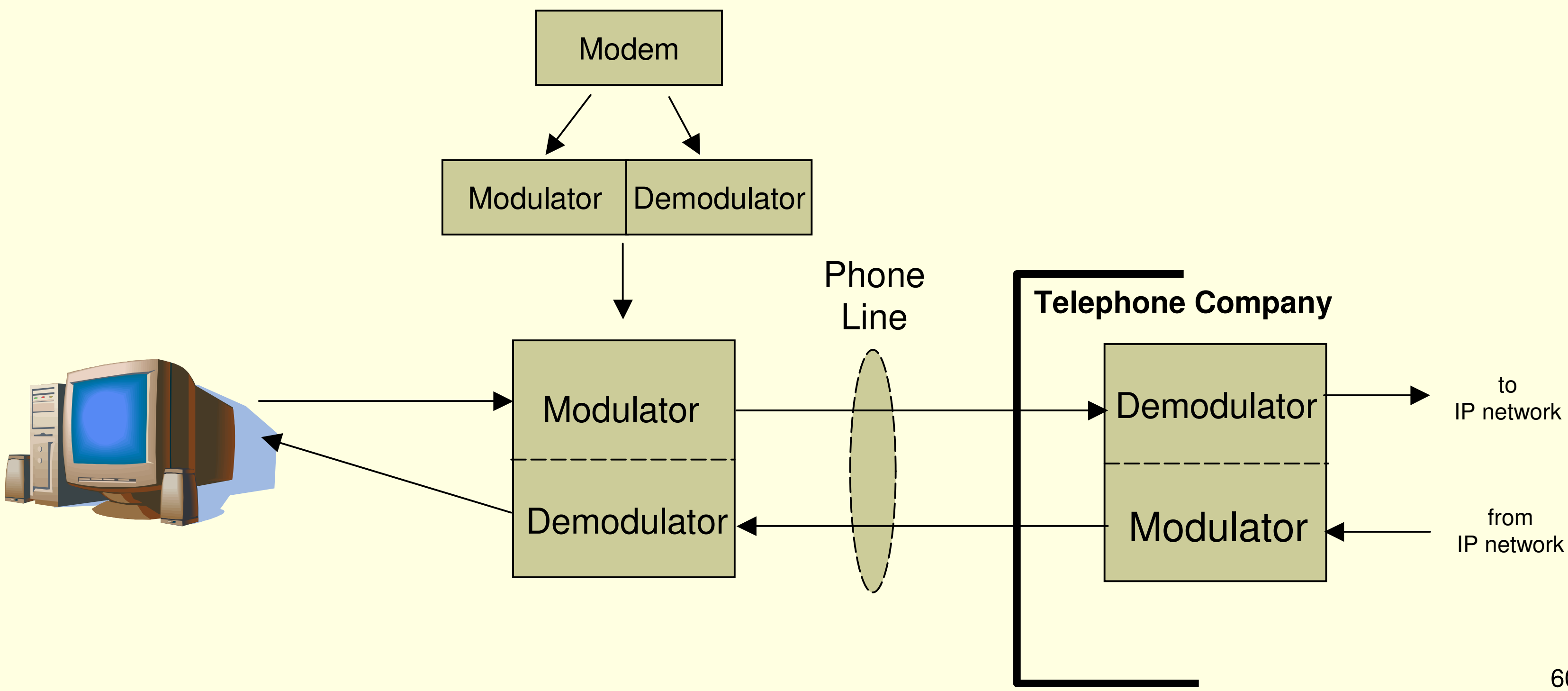
“Modem” = **MO**dulator + **DEM**odulator



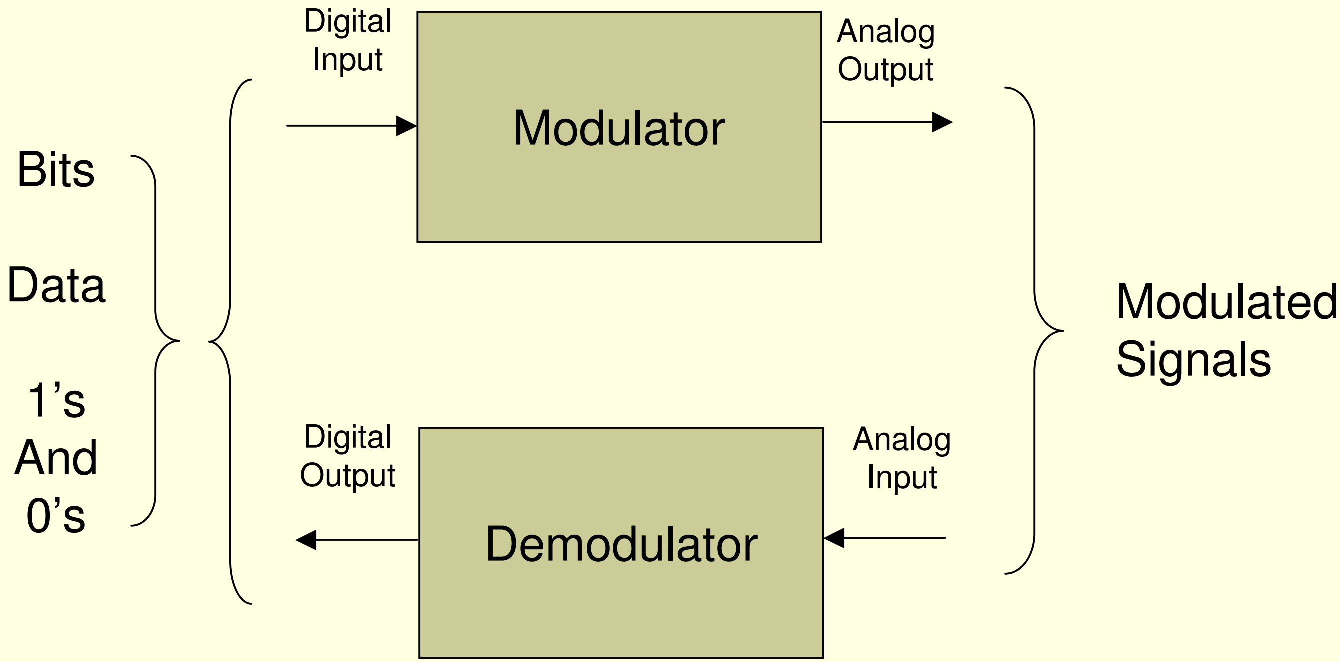
Modems (1)



"Modem" = **MO**dulator + **DEM**odulator



Modems (2)


Digital
Input
Modulator
Analog
Output
Bits
Data
1's
And
0's
Modulated
Signals
Digital
Output
Demodulator
Analog
Input

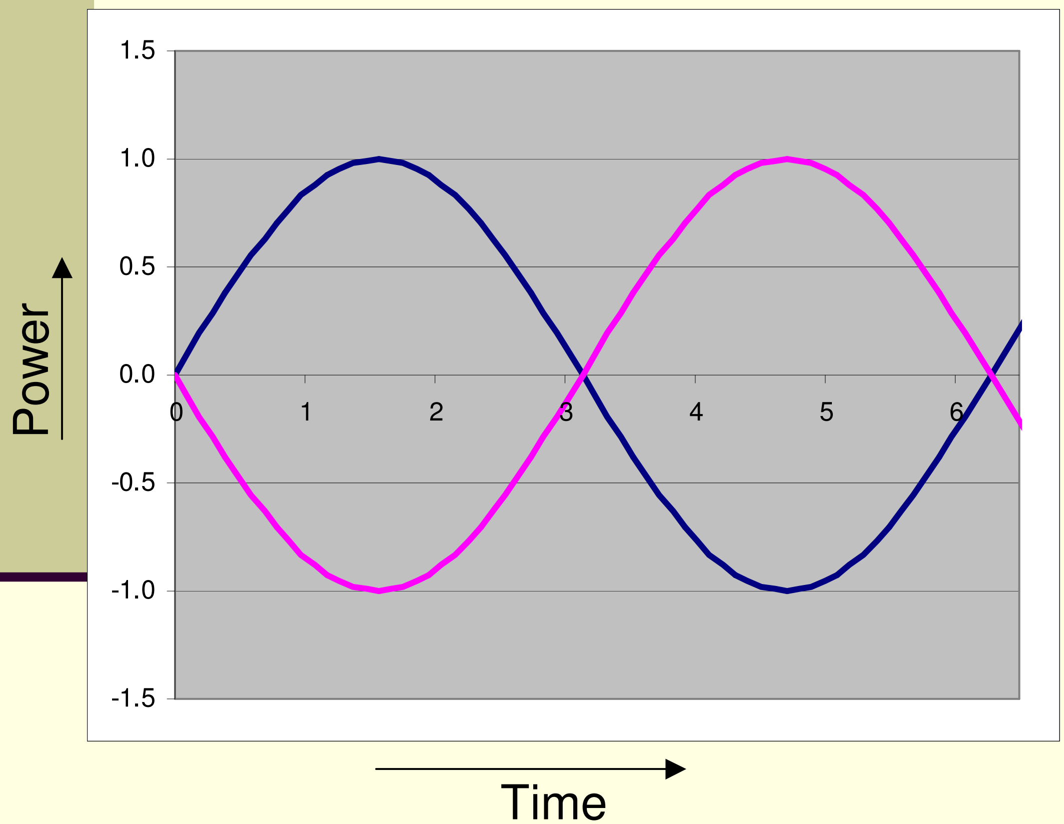
Digital Modulation Fundamentals

- What: Converts digital signals from ones and zeroes to a form that can be transmitted
- Why:
  - Binary digital signals from a computer are either of two voltages: 0 volts/+5 volts; +1 volt/-1 volt, etc.
  - voltages can only be transmitted over wires;
  - long-distance transmission requires putting signals in a different form
- How: the 1's and 0's are used to change the state of another signal
- Example:
  - To send a 0, send a tone at 1 kHz
  - To send a 1, send a tone at 2 kHz

  Called FSK: the digital data signals change or "shift" the frequency of a tone
- More common technique - phase shift keyed (PSK) modulation:
  - To send a 0, send a tone at 1 MHz (for example)
  - To send a 1, send a tone at 1 MHz that has been inverted by 180 degrees
  - This is termed "2-phase" or "bi-phase" keying (abbreviated as BPSK)
  - Other types: 4-phase PSK (also called quaternary phase shift keying or QPSK), 8-phase PSK, 16-phase PSK

Two-Phase Modulation

- Time representation of two-phase modulation:

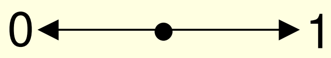


Sample Rules:

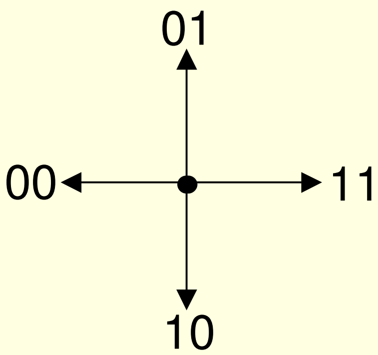
- To send a "one" use the blue phase of the signal
- To send a "zero" use the pink phase
- The frequency (number of cycles per second) is the same in either case; only the phase of the signal changes

Digital Modulation
Phase Representation

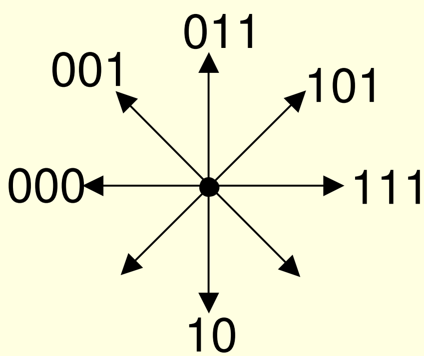
BPSK:



QPSK:



8PSK:



Bit Rate

- Bit rate = # of bits/second
- Bit rate is a function of amount of information to be transmitted
- Examples:
  - Voice: 2400 bits/sec to 64,000 bits/sec (64 kbits/sec)
  - Telconferencing: 384 kbits/sec
  - Full-motion video: 1.5-6 Mbits/sec
- Satellite carrier bit rates: 2400 b/s – 20 Mb/s and up

Error Rate

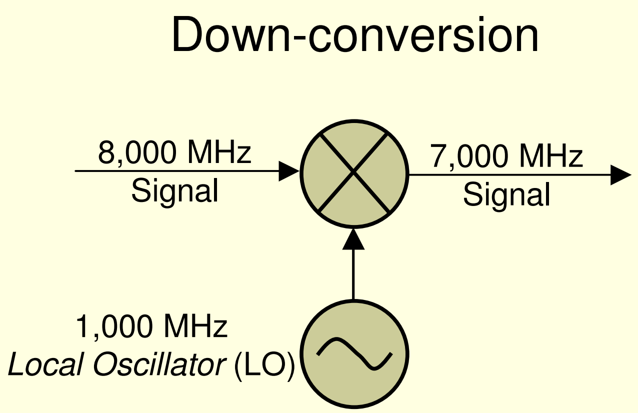
- Received digital signals always contain errors
- Figure of merit is "bit error rate" (BER)
- BER = fraction of received bits in error
- Expressed as an exponential
  - 1×10^{-10} (excellent)
  - 1×10^{-8} (very good)
  - 1×10^{-6} (good)
  - 1×10^{-4} (marginal)

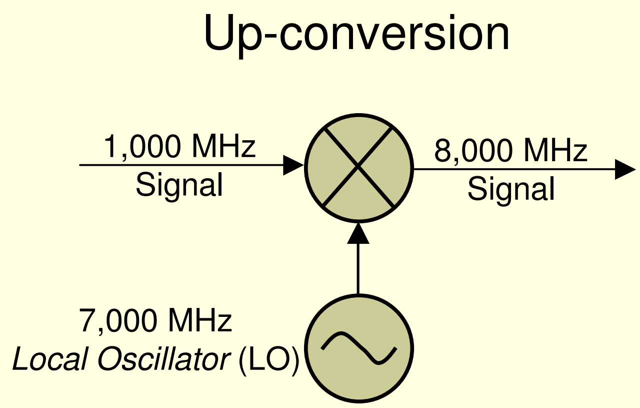
Error Rate Improvement

- Two tasks:
  - Error detection
  - Error correction
- Basic principal of Forward Error Coding (FEC)
  - Add bits at transmitter
    - Bit state computed from data bit states
  - At receiver:
    - For each bit, compute states that should have been received
    - Identify location of bits in error and flip
- FEC very effective (10^{-3} error rate before decoding $\rightarrow 10^{-8}$ error rate after decoding)
- Encoding techniques
  - Convolutional encoding (streaming technique)
  - Block coding (one block of bits at a time)
- Decoding techniques
  - Used with convolutional encoding
    - Viterbi
    - Trellis
    - Turbo product codes
  - Used with block encoding
    - Reed-Solomon

Frequency Conversion

- Signal frequency may be raised (up-conversion) or lowered (down-conversion) through the use of a mixer and a fixed-frequency source
- Information (modulation) on the signal is preserved through the mixing operation

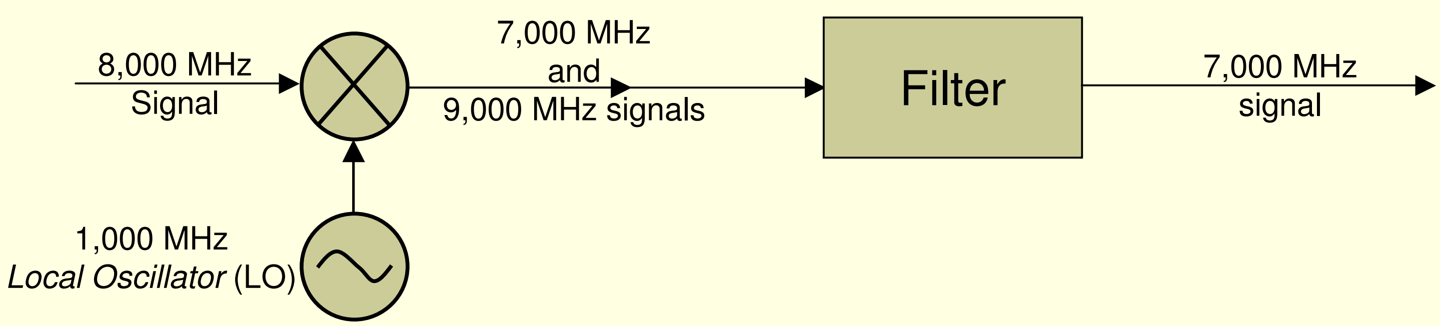




Filters

- Provide a means of selecting or rejecting a specific group of frequencies from a larger group
- Sample uses:
  - Select one signal from a group for processing
  - Reject off-frequency signals that would otherwise interfere
  - Restrict signals to the frequency range at which certain equipment works
- Example:

Down-conversion



Filters

- Provide a means of selecting or rejecting a specific group of frequencies from a larger group
- Sample uses:
  - Select one signal from a group for processing
  - Reject off-frequency signals that would otherwise interfere
  - Restrict signals to the frequency range at which certain equipment works

Digital Communications Components

Digital Modulator

- Converts digital signal into phase- or phase- and amplitude-modulated carrier
- Common modulation schemes:
  - BPSK
  - QPSK
  - OQPSK
  - 8PSK
  - 16PSK
  - 16QAM
- Error control:
  - Forward-error correcting coding (“FEC”)
    - Convolutional
    - Block
    - Turbo (special case of block coding)
  - Interleaving
- Data encoding:
  - Direct
  - Differential

Channel

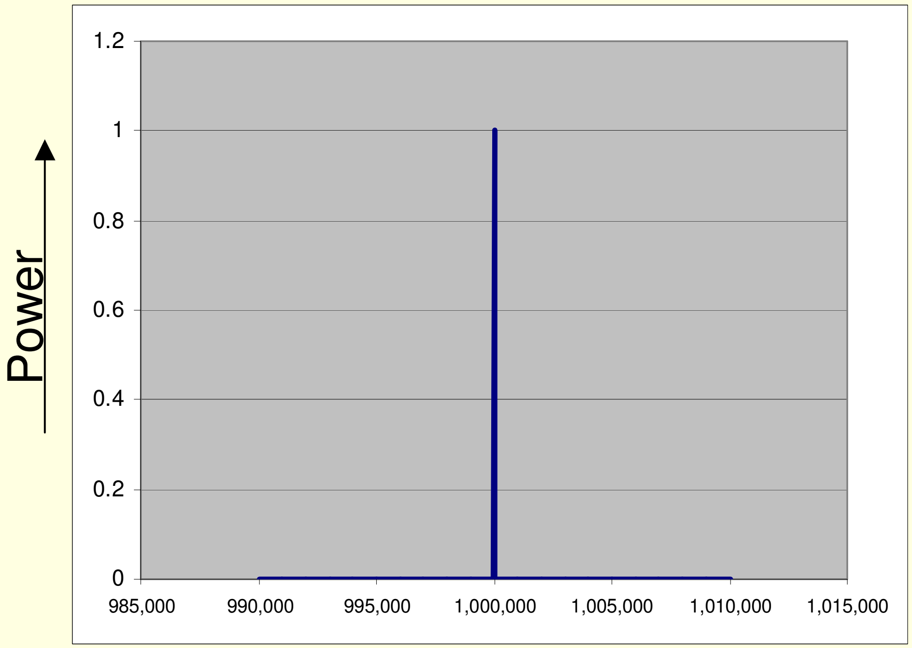
- Medium through which signal passes on its way from modulator to demodulator
- Common channel impairments:
  - Thermal noise
  - Impulse noise
  - Non-linear amplitude response
  - Non-linear phase response
  - Non-linear frequency response

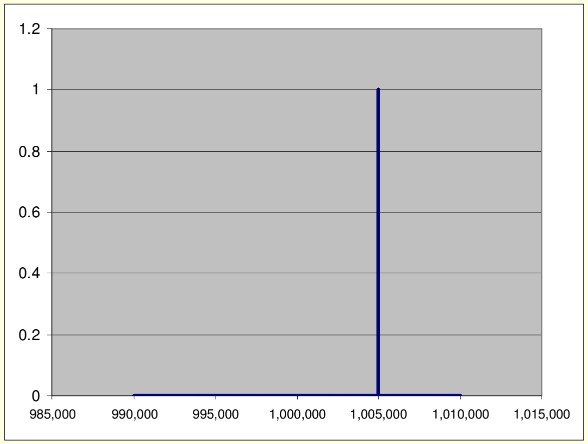
Demodulator

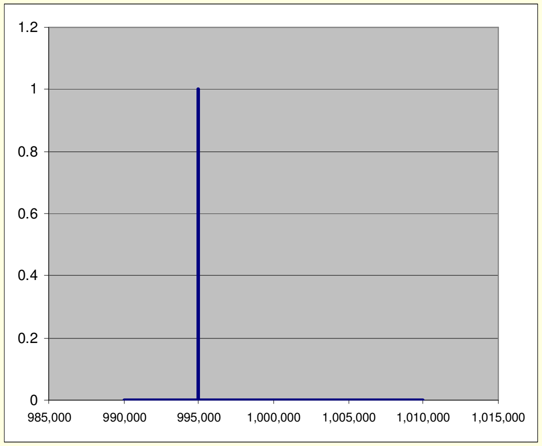
- Converts received modulated carrier containing channel impairments into digital signal
- Demodulator tasks
  - Demodulation
    - Coherent demodulation
      - Hard decision
      - Soft decision
    - Differential demodulation
  - De-interleaving
  - FEC decoding
  - Data decoding

The Frequency Domain

- Notes on a piano have fixed frequencies
- A 1 MHz signal has a fixed frequency
- Viewing a 1 MHz signal in a display that shows frequency vs. amplitude, it would appear like this:





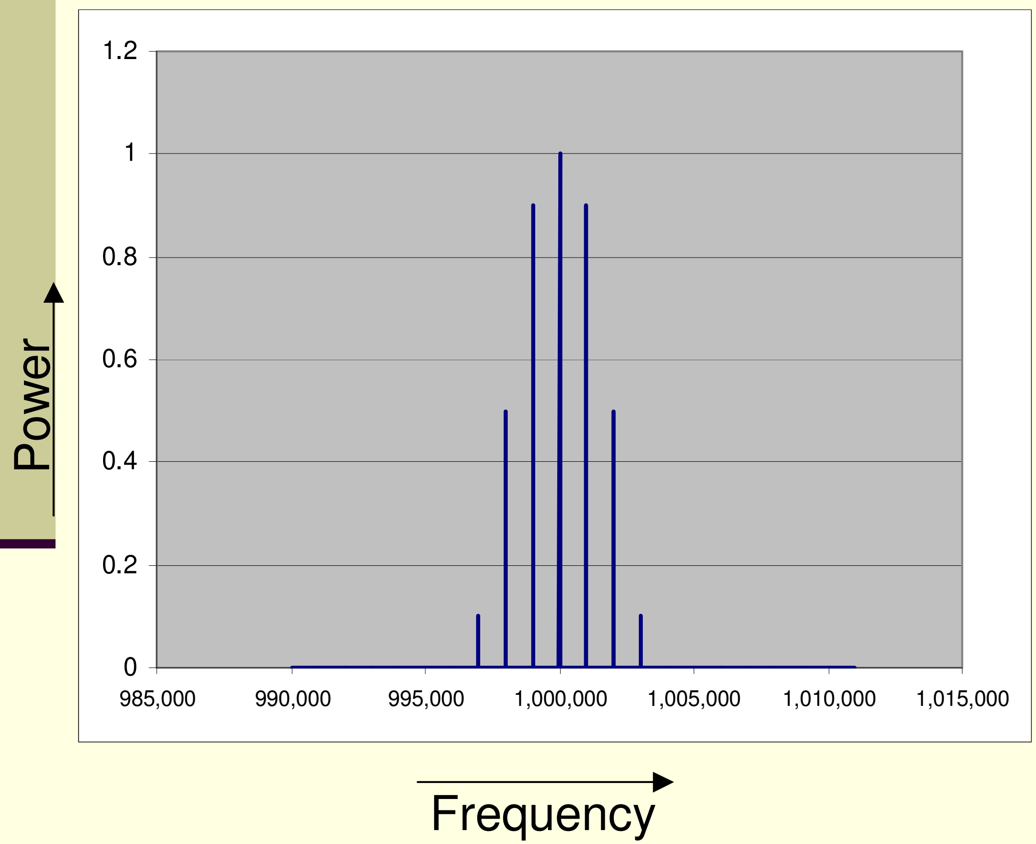


Signal has a frequency of 1,000,000 cycles per second, or 1 Megahertz (1 MHz)

Frequency

Digital Modulation

- Frequency-domain representation of a modulated signal



- Center of the signal is still at 1,000,000 cycles per second (1 Megahertz)
- Note, however, that there is some “grass” growing beside the carrier. These are termed “sidebands” and show what happens to an unmodulated signal (carrier) when modulation is added
- “Carrier” – a signal that carries information

Carrier Bandwidth

- The extent of frequency required to support a carrier
- Bandwidth increases with bit rate
- Bandwidth required to support a particular bit rate is a function of information rate and modulation technique
- Example for an information rate of 1000 bits/second:
  - Using BPSK, bandwidth ≈ 1000 Hz
  - Using QPSK, bandwidth ≈ 500 Hz
  - Using 8PSK, bandwidth ≈ 250 Hz