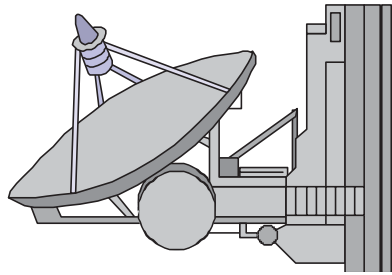


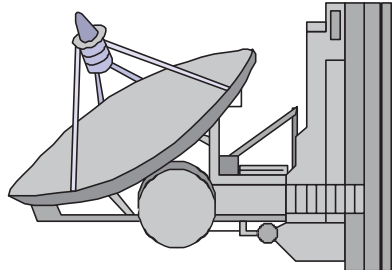
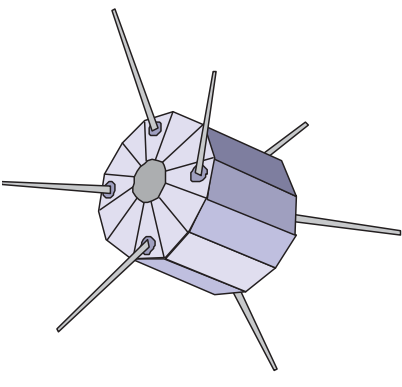
Satellite Communication



Col John Keesee

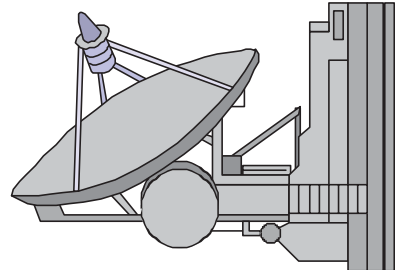
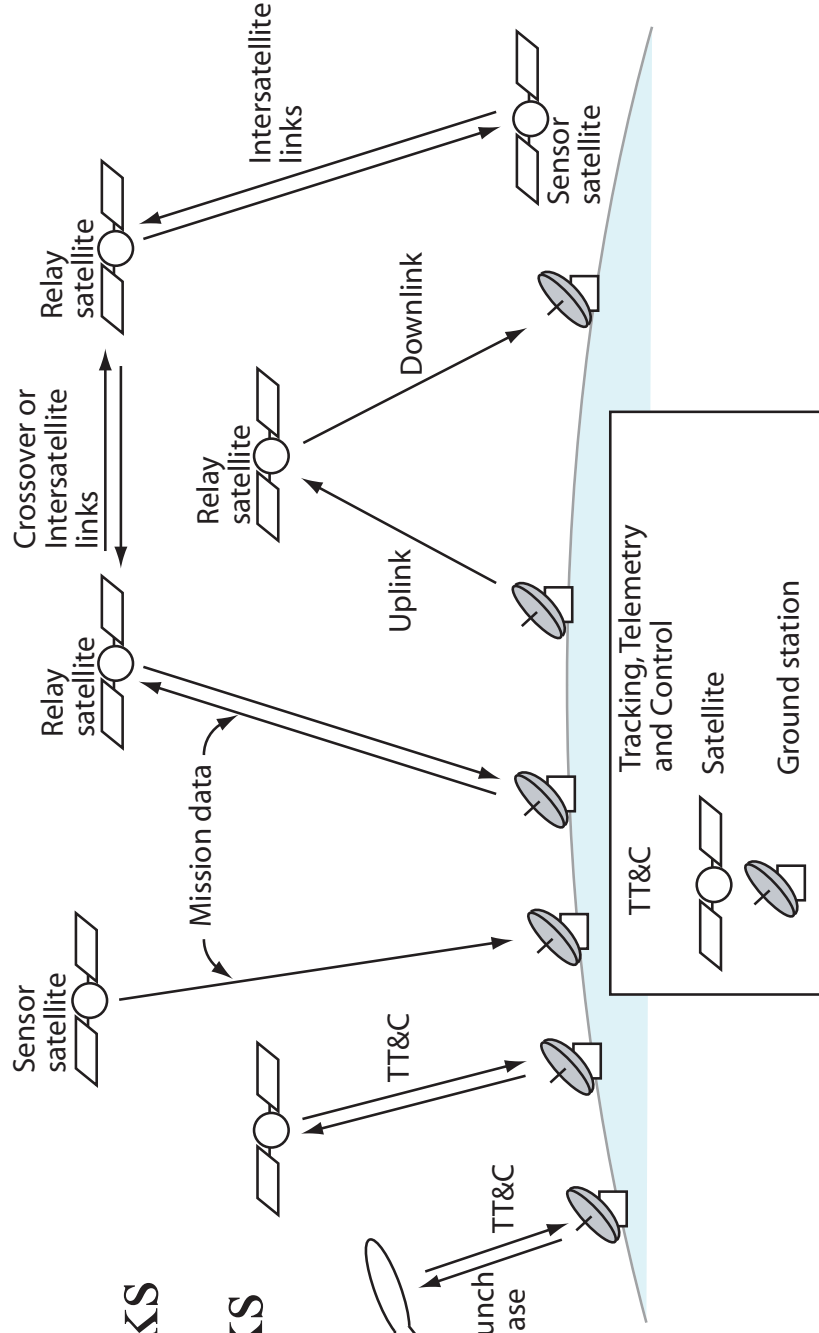
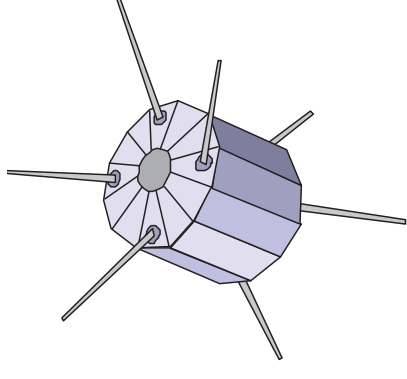
Satellite Communications Architecture

- Identify Requirements
- Specify Architectures
- Determine Link Data Rates
- Design & Size each link
- Document your rationale



Definition

- Uplinks
- Downlinks
- Crosslinks
- Relays
- TT & C

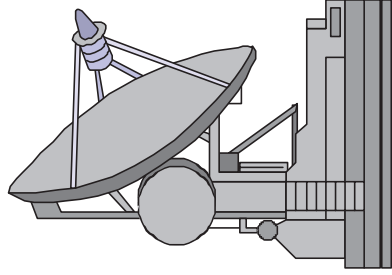
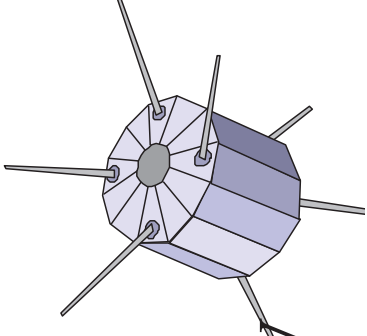
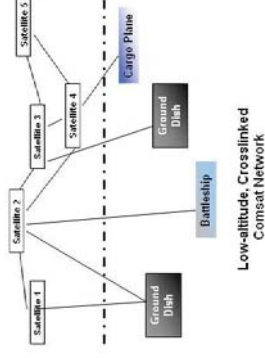
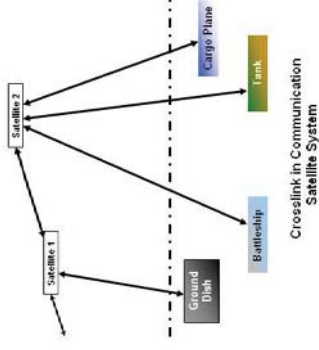
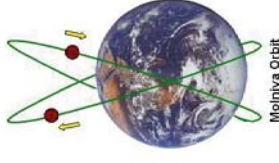
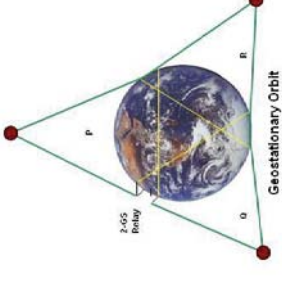
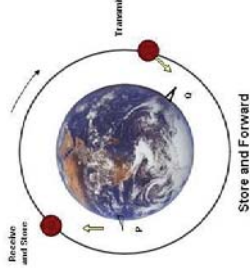


The communications architecture consists of satellites and ground stations interconnected with communications links. (Adapted from SMAD.)

Architectures:

Defined by Satellite-Ground Geometry

- Store & Forward
- Geostationary
- Molniya
- Geostationary/
Crosslink
- LEO/ Crosslink

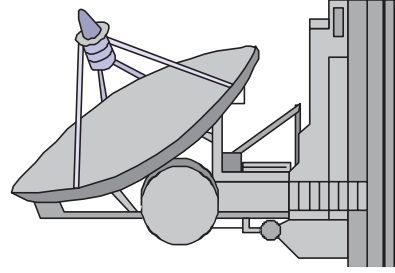
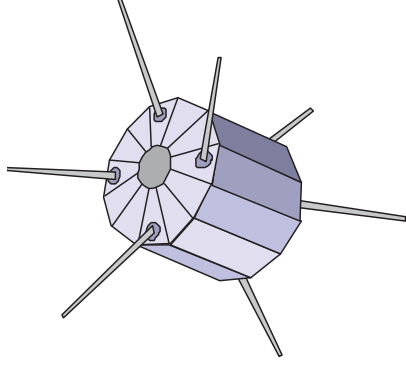


Adapted from SMAD.

Low-altitude, Crosslinked
Comsat Network

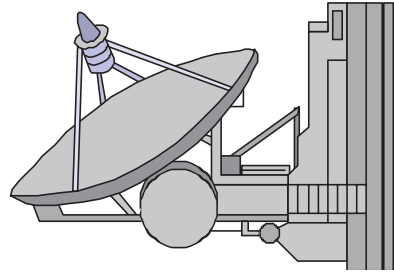
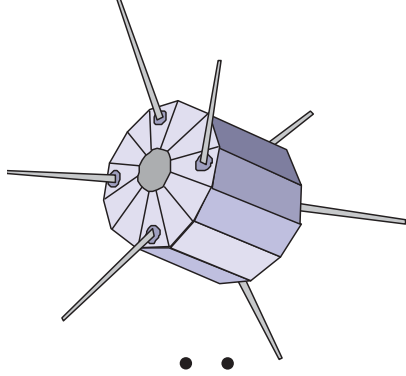
Architectures: Defined by Function

- System Function
 - Tracking Telemetry & Command
 - Data Collection
 - Data Relay
- Satellite Design
 - Onboard Processing
 - Autonomous Satellite Control
 - Network Management



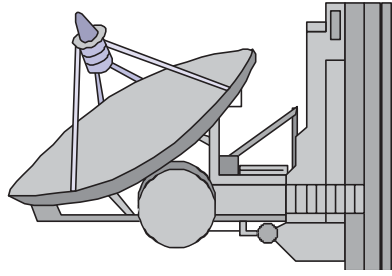
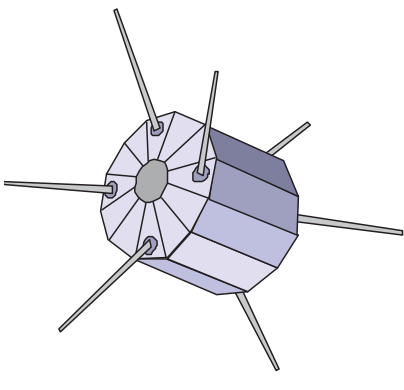
Communications Architecture: Selection Criteria

- Orbit
- RF Spectrum
- Data Rate
- Duty Factor
- Link Availability
- Link Access Time
- Threat

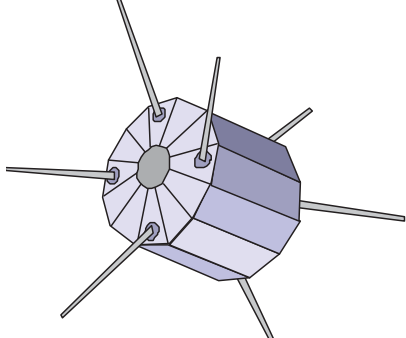


Advantages of Digital Communication

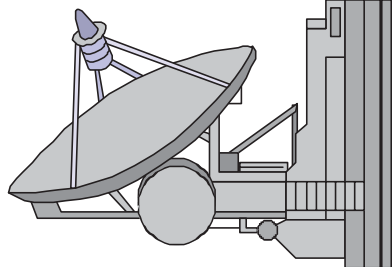
- Less distortion and interference
- Easy to regenerate
- Low error rates
- Multiple streams can be easily multiplexed into a single stream
- Security
- Drift free, miniature, low power hardware



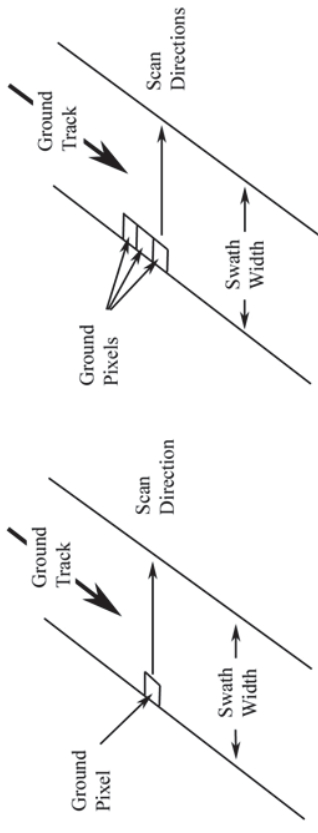
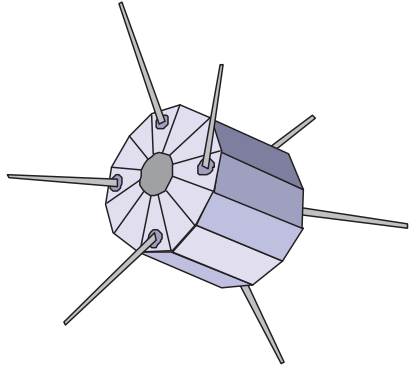
Tracking Telemetry & Control



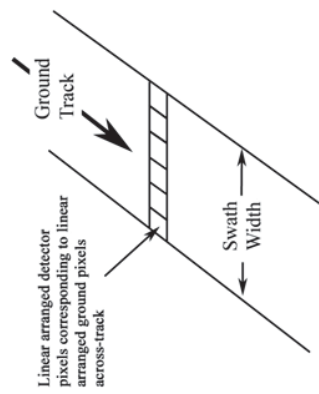
- **Telemetry**
 - Voltages, currents, temperatures, accelerations, valve and relay states
- **Commanding**
 - Low data rate
 - Store, verify, execute or execute on time
 - Programmable control
- **Range or Range Rate**
 - Round trip delay yields range
 - Doppler shift yields range rate
 - Pseudo-random code
- **Existing TT&C Systems**
 - AFSCN (SGLS) - AF Satellite Control Network (Space Ground Link System)
 - NASA DSN - Deep Space Network
 - Intelsat/ □ COMSAT
 - TDRS - Tracking and Data Relay Satellite



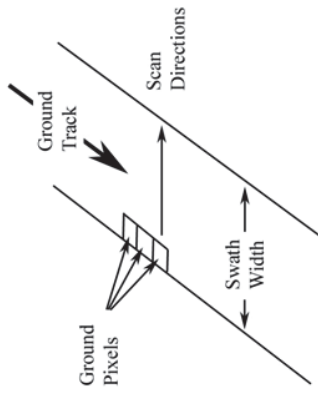
Data Collection Mission



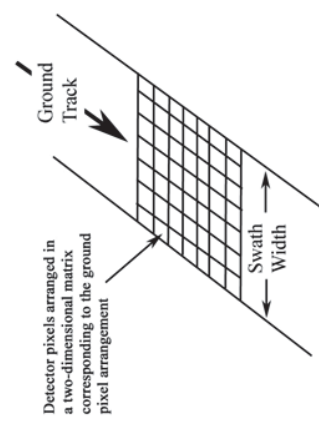
A) Single-element Whiskbroom Sensor



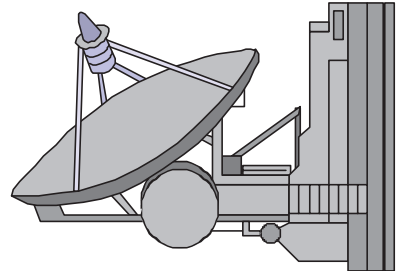
C) Push Broom Sensor



B) Multi-element Whiskbroom Sensor



D) Matrix Imager



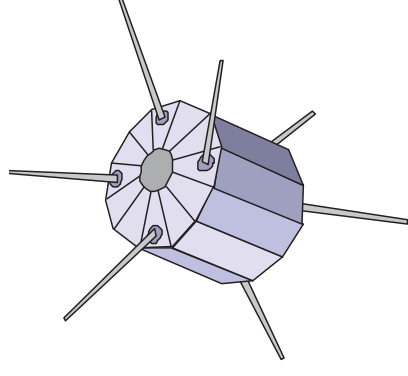
$$DR(\text{pushbroom}) = \frac{S_w}{X} * \frac{V_n}{Y} * b$$

$$DR(\text{imager}) = \frac{\text{Bits}}{\text{pixel}} * \frac{\text{Pixels}}{\text{sample}} * \frac{\text{Samples / Second}}{\text{duty_cycle}}$$

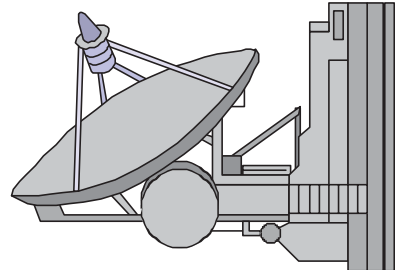
Adapted from SMAD.

Variable Definitions

Chart 9

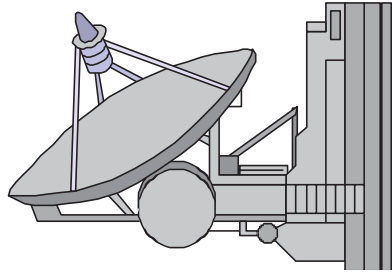
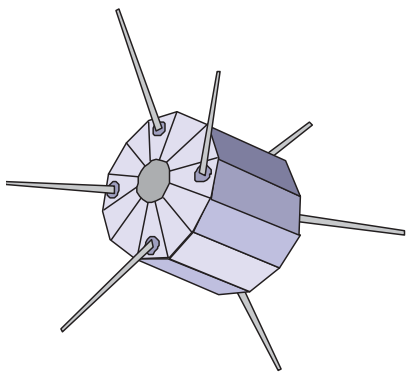


Variable	Definition	Units
DR	Data Rate	Bits/second
SW	Swath Width	Meters
X	Across track pixel dimension	Meters
Vn	Ground track velocity	Meters/second
Y	Along track pixel dimension	Meters
b	Bits/pixel	Bits

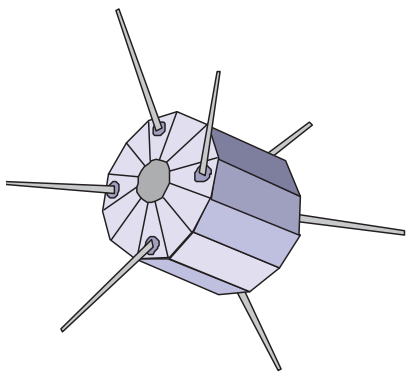


Reducing the Data Rate

- Increase the Duty Cycle
- Collect only above-threshold data
- Amplitude changes only
- Data compression



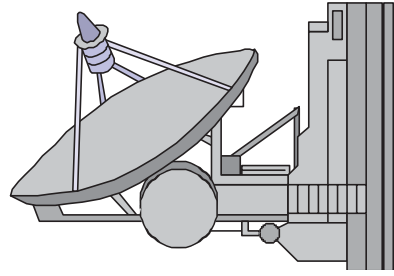
Link Design Process



1. Define Requirements for each link
2. Design Each Link
 - Select frequency
 - Select modulation & coding
 - Apply antenna size & beam width constraints
 - Estimate atmospheric, rain attenuation
 - Estimate received noise, interference power
 - Calculate required antenna gain & transmitter power

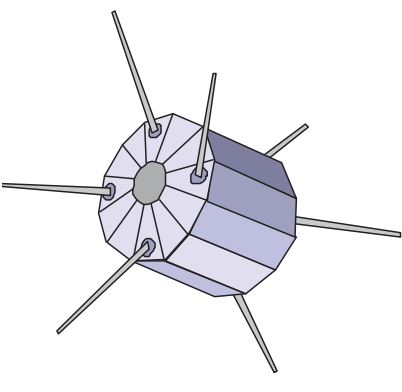
3. Size the Payload

- Payload antenna configuration, size & mass
- Estimate transmitter mass & power
- Estimate payload mass & power

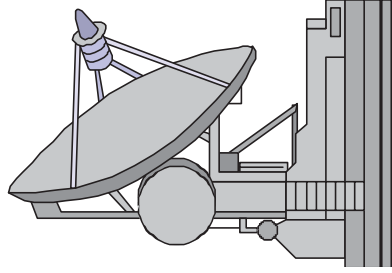


Link Equation

$$\frac{E_b}{N_o} = \frac{P L_t G_t L_s L_a G_r}{k T_s R}$$



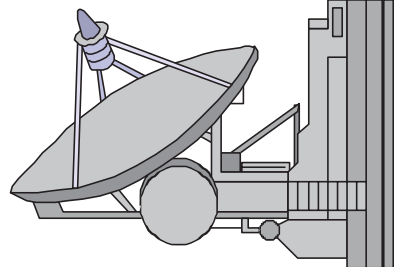
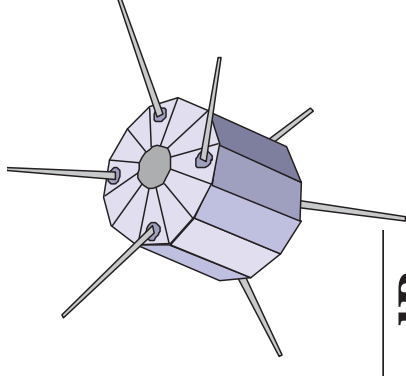
Energy/bit to noise-density ratio



Variable Definitions

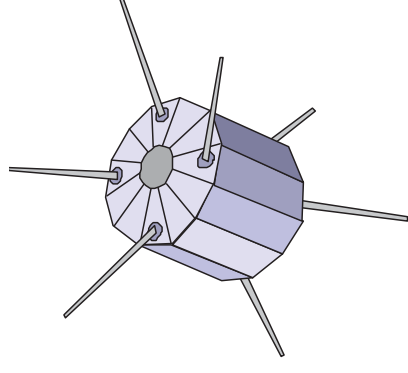
Chart 12

Variable	Definition	Units	Units dB
E_b	Energy per bit	Watt-seconds	dB
N_o	Noise spectral density	Watts/hertz	dB
P	Transmitter power	Watts	dBW
L_1	Line loss		dB
G_t	Transmitter antenna gain		db
L_s	Space loss		DB

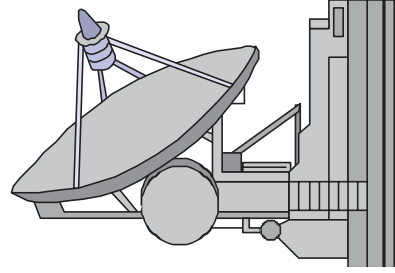


Variable Definitions

Chart 12 continued

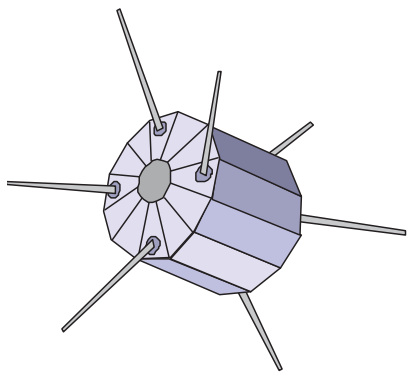


Variable	Definition	Units	Units (dB)
L_a	Transmission path loss		dB
G_r	Receiver gain		dB
k	Boltzmann constant	J/K	dBW/(Hz-K)
T_s	System noise temperature	K	
R	Data rate	Bits/ second	

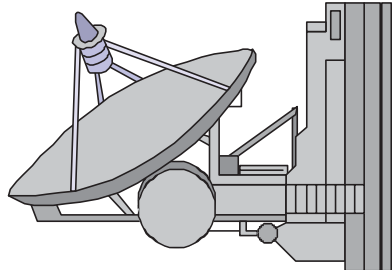


Power Flux Density

$$W_f = \frac{PL_t G_t L_a}{4\pi S^2} = \frac{(EIRP) L_a}{4\pi S^2}$$

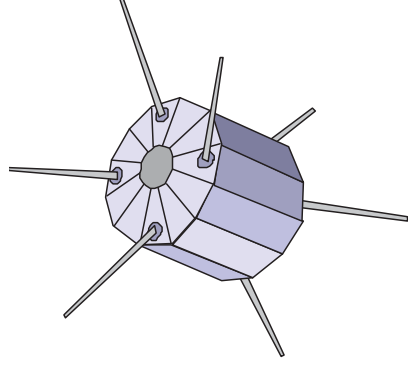


EIRP - Effective Isotropic Radiated Power

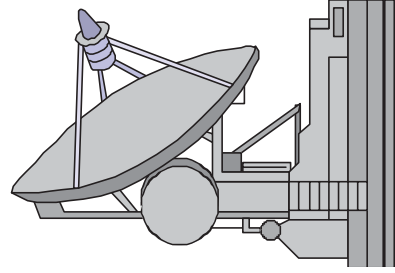


Variable Definitions

for Chart 16



Variable	Definition	Units	Units (dB)
W_f	Power flux density	W/m^2	
S	Path length	M	
EIRP	Effective	W	DBW
	Isentropic		
	Radiated		
	Power		



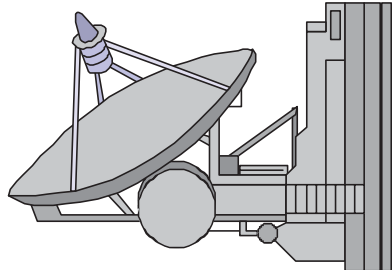
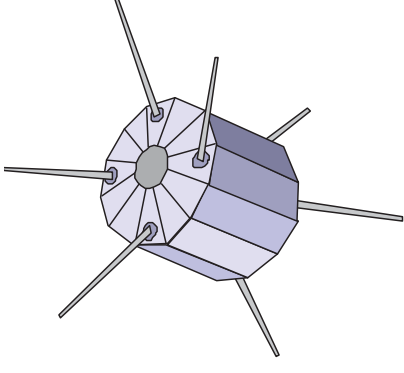
Received Power

$$C = Wf \cdot \frac{\pi D r^2 \eta}{4} = \frac{P L_t G_t L_a D r^2 \eta}{16 S^2}$$

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

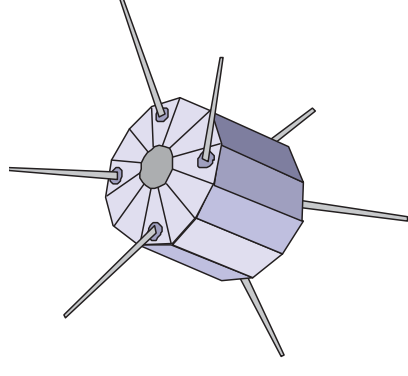
$$\text{Space Loss} \quad L_s = \left(\frac{\lambda}{4\pi S} \right)^2$$

$$C = \text{EIRP} * L_s * L_a * G_r$$

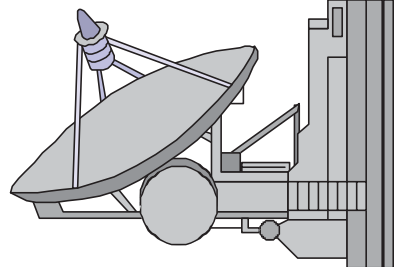


Variable Definitions

Chart 18



Variable	Definition	Units	Units (dB)
C	Received power	W	
D_r	Receiver antenna diameter	m	dB
η	Antenna efficiency		
λ	Wavelength	m	
L_s	Space loss		



Link Equation Concluded

$$E_b = \text{energy/bit} = \frac{C}{R}$$

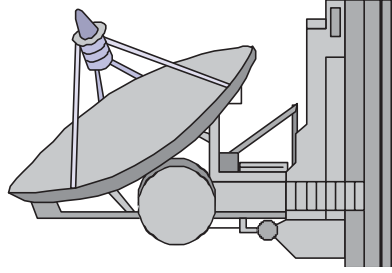
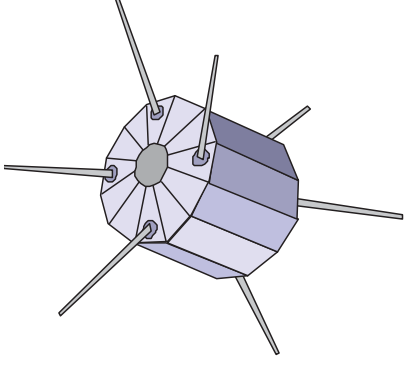
N_o = noise spectral density

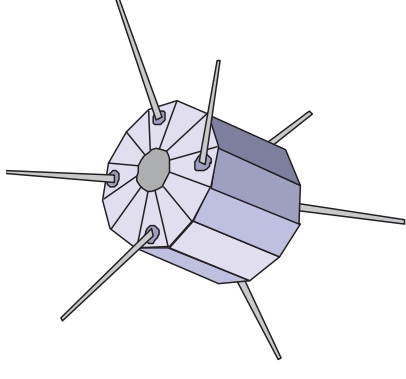
N = total received noise power

B = receiver noise bandwidth

$$N_o = kT_s = N / B$$

$$\frac{E_b}{N_o} = \frac{P \times L_l \times G_t \times L_a \times G_r \times L_s}{k \cdot T_s \cdot R}$$





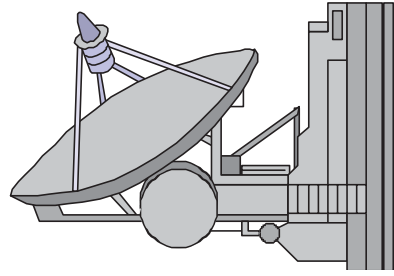
Link Equation in dB

$$\begin{aligned} \frac{E_b}{N_o} &= P + L_t + G_t + L_s + L_a + G_r + 228.6 - 10 \log T_s - 10 \log R \\ &= EIRP + L_s + L_a + G_r + 228.6 - 10 \log T_s - 10 \log R \end{aligned}$$

$$\frac{C}{N_o} = EIRP + L_s + L_a + \frac{G_r}{T_s} + 228.6$$

$$\frac{C}{N} = EIRP + L_s + L_a + \frac{G_r}{T_s} + 228.6 - 10 \log B$$

$$RIP = \frac{E_b}{N_o} - \frac{G_r}{T_s} - 228.6 + 10 \log R \quad \text{(Received isentropic power)}$$

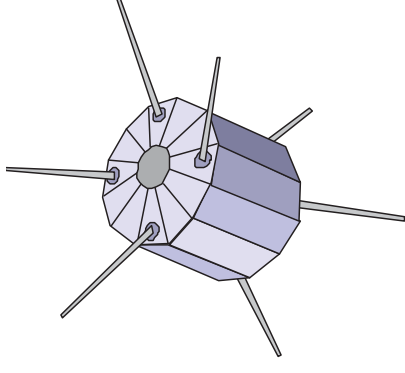
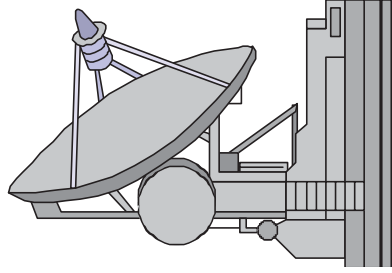


Gain in dB

$$G_r = \frac{\pi^2 D_r^2 \eta}{\lambda^2}$$

$$f = \frac{c}{\lambda}$$

$$\begin{aligned} G &= 20 \log \pi + 20 \log D + 20 \log f + 10 \log \eta \\ &\quad - 20 \log c \quad (\text{dB}) \\ &= -159.59 + 20 \log D + 20 \log f + 10 \log \eta \quad (\text{dB}) \end{aligned}$$



Beamwidth

$$\theta = \frac{21}{f \cdot D}$$

θ [degrees]

f [GHz]

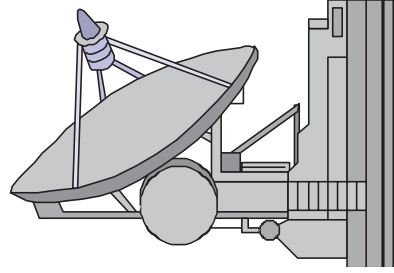
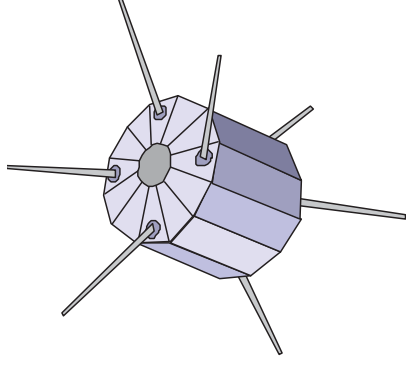
D [m]

$$G = \frac{27,000}{\theta^2}$$

Antenna gain

$$L_{\theta} = -12(e/\theta)^2 \quad (\text{dB})$$

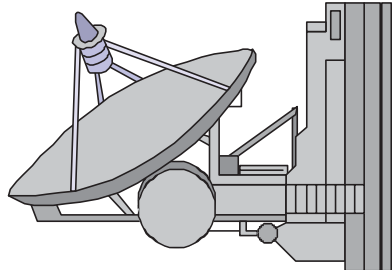
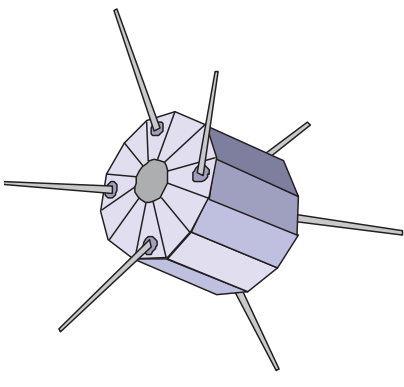
Offset beam loss



Space loss in dB

$$L_s = \left(\frac{\lambda}{4\pi S} \right)^2 \quad (\text{ratio})$$

$$L_s = 147.55 - 20 \log S - 20 \log f \quad (\text{dB})$$

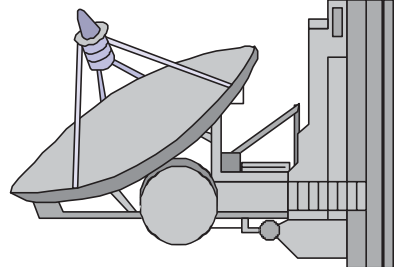
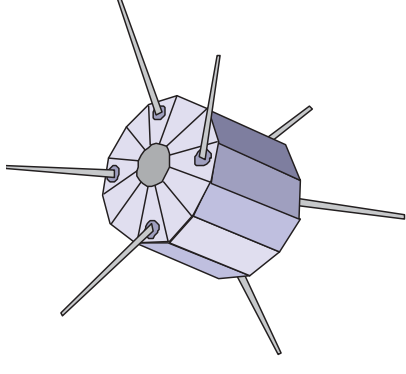


System Noise Temperature

- External to Antenna

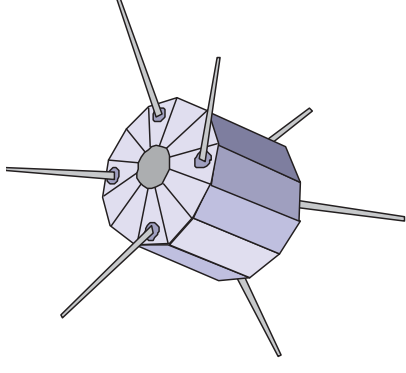
- Galactic noise
- Clouds, rain in path
- Solar noise (in mainbeam or sidelobe)
- Earth (290K)
- Man-made noise
- Nearby objects
- Satellite structure

(See SMAD Fig 13-7)



System Noise Temperature

- Internal to System



- Transmission lines and filters

$$T_r = (1 - L)T$$

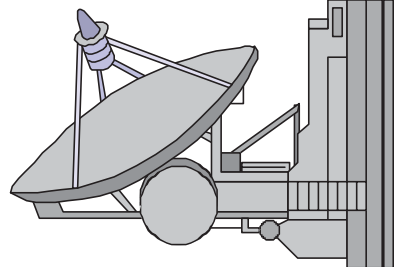
$$L = \frac{P_o}{P_i}$$

F is a figure of merit for a receiver

- Low noise amplifier

$$T_r = (F - 1)290K$$

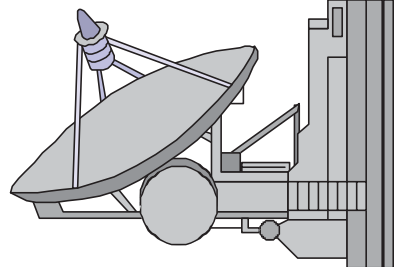
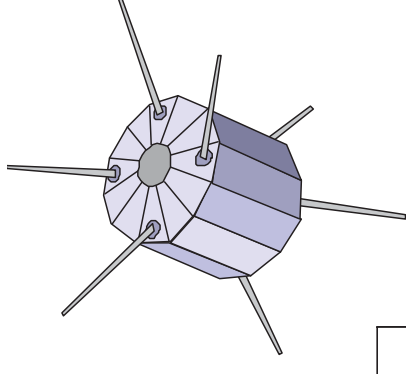
$$T_s = T_{ant} + T_o \left(\frac{1 - L_r}{L_r} \right) + T_o \left(\frac{F - 1}{L_r} \right)$$



Variable Definitions

Chart 21

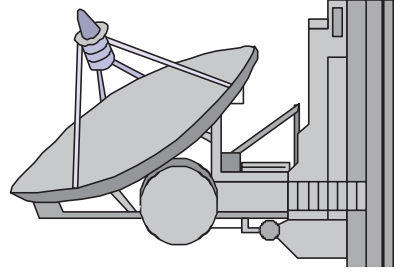
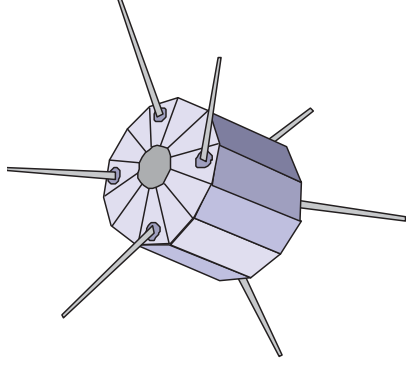
Variable	Definition	Units
T_r	Receiver noise temperature	K
L	Power ratio	
T	Component temperature	K
P_o	Output power	W
P_i	Input power	W
F	Noise figure	
T_o	Reference temperature (usually 290 K)	K



Modulation

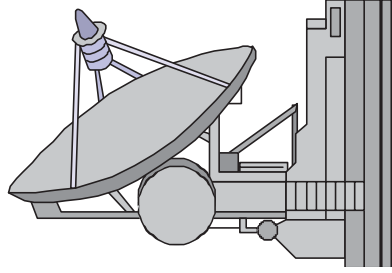
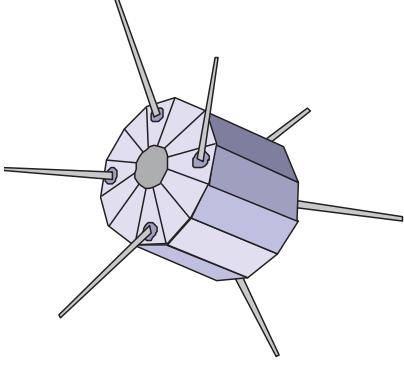
- Modulation modifies an RF Carrier signal so that it contains input signal information

- Amplitude
- Frequency
- Phase
- Polarization



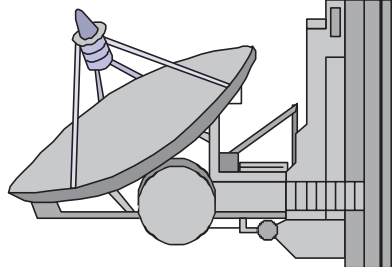
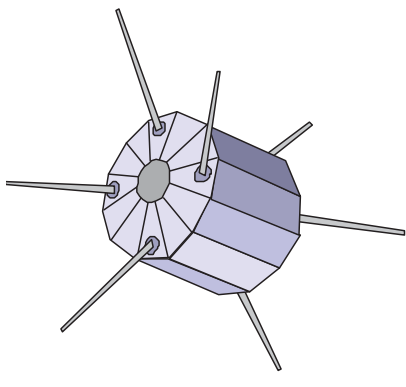
Modulation Techniques

- BPSK - Binary Phase Shift Keying
- QPSK - Quadrature Phase Shift Keying
- FSK - Frequency Shift Keying
- MFSK - Multiple FSK
- DPSK - Differential Shift Keying



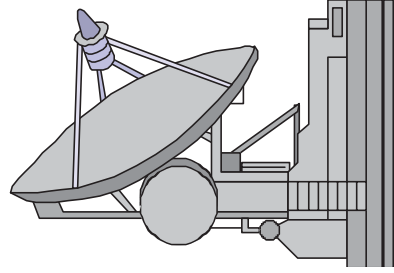
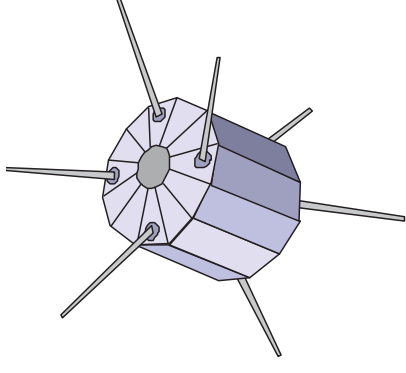
Bit Error Rate

- Primary Figure of Merit for Digital Link Performance
- Energy/bit (E_b) must exceed the noise spectral density (N_0) to achieve a required BER

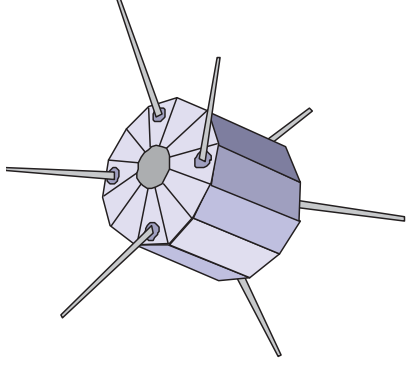


Coding

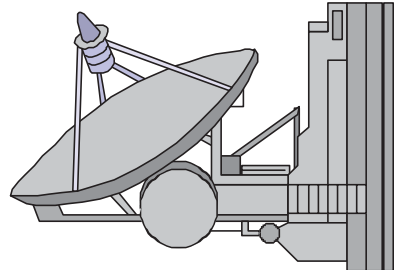
- Forward Error Correction sends additional data to help detect and correct errors.
 - Reduces the E_b/N_0 requirement
 - Reduces required transmitter power
 - Reduces antenna size
 - Increases margin
 - Increases data rate and bandwidth



Convolutional Coding with Viterbi Decoding

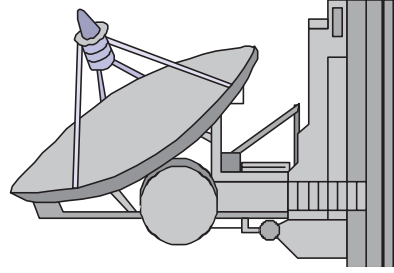
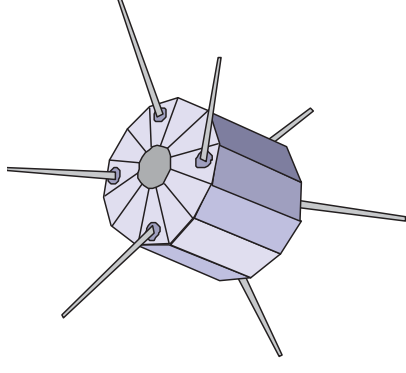


- Extra bits sent with each block of data bits
- Receiver examines string of bits, generates possible code sequences, selects most likely
- Shannon limit $E_b/N_o = -1.6$ dB
- Double coding necessary on deep space probes



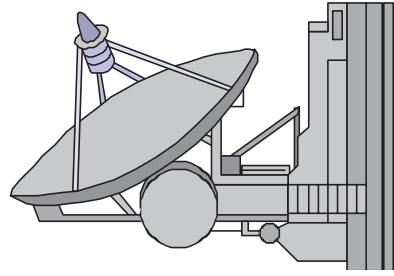
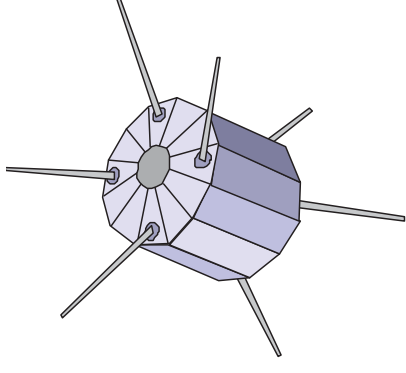
Attenuation

- Atmosphere absorbs some frequencies
- Divide zenith attenuation by $\sin(\text{elevation angle})$
- Oxygen absorption at 60 GHz
- Scintillation disrupts below 200 MHz

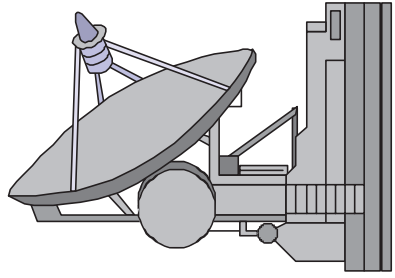
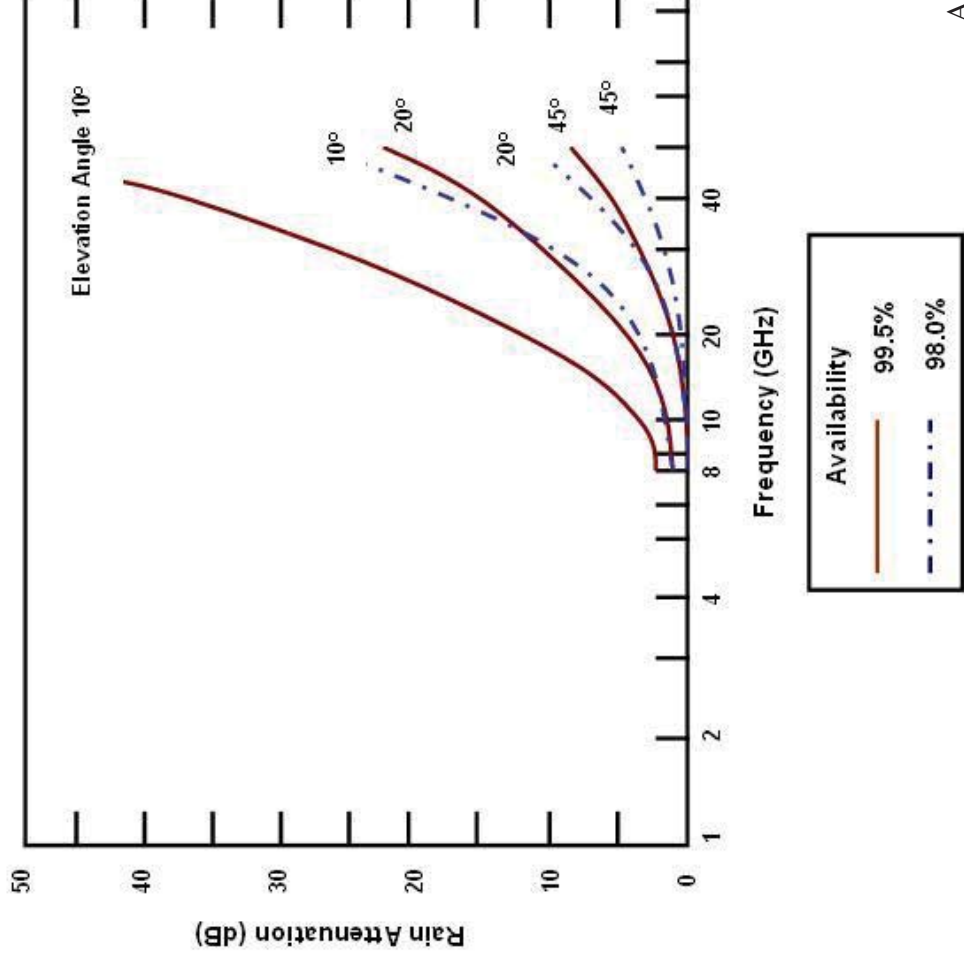
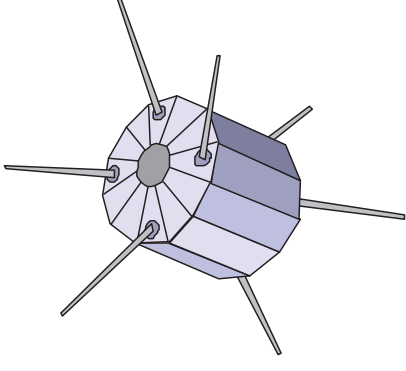


Rain and Cloud Attenuation

- Crane model for world's climatic data
- Important above 10 GHz
- Worst for elevation angles < 20 degrees
- Rain reduces availability



Rain and Cloud Attenuation



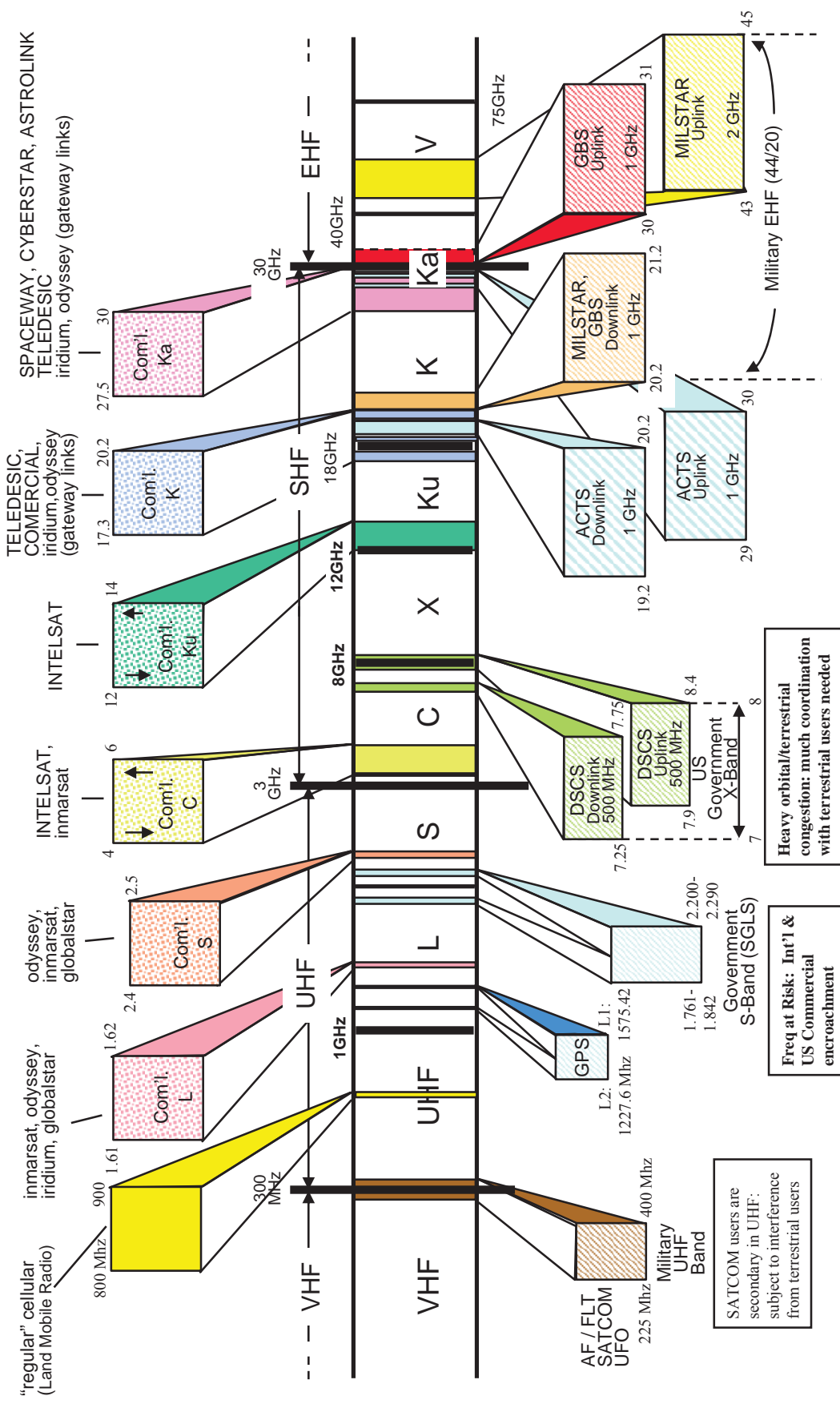
Adapted from SMAD.

SATCOM Frequencies Usage

Commercial SATCOM Services

ALL CAPS = Fixed Satellite Service (FSS)

small case = Mobile Satellite Service (MSS)/Personal Comm Services (PCS)



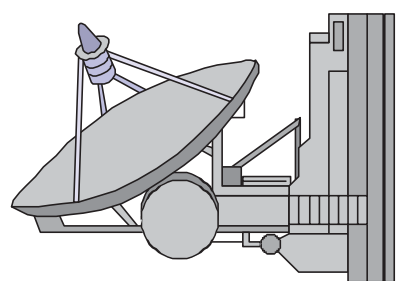
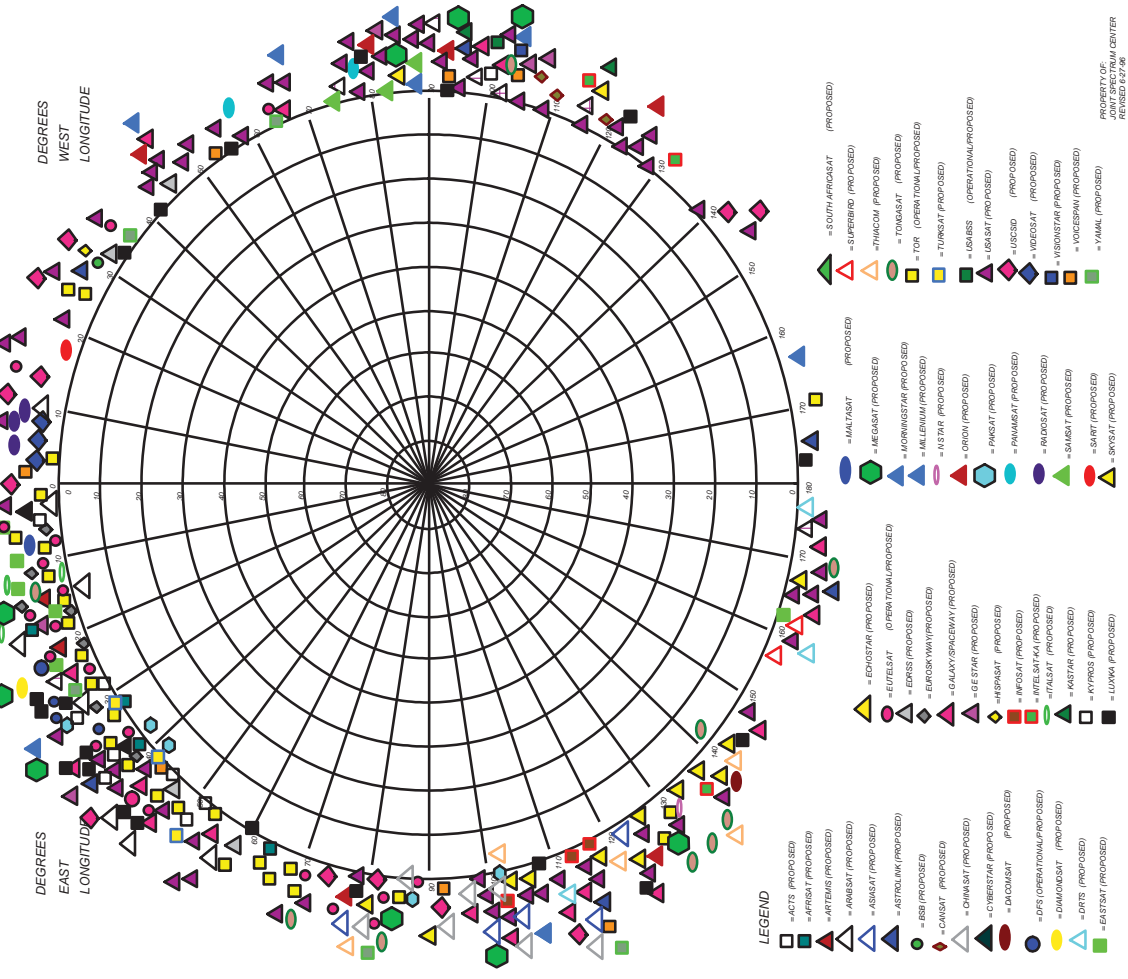
SATCOM users are secondary in UHF: subject to interference from terrestrial users

Freq at Risk: Int'l & US Commercial encroachment

Heavy orbital/terrestrial congestion: much coordination with terrestrial users needed

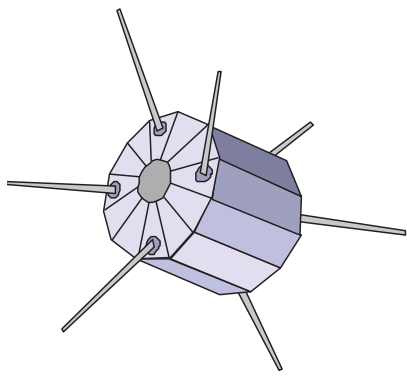
Government / Military SATCOM Services

LOCATIONS OF CURRENT & PROPOSED GEOSTATIONARY SATELLITES WITH 17.3-GHz THRU 20.2-GHz DOWNLINKS

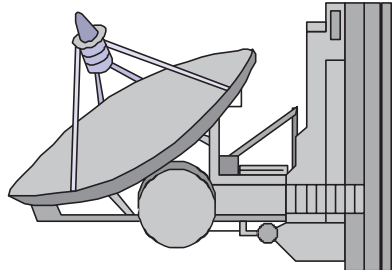


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JOINT SPECTRUM CENTER
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Frequency Selection Drivers



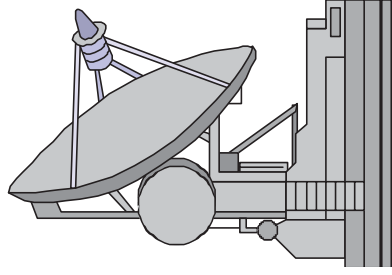
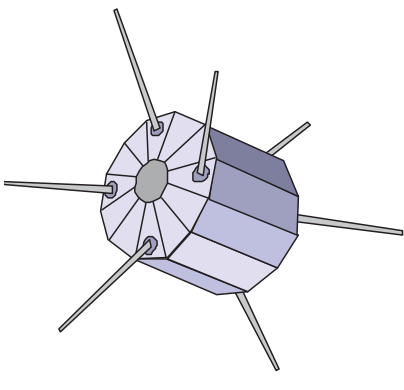
- Spectrum availability and FCC allocation
- Relay/Ground Station frequency
- Antenna size
- Atmospheric/Rain attenuation
- Noise temperature
- Modulation and coding



Communication Payload

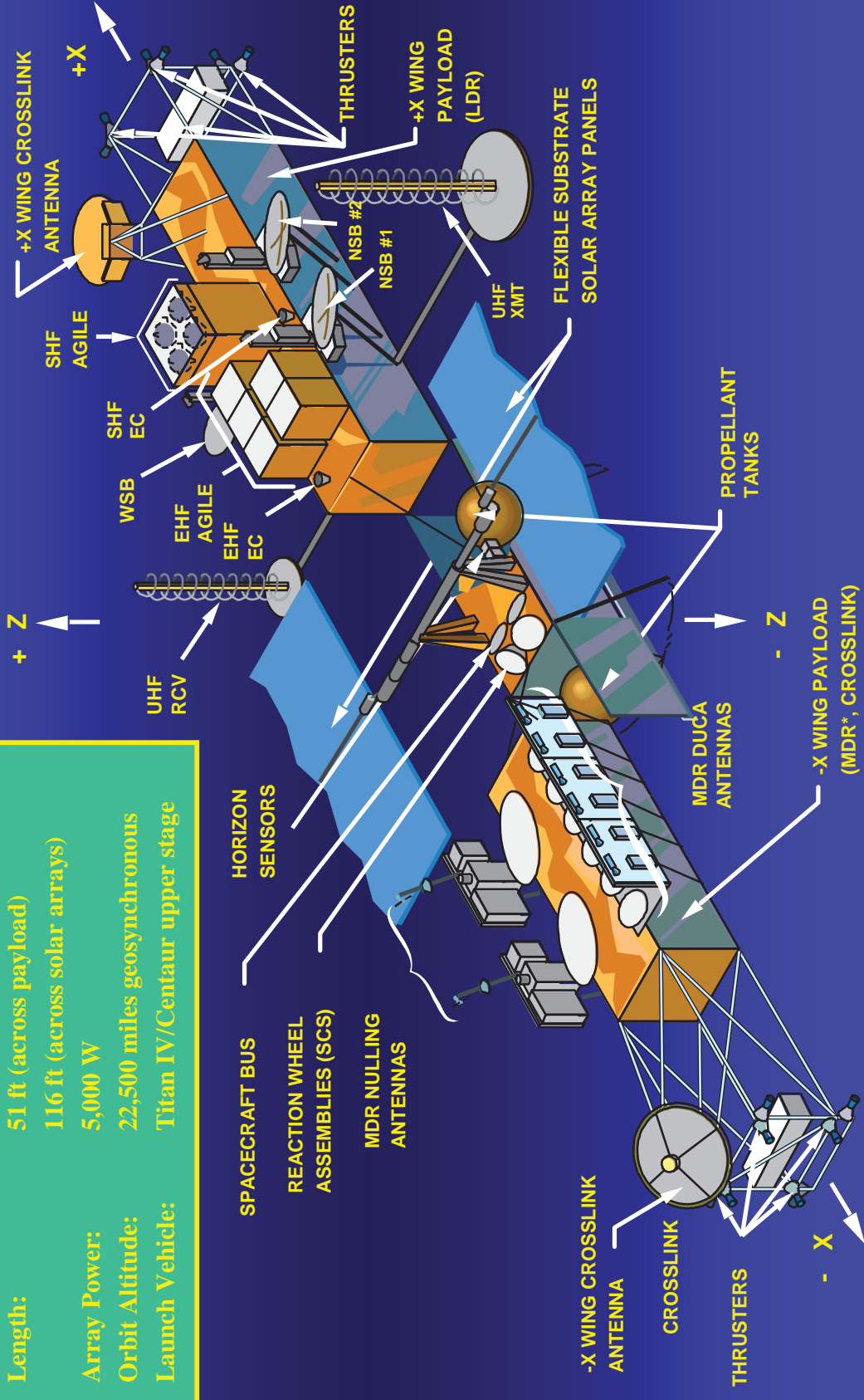
Antennas

- Parabolic
- Helix
- Horn
- Phased Arrays
 - Multiple beams
 - Hopping beams



Milstar Satellite Layout

- **Weight:** 10,000 lb
- **Length:** 51 ft (across payload)
116 ft (across solar arrays)
- **Array Power:** 5,000 W
- **Orbit Altitude:** 22,500 miles geosynchronous
- **Launch Vehicle:** Titan IV/Centaur upper stage



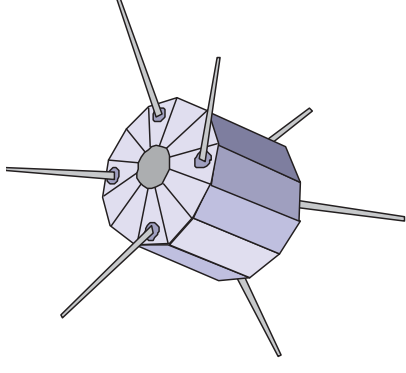
(Image removed due to copyright considerations.)

- ▶ **UPLINK:**
5 AGILES, 2 NARROW SPOTS,
1 WIDE SPOT, 1 EARTH COVERAGE
- ▶ **DOWNLINK:**
SINGLE DOWNLINK TIME-SHARED BY:
1 AGILE, 2 NARROW SPOTS,
1 WIDE SPOT, 1 EARTH COVERAGE

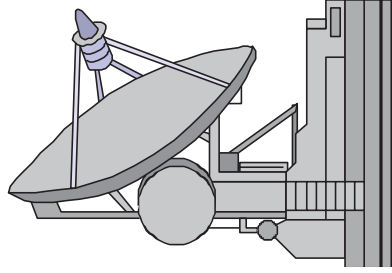
(Image removed due to copyright considerations.)

- ▶ **UPLINK:**
2 NULLING SPOTS
6 DISTRIBUTED USER COVERAGE
(DUCs)
- ▶ **DOWNLINK:**
SINGLE DOWNLINK TIME-SHARED BY:
2 SPOTS AND 6 DUCs

Multiple Access Strategies

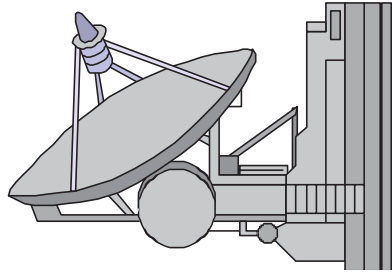
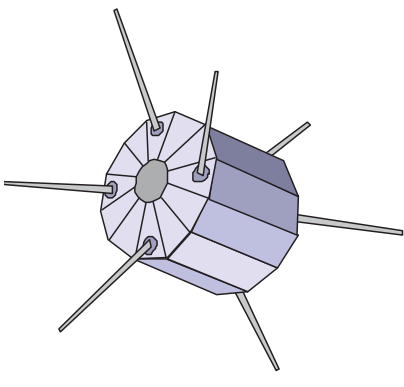


- FDMA - Frequency Division Multiple Access
- TDMA - Time Division Multiple Access
- CDMA - Code Division Multiple Access
 - Phase Modulation plus pseudo-random noise



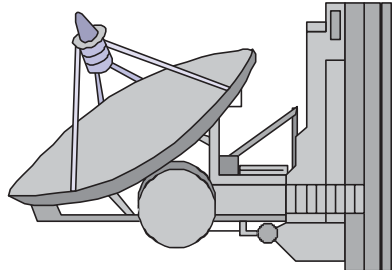
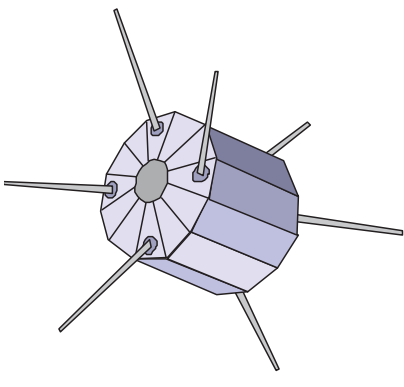
Antijam Techniques

- Spread Spectrum
- Narrow beamwidths
- On board processing
- Nulling antennas



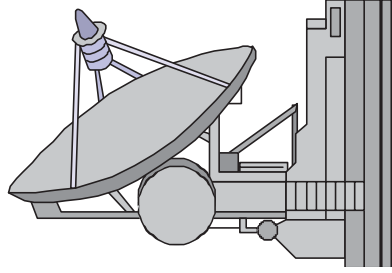
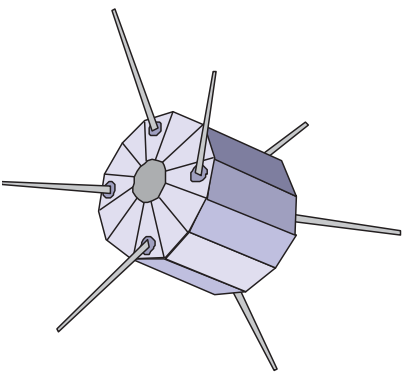
Special Topics

- Data security through encryption
- Spatial, time and satellite diversity
- Frequency hopping
- Interleaving

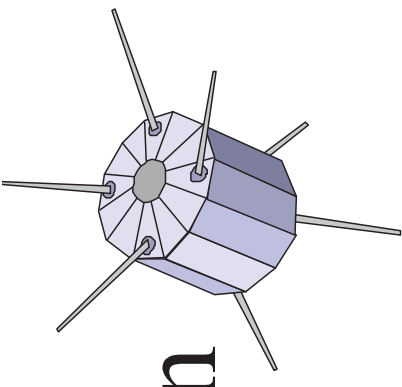


Why Compress Data

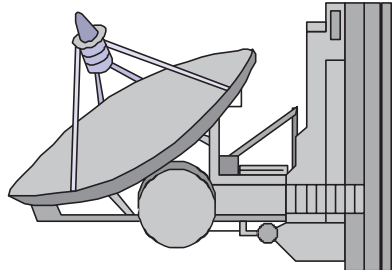
- Need to send more data than bandwidth accommodates
 - Digital image files in particular are very large
- Bandwidth is limited by the link equation and international regulation
- Concept inseparable from data encoding



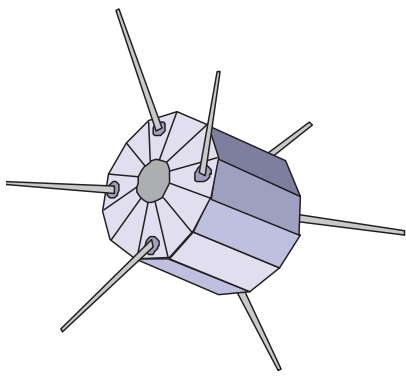
Early Development -- Huffman codes



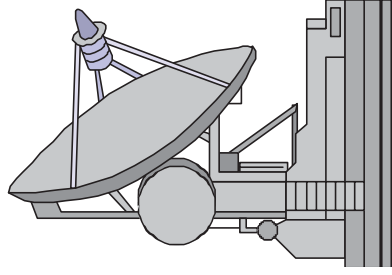
- Assign different number of bits to each possible symbol to minimize total number of bits
 - Example: Encode letters of alphabet
 - 26 symbols, each with equal chance of occurring \Rightarrow 5bits/symbol ($2^5 = 32 =$ lowest power of 2 above 26)
 - If R occurs 50% of time, use fewer bits to encode R.



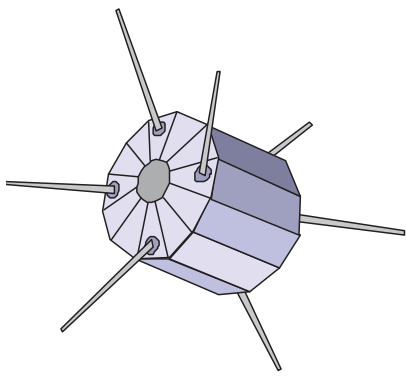
Compression Algorithms



- **Lossless compression**
 - Ensures data recovered is exactly same as original data
 - Used for executable code, numeric data -- cannot tolerate mistakes
- **Lossy compression**
 - Does not promise that data received is the same as data sent
 - Removes information that cannot later be restored
 - Used for still images, video, audio - Data contains more info than human can perceive
 - Data may already contain errors/imperfections
 - Better compression ratios than Lossless (order of magnitude)



When does Compression Pay Off?



- Compression/decompression algorithms involve time-consuming computations
- Compression beneficial when

$$\mathbf{x} / \mathbf{B}_c + \mathbf{x} / (\mathbf{r} \mathbf{B}_n) < \mathbf{x} / \mathbf{B}_n$$

Where B_c = data bandwidth through compressed/decompress process

B_n = network bandwidth for uncompressed data

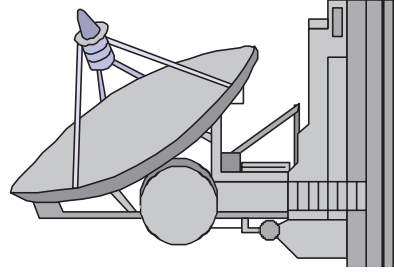
r = average compression ratio

$\mathbf{x} / \mathbf{B}_n$ = time to send \mathbf{x} bytes of uncompressed data

$\mathbf{x} / \mathbf{B}_c + \mathbf{x} / (\mathbf{r} \mathbf{B}_n)$ = time to compress and send

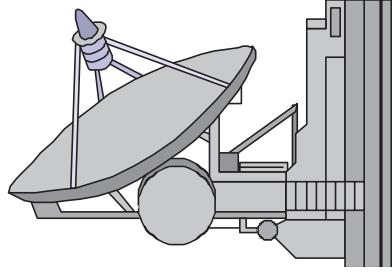
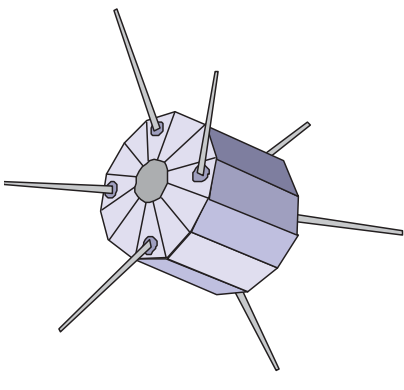
- Simplified:

$$\mathbf{B}_c > + \mathbf{r} / (\mathbf{r} - 1) * \mathbf{B}_n$$

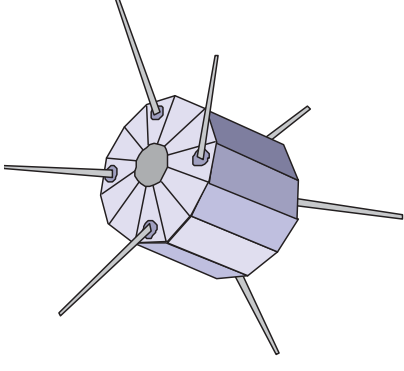


Lossless Compression Algorithms

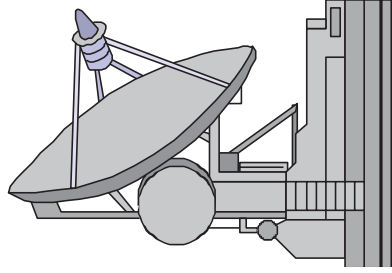
- Run Length Encoding
- Differential Pulse Code Modulation -
DPCM
- Dictionary-Based Methods



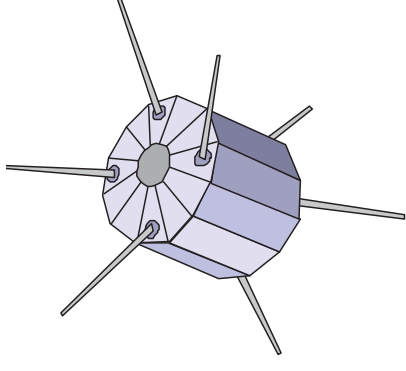
Run Length Encoding



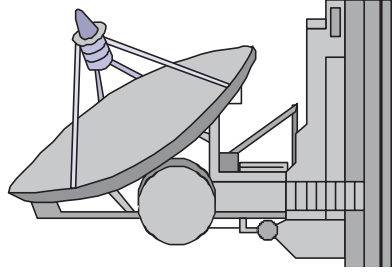
- Replace consecutive occurrences of symbol with 1 copy plus count of how many times symbol occurs:
AAABBCDDDD => 3A2B1C4D
- Can be used to compress digital imagery
 - Compare adjacent pixel values and encode only changes
- Scanned text can achieve 8-to-1 compression due to large white space
- Key compression algorithm used to transmit faxes
- Large homogeneous regions -- effective
- Small degree of local variation increases image byte size
 - 2 bytes represent 1 symbol when not repeated



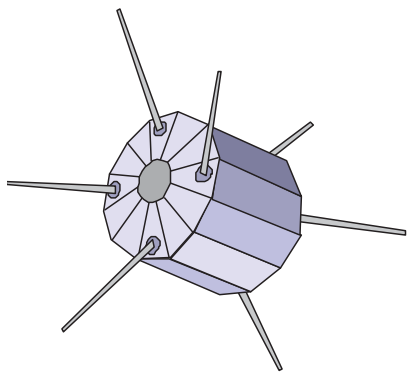
Differential Pulse Code Modulation - DPCM



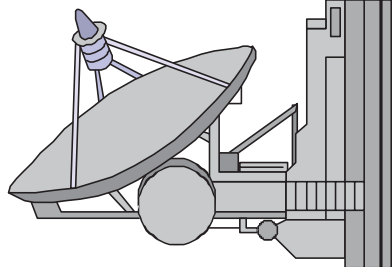
- Represent differences between data
 - Output reference symbol
 - For each symbol in data, output difference between it and reference symbol: AAABBCDDDD -> A0001123333
- When differences are small, encode with fewer bits (2 bits vs 8 bits)
- Takes advantage of fact that adjacent pixels are similar - 1.5-to-1
- **Delta encoding** encodes symbol as difference from previous one: AAABBCDDDD -> A001011000.
- Works well when adjacent pixels are similar
- Can combine delta encoding and RLE



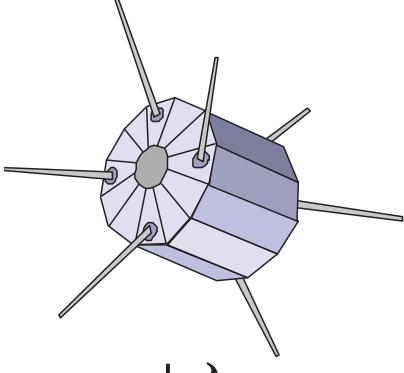
Dictionary-Based Methods



- Lempel-Ziv (LZ) most well known, used by Unix *compress* command
 - Build dictionary of expected data strings
 - Replace strings with index to dictionary
- Example: "compression" (77-bits of 7-bit ASCII) has index 4978 (15 bits) in /usr/share/dict/words -- 5-to-1 compression ratio
- How is the dictionary built?
 - A priori, static, tailored to data
 - Adaptively define based on contents of data. However, dictionary must be sent with data for proper decompression



Graphical Interchange Format (GIF)



- Variation of LZ algorithm used for digital images
 - Reduce 24-bit color to 8-bit-color
 - Store colors in table which can be indexed by an 8-bit number
 - Value for each pixel replaced by appropriate index
 - Run LZ over result and create dictionary by identifying common sequences of pixels
- If picture contains \ll 256 colors, can achieve 10-to-1 compression
- If picture contains $>$ 256 colors, Lossy! (e.g., natural scenes)

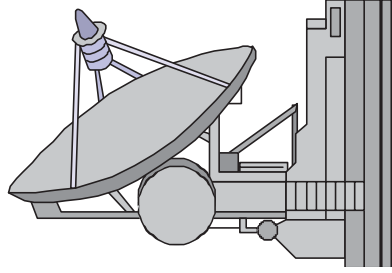
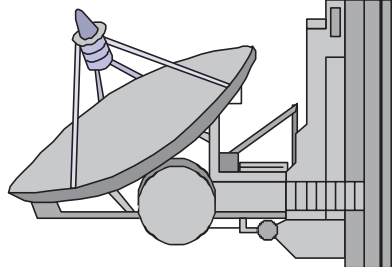
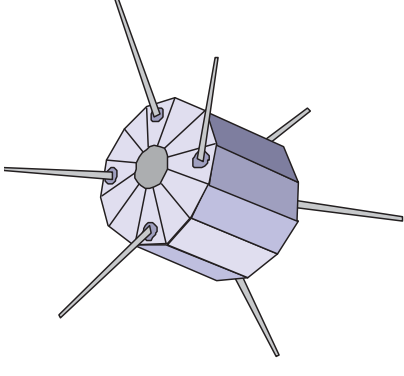


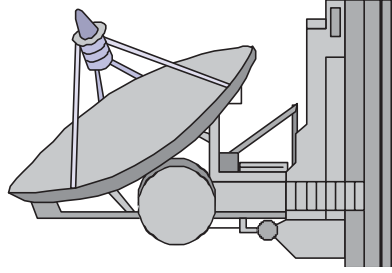
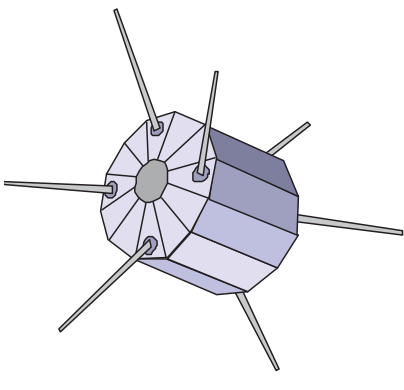
Image Compression

- JPEG (Joint Photographic Experts Group) defines an algorithm and a format
 - Apply discrete cosine transform (DCT) to 8 x 8 block (transform into spatial frequency domain). Lossless.
 - Low frequency = gross features; high frequency = detail
 - Quantize result, losing least significant info. Lossy
 - Encode result - RLE applied to coefficients. Lossless.



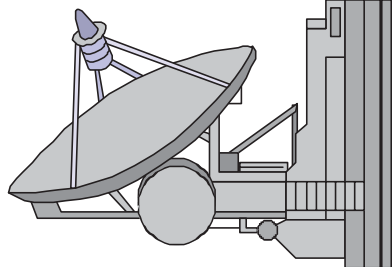
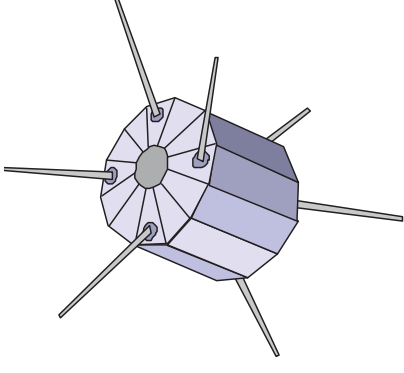
Color Images

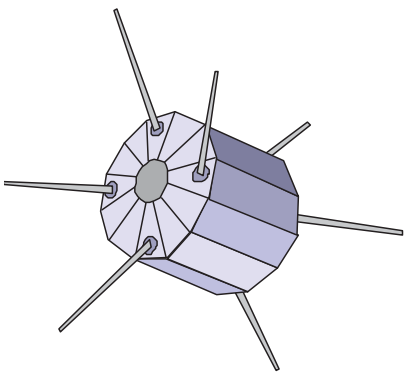
- Three components used to represent each pixel - 3D
 - RGB - red, green, blue
 - YUV - luminance (Y) and two chrominance (U and V)
- To compress, each component is processed independently
- Three components used to represent each pixel - 3D
- JPEG can also compress multi-spectral images
- Compress 24-bit color images by 30-to-1 ratio
 - 24 bits -> 8 bits (GIF) gives 3-to-1
 - 3D JPEG compression gives 10-to-1



Video Compression

- Moving Picture Experts Group (MPEG)
- Succession of still images displayed at video rate
 - Each frame compressed using DCT technique (JPEG)
 - Interframe redundancy
- Typically, can achieve 90-to-1 ratio; 150-to-1 possible
- Involves expensive computation, typically done offline.





References

- Wertz, James R. and Wiley J.Larson, Space Mission Analysis and Design, Microcosm Press, El Segundo CA 1999, pg 533-586
- Morgan and Gordon, Communication Satellite Handbook, 1989
- Peterson and Davie, on reserve in Barker Library
- <http://www-isl.stanford.edu/people/gray/fundcom.pdf>

