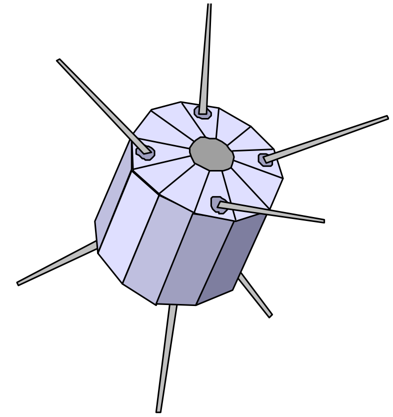
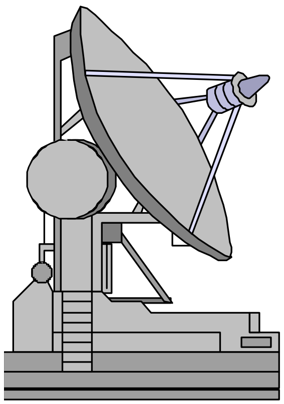
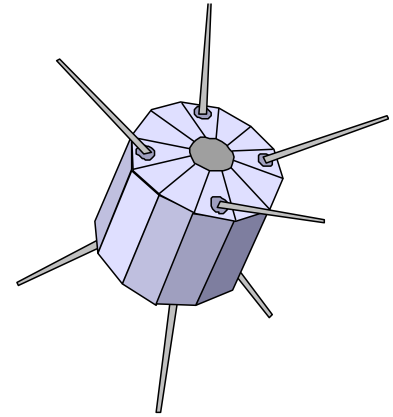


Satellite Communication

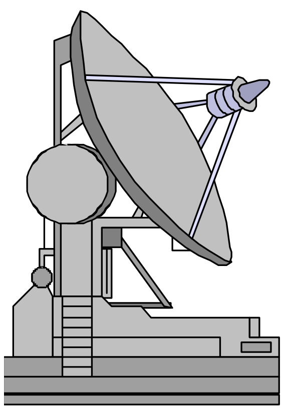


Col John Keesee

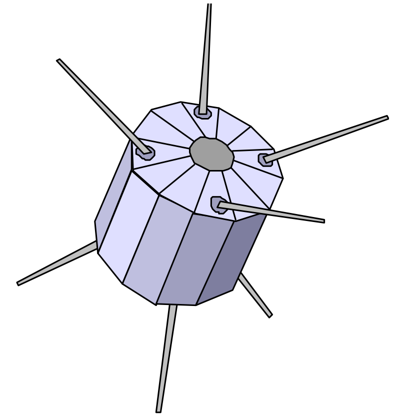
Satellite Communications Architecture



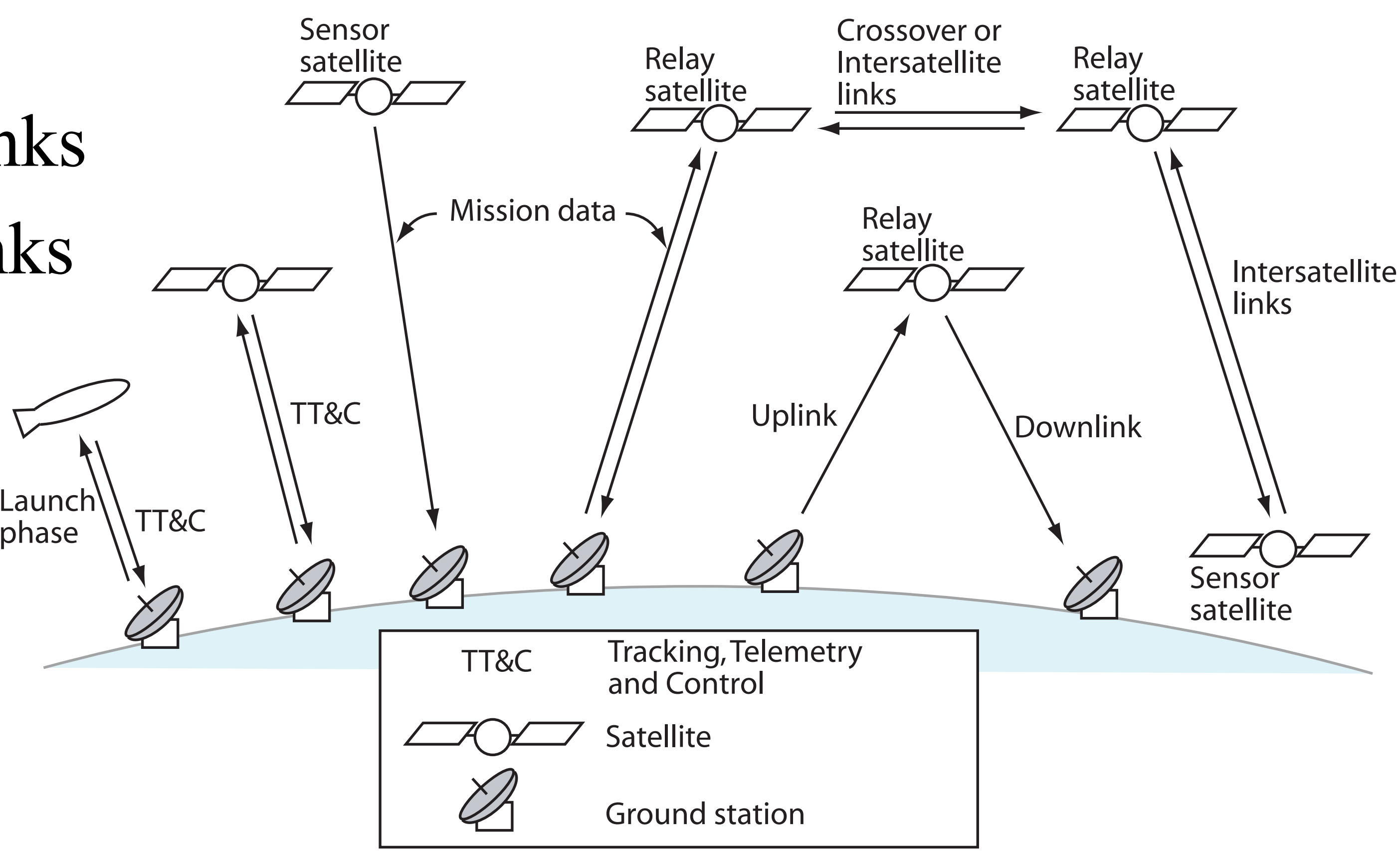
- Identify Requirements
- Specify Architectures
- Determine Link Data Rates
- Design & Size each link
- Document your rationale



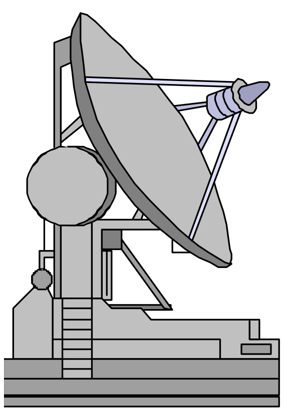
Definition



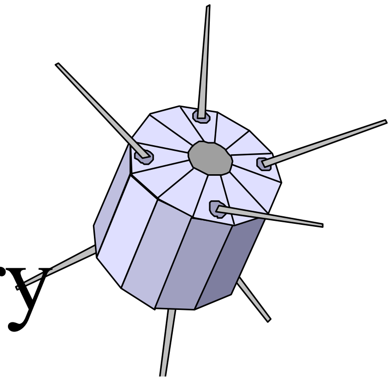
- Uplinks
- Downlinks
- Crosslinks
- Relays
- TT & C



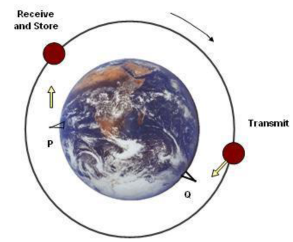
The communications architecture consists of satellites and ground stations interconnected with communications links. (Adapted from SMAD.)



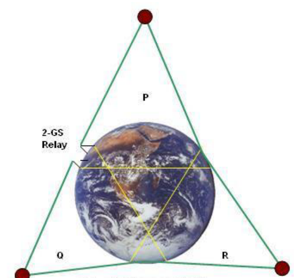
Architectures:
Defined by Satellite-Ground Geometry



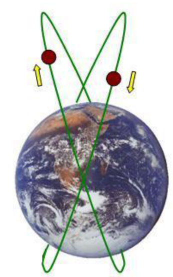
- Store & Forward
- Geostationary
- Molniya
- Geostationary/ Crosslink
- LEO/ Crosslink



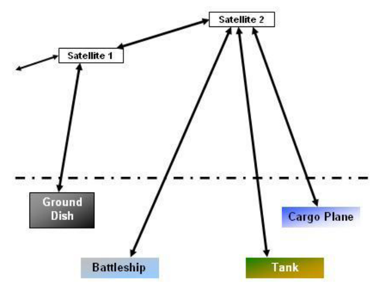
Store and Forward



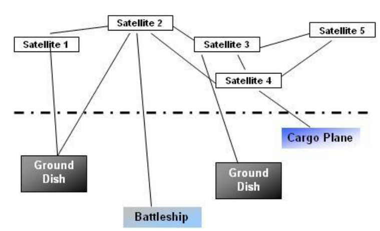
Geostationary Orbit



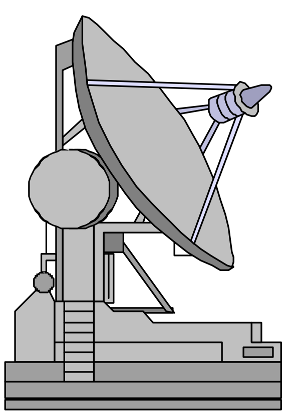
Molniya Orbit



Crosslink in Communication Satellite System

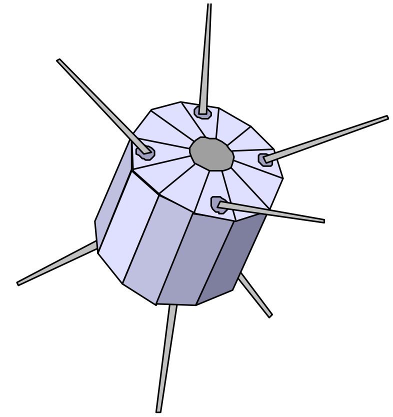


Low-altitude, Crosslinked Comsat Network

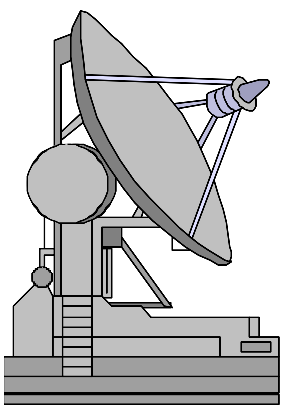


Adapted from SMAD.

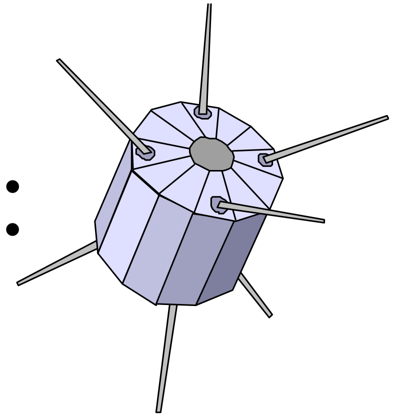
Architectures:
Defined by Function



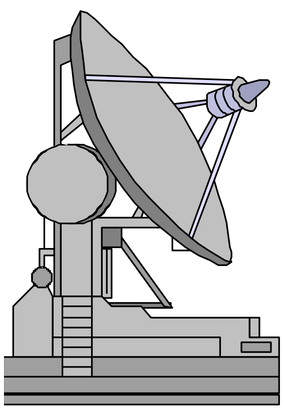
- System Function
  - Tracking Telemetry & Command
  - Data Collection
  - Data Relay
- Satellite Design
  - Onboard Processing
  - Autonomous Satellite Control
  - Network Management



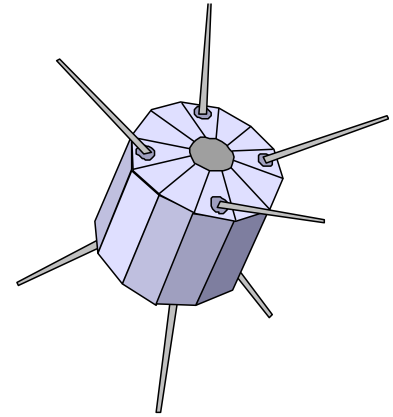
Communications Architecture:
Selection Criteria



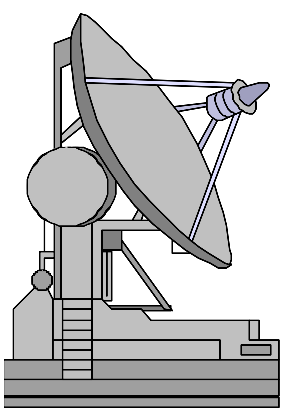
- Orbit
- RF Spectrum
- Data Rate
- Duty Factor
- Link Availability
- Link Access Time
- Threat



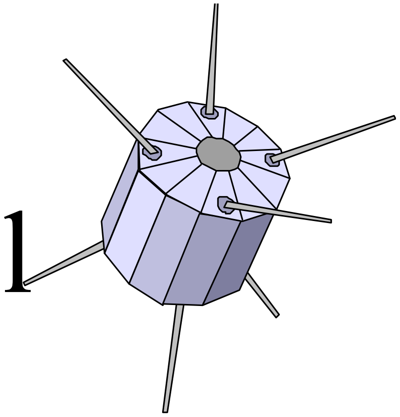
Advantages of Digital Communication



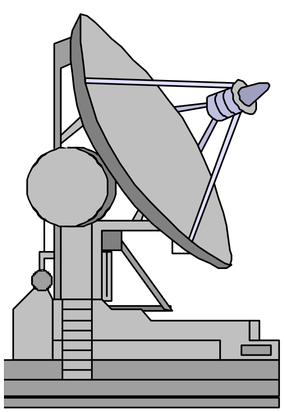
- Less distortion and interference
- Easy to regenerate
- Low error rates
- Multiple streams can be easily multiplexed into a single stream
- Security
- Drift free, miniature, low power hardware



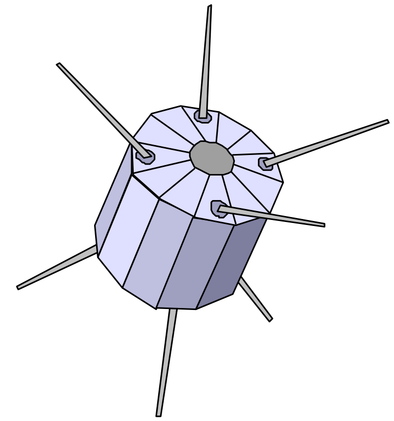
Tracking Telemetry & Control

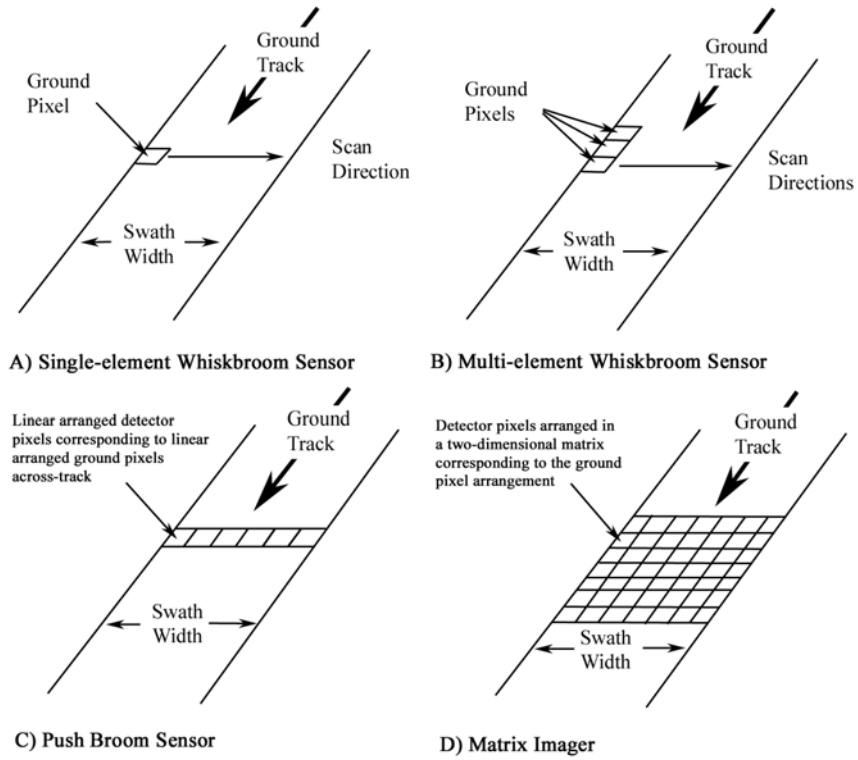


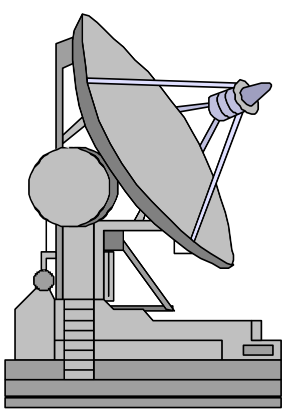
- Telemetry
  - Voltages, currents, temperatures, accelerations, valve and relay states
- Commanding
  - Low data rate
  - Store, verify, execute or execute on time
  - Programmable control
- Range or Range Rate
  - Round trip delay yields range
  - Doppler shift yields range rate
  - Pseudo-random code
- 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







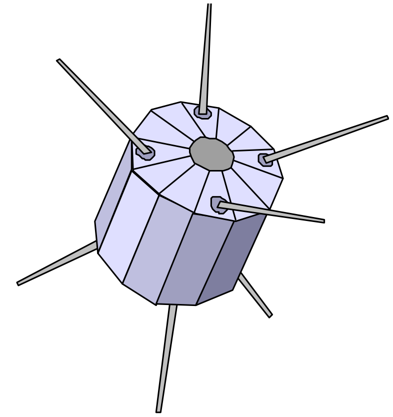
$$DR(pushbroom) = \frac{Sw}{X} * \frac{Vn}{Y} * b$$

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

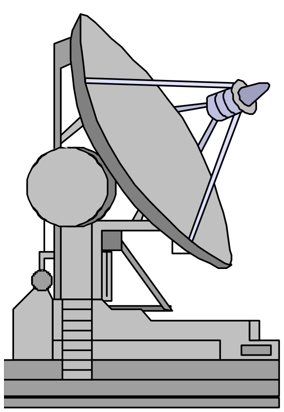
Adapted from SMAD.

Variable Definitions

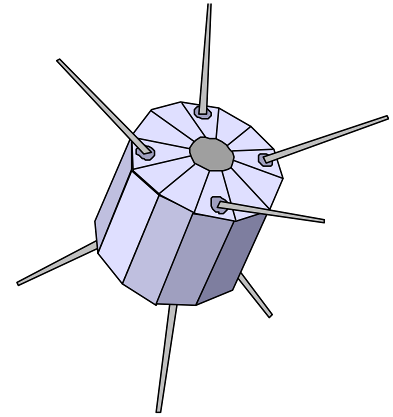
Chart 9



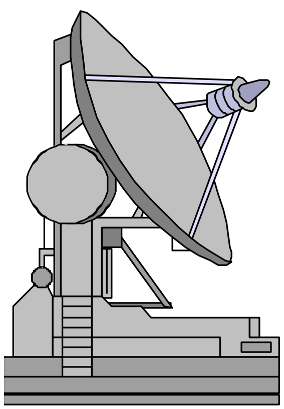
Variable	**Definition**	**Units**
DR	Data Rate	Bits/second
SW	Swath Width	Meters
X	Across track pixel dimension	Meters
Vn	Ground track velocity	Meters/second
Y	Along track pixel dimension	Meters
b	Bits/pixel	Bits



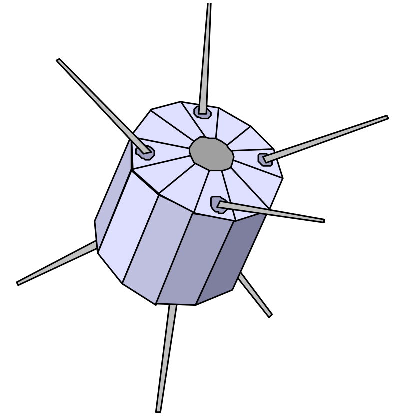
Reducing the Data Rate



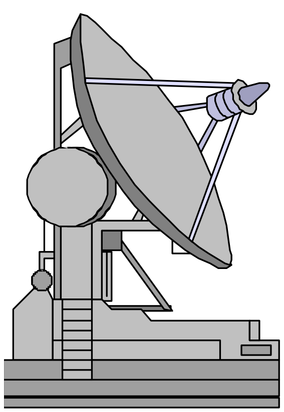
- Increase the Duty Cycle
- Collect only above-threshold data
- Amplitude changes only
- Data compression



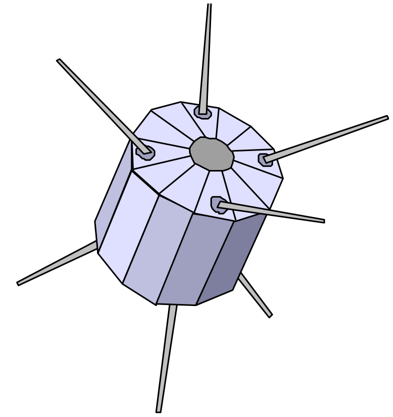
Link Design Process



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

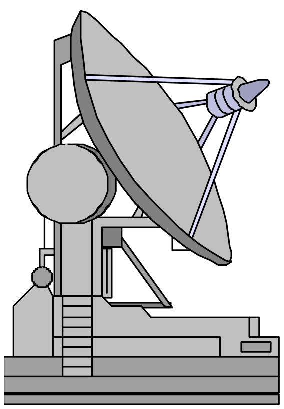


Link Equation



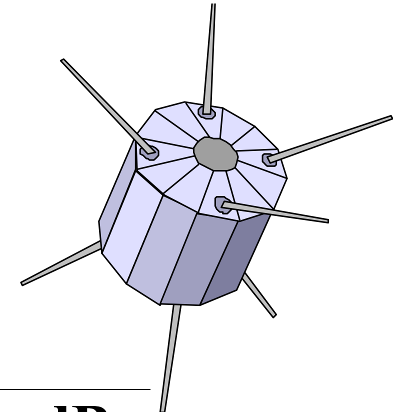
$$\frac{E_b}{N_o} = \frac{P\, L_l\, G_t\, L_s\, L_a\, G_r}{k\, T_s\, R}$$

Energy/bit to noise-density ratio

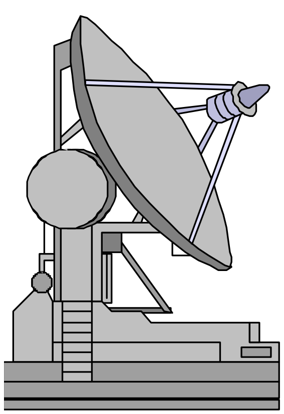


Variable Definitions

Chart 12

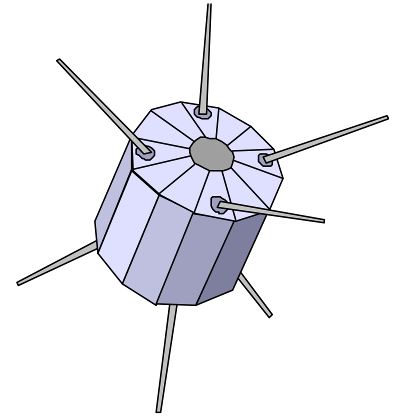


Variable	**Definition**	**Units**	**Units dB**
E_b	Energy per bit	Watt-seconds	dB
N_o	Noise spectral density	Watts/hertz	dB
P	Transmitter power	Watts	dBW
L_l	Line loss		dB
G_t	Transmitter antenna gain		db
L_s	Space loss		DB

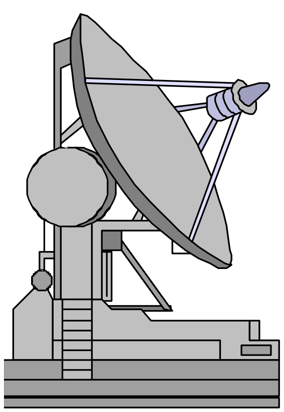


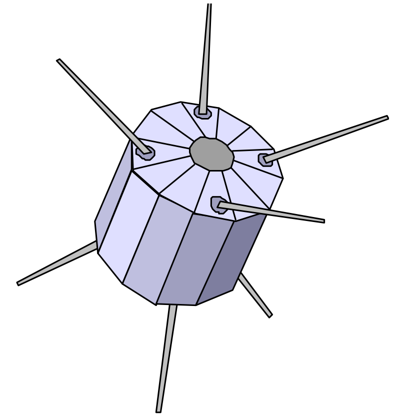
Variable Definitions

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	

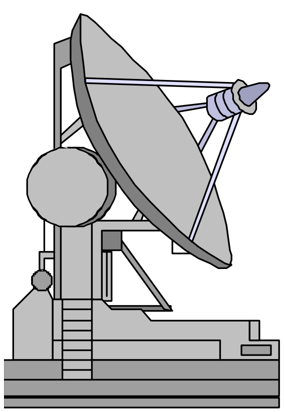


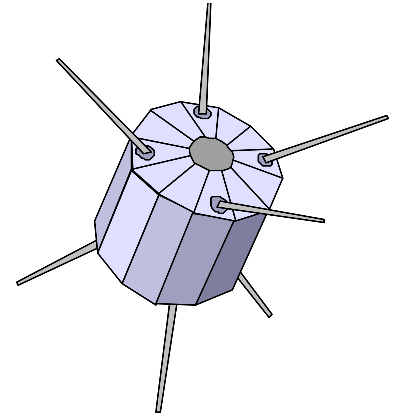


Power Flux Density

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

EIRP - Effective Isotropic Radiated Power

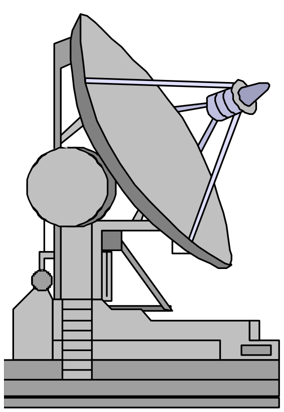


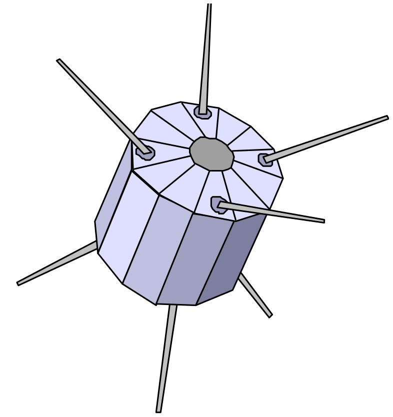


Variable Definitions

for Chart 16

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



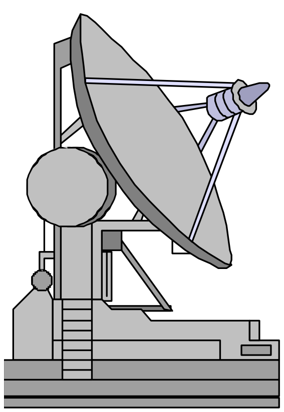


Received Power

$$C = Wf \cdot \frac{\pi Dr^2 \eta}{4} = \frac{PL_l G_t L_a Dr^2 \eta}{16S^2}$$

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

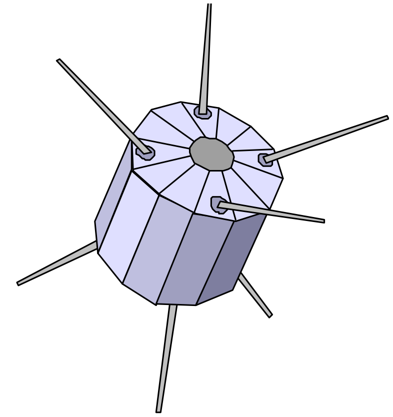
Space Loss $\quad L_s = \left(\frac{\lambda}{4\pi S}\right)^2$



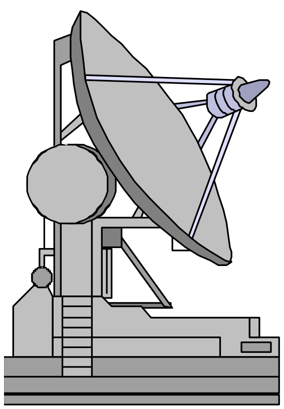
$$C = EIRP * L_s * L_a * G_r$$

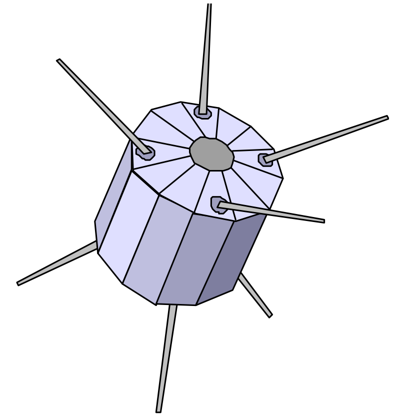
Variable Definitions

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

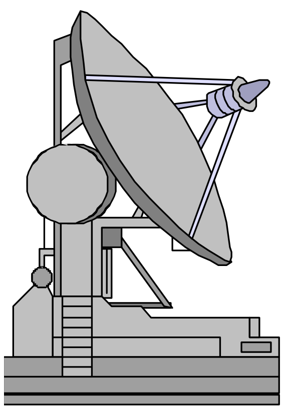
$$E_b = \text{energy/bit} = \frac{C}{R}$$

N_o = noise spectral density

N = total received noise power

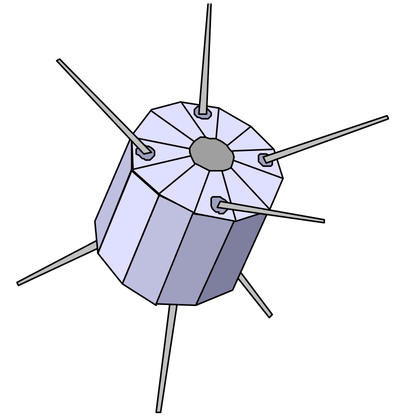
B = receiver noise bandwidth

$$N_o = k\,T_s = N / B$$



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

Link Equation in dB

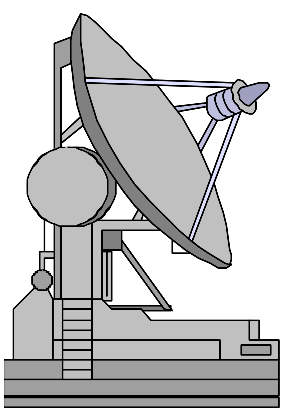


$$\frac{E_b}{N_o} = P + L_l + G_t + L_s + L_a + G_r + 228.6 - 10\log T_s - 10\log R$$

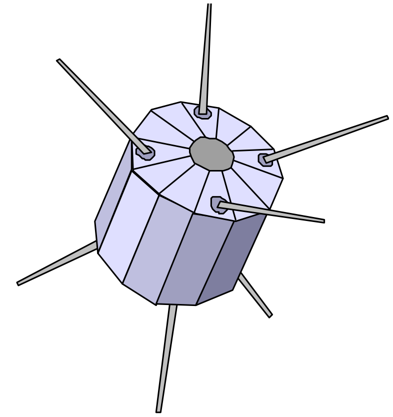
$$= EIRP + L_s + L_a + G_r + 228.6 - 10\log T_s - 10\log R$$

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

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



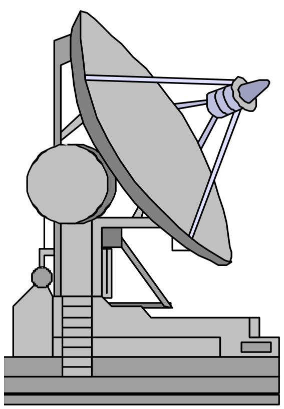
$$RIP = \frac{E_b}{N_o} - \frac{G_r}{T_s} - 228.6 + 10\log R$$ (Received isentropic power)



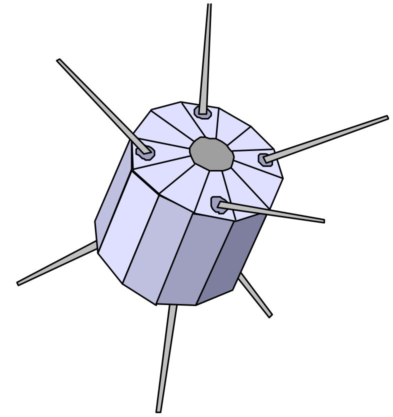
Gain in dB

$$G_r = \frac{\pi^2 D_r^{\,2} \eta}{\lambda^2} \qquad\qquad f = \frac{c}{\lambda}$$

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



Beamwidth



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

θ [degrees]

f [GHz]

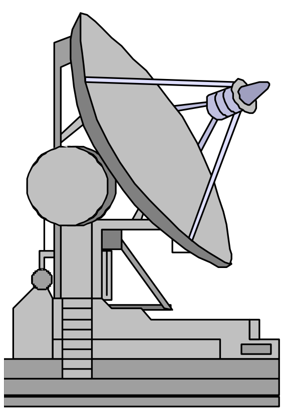
D [m]

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

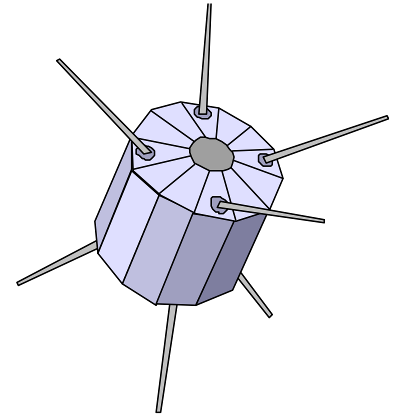
Antenna gain

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

Offset beam loss

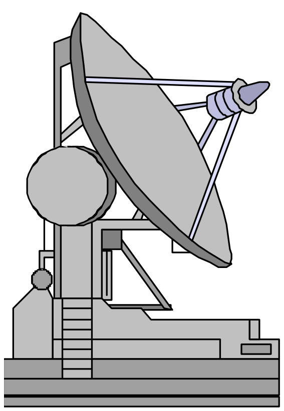


Space loss in dB

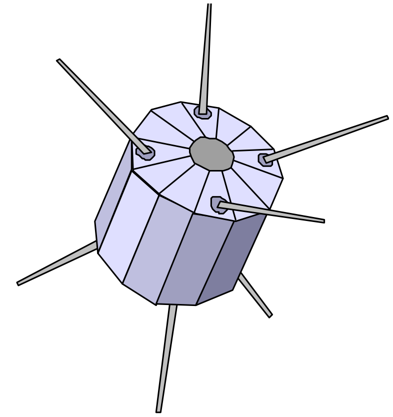


$$L_s = \left(\frac{\lambda}{4\pi S} \right)^2 \quad \text{(ratio)}$$

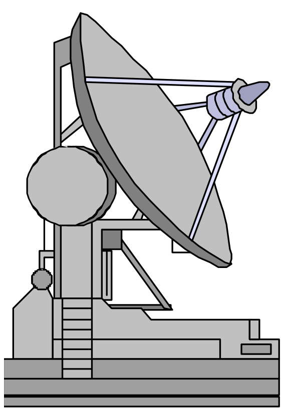
$$L_s = 147.55 - 20\log S - 20\log f \quad \text{(dB)}$$



System Noise Temperature - External to Antenna

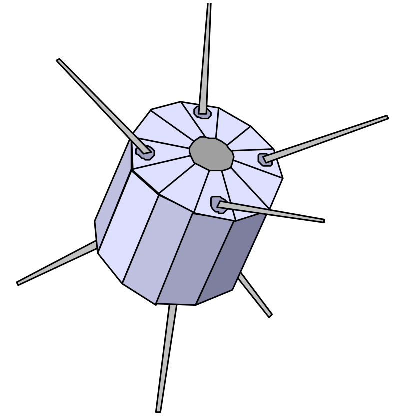


- Galactic noise
- Clouds, rain in path
- Solar noise (in mainbeam or sidelobe)
- Earth (290K)
- Man-made noise
- Nearby objects
- Satellite structure



(See SMAD Fig 13-7)

System Noise Temperature - Internal to System



- Transmission lines and filters

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

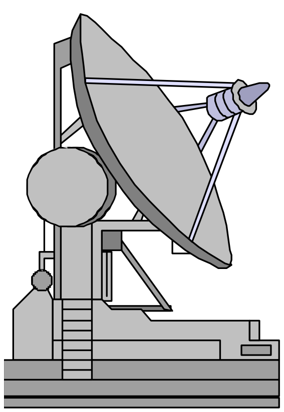
$$L = \frac{P_o}{P_i}$$

- Low noise amplifier

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

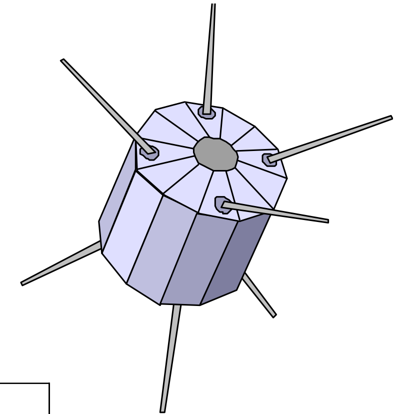
$$T_s = T_{ant} + T_o\left(\frac{1 - L_r}{L_r}\right) + T_o\left(\frac{F - 1}{L_r}\right)$$

F is a figure of merit for a receiver

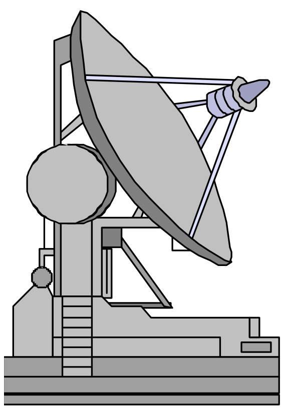


Variable Definitions

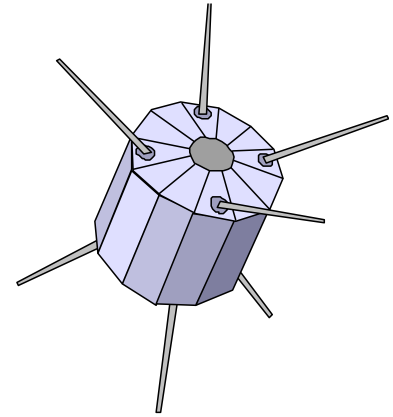
Chart 21



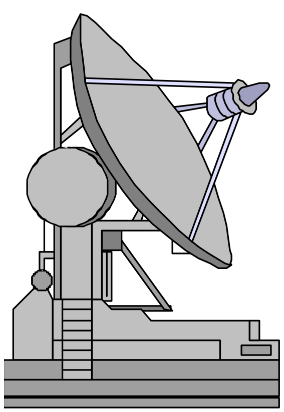
Variable	Definition	Units
T_r	Receiver noise temperature	K
L	Power ratio	
T	Component temperature	K
P_o	Output power	W
P_I	Input power	W
F	Noise figure	
T_o	Reference temperature (usually 290 K)	K



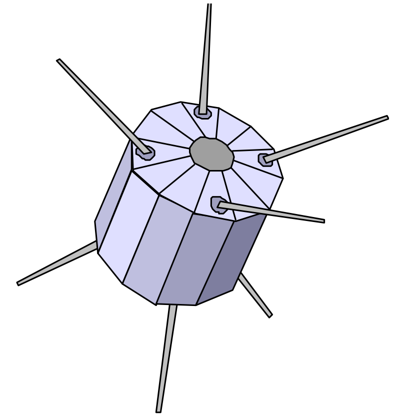
Modulation



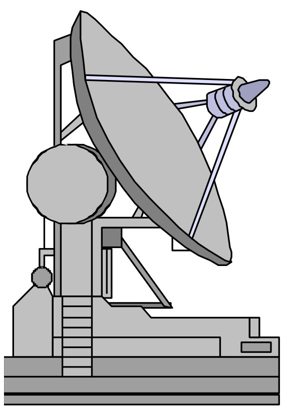
- Modulation modifies an RF Carrier signal so that it contains input signal information
  - Amplitude
  - Frequency
  - Phase
  - Polarization



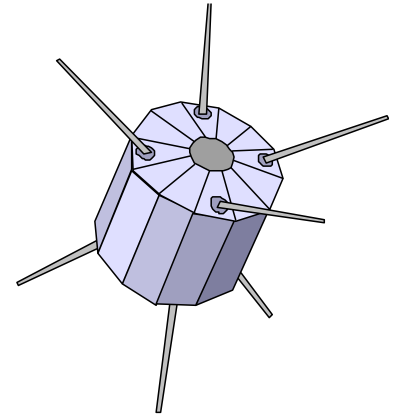
Modulation Techniques



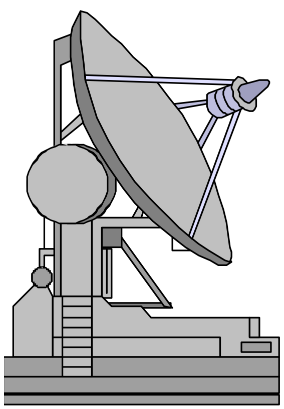
- BPSK - Binary Phase Shift Keying
- QPSK - Quadriphased Phase Shift Keying
- FSK - Frequency Shift Keying
- MFSK - Multiple FSK
- DPSK - Differential Shift Keying



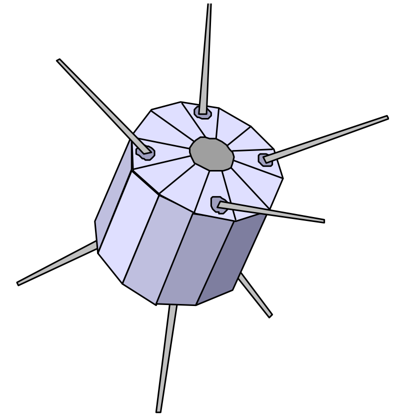
Bit Error Rate



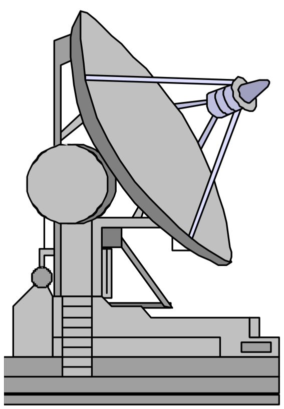
- Primary Figure of Merit for Digital Link Performance
- Energy/bit (Eb) must exceed the noise spectral density (N_o) to achieve a required BER



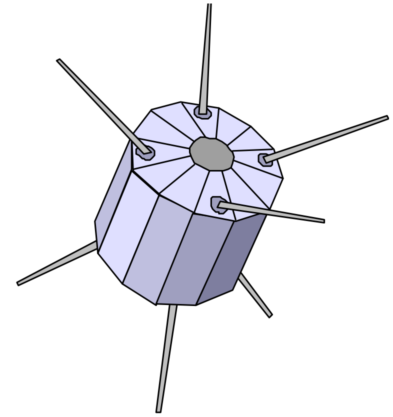
Coding



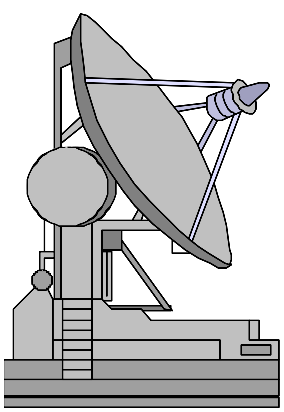
- Forward Error Correction sends additional data to help detect and correct errors.
  - Reduces the Eb/No requirement
  - Reduces required transmitter power
  - Reduces antenna size
  - Increases margin
  - Increases data rate and bandwidth



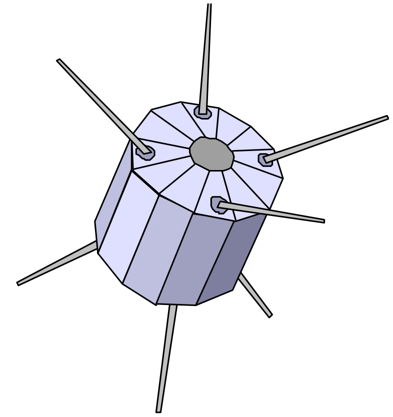
Convolutional Coding with Viterbi Decoding



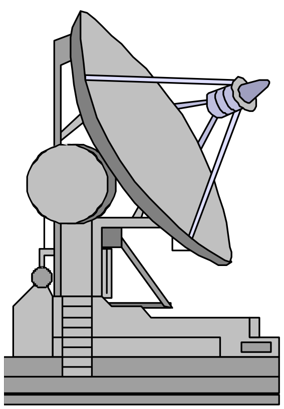
- Extra bits sent with each block of data bits
- Receiver examines string of bits, generates possible code sequences, selects most likely
- Shannon limit E_b/N_o = -1.6 dB
- Double coding necessary on deep space probes



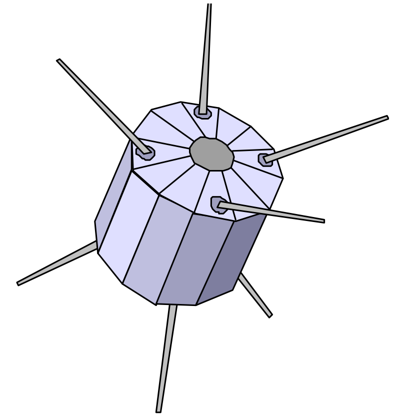
Attenuation



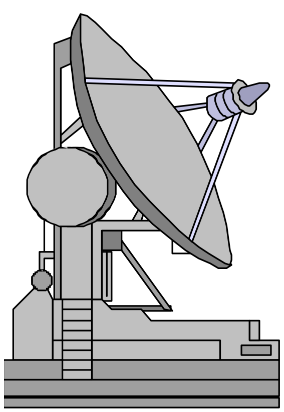
- Atmosphere absorbs some frequencies
- Divide zenith attenuation by sin(elevation angle)
- Oxygen absorption at 60 GHz
- Scintillation disrupts below 200 MHz



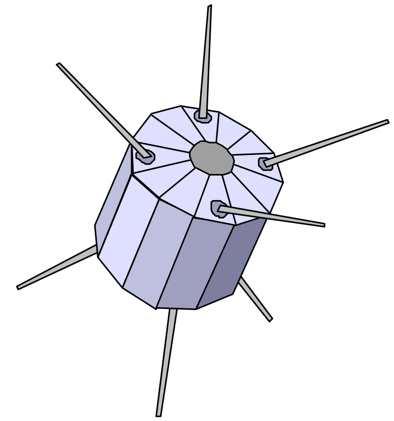
Rain and Cloud Attenuation

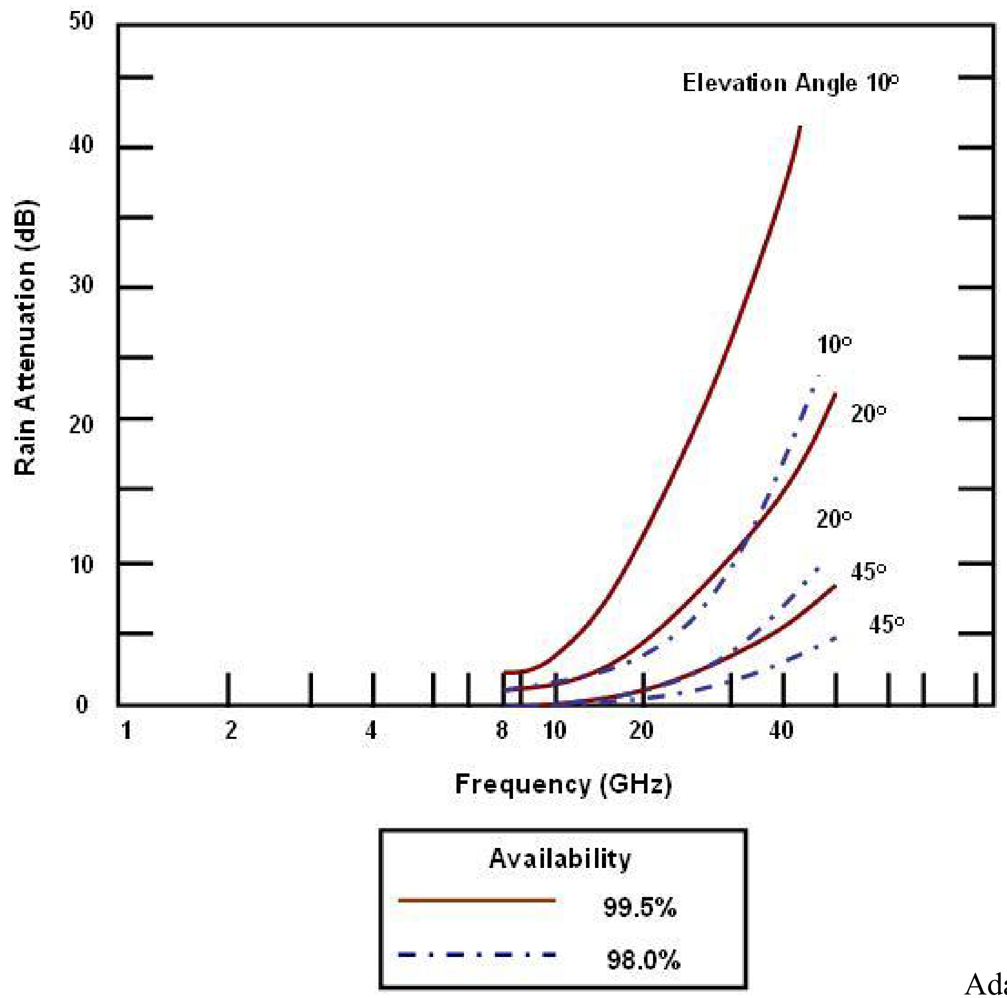


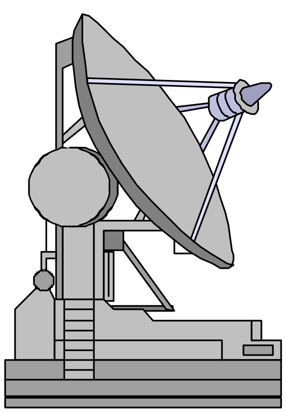
- Crane model for world's climatic data
- Important above 10 GHz
- Worst for elevation angles < 20 degrees
- Rain reduces availability



Rain and Cloud Attenuation

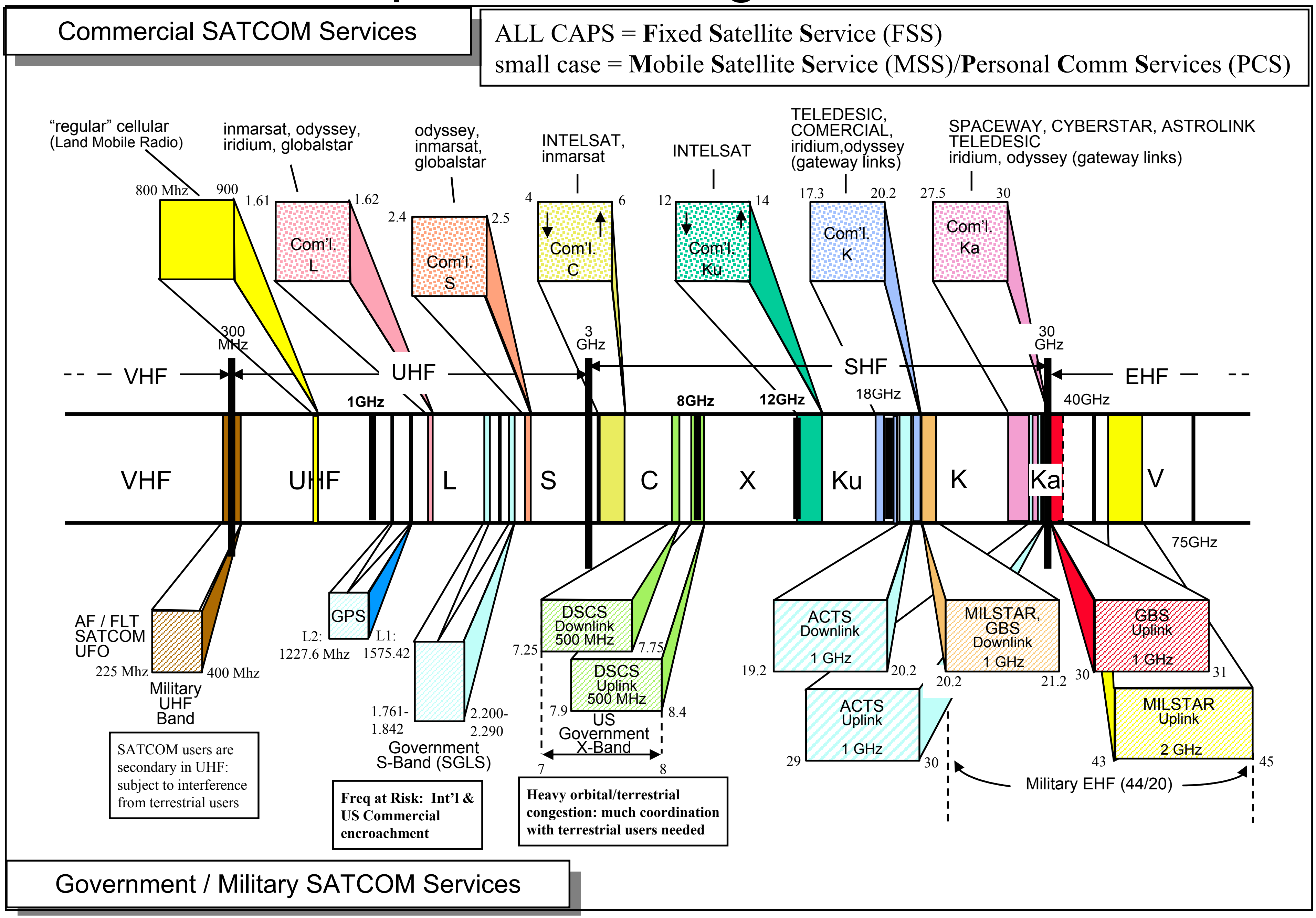




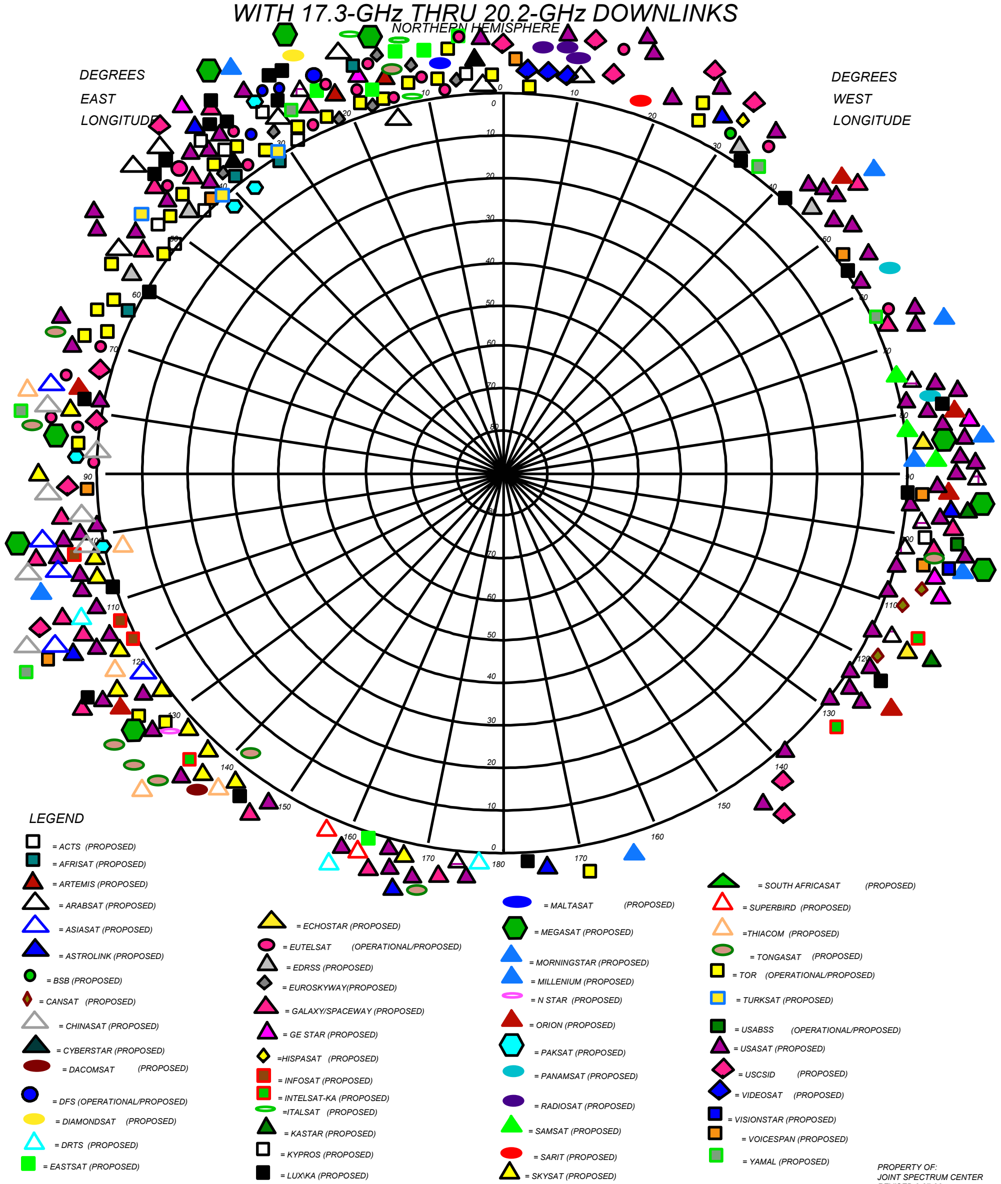


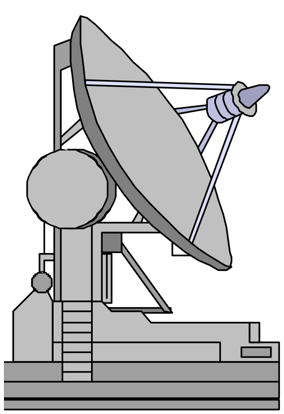
Adapted from SMAD.

SATCOM Frequencies Usage



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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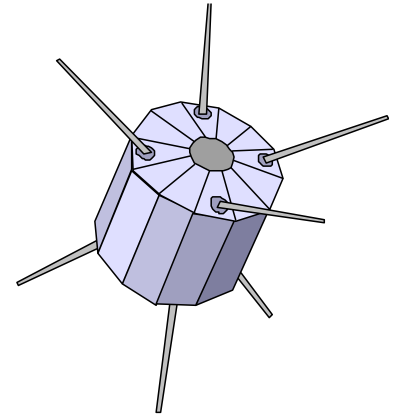
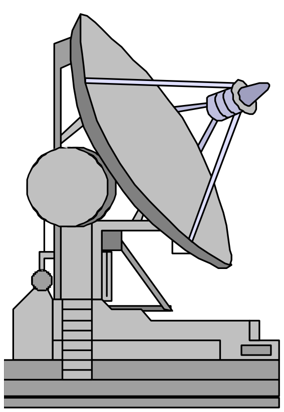
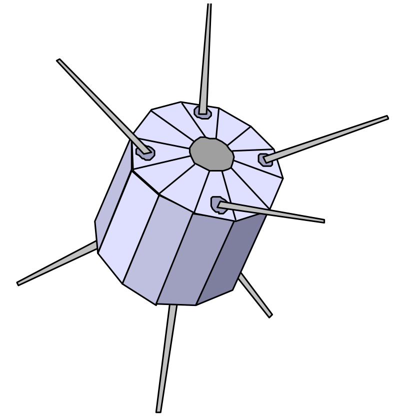
Frequency Selection Drivers



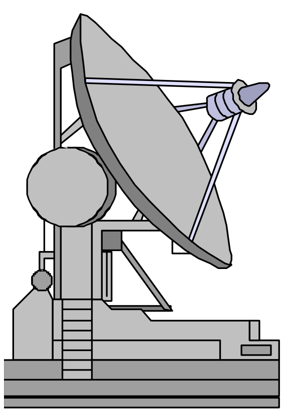
- Spectrum availability and FCC allocation
- Relay/Ground Station frequency
- Antenna size
- Atmospheric/Rain attenuation
- Noise temperature
- Modulation and coding



Communication Payload Antennas

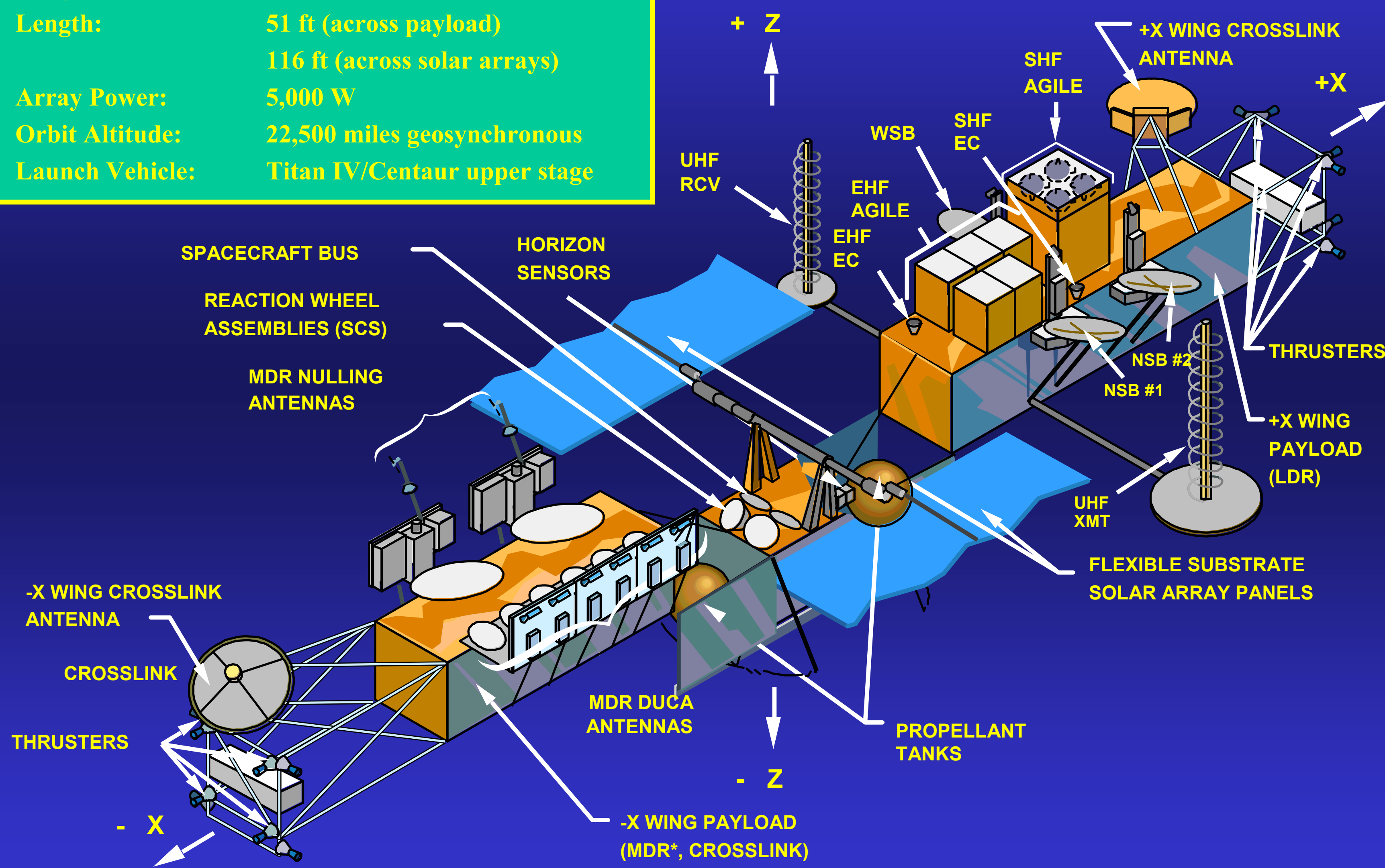


- Parabolic
- Helix
- Horn
- Phased Arrays
  - Multiple beams
  - Hopping beams



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



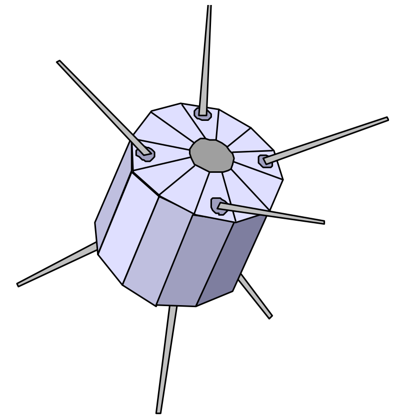
(Image removed due to copyright considerations.)

- **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

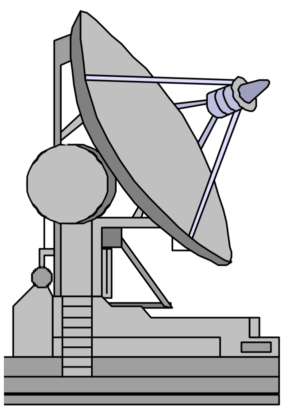
(Image removed due to copyright considerations.)

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

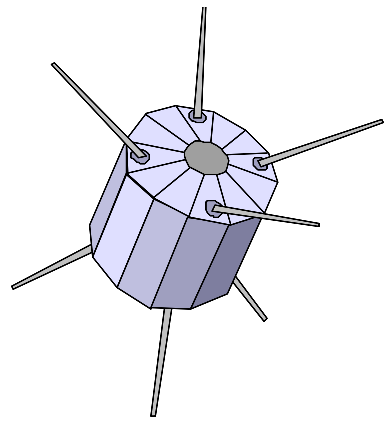
Multiple Access Strategies



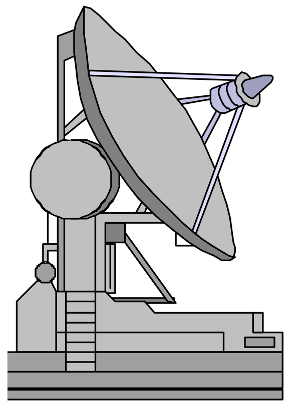
- FDMA - Frequency Division Multiple Access
- TDMA - Time Division Multiple Access
- CDMA - Code Division Multiple Access
  - Phase Modulation plus pseudo-random noise



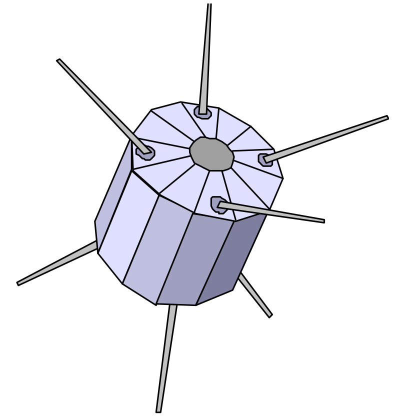
Antijam Techniques



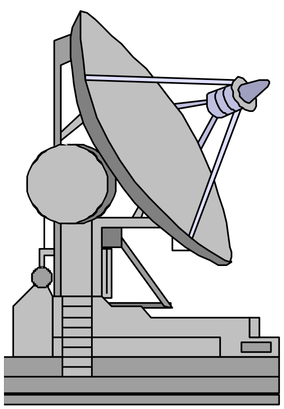
- Spread Spectrum
- Narrow beamwidths
- On board processing
- Nulling antennas



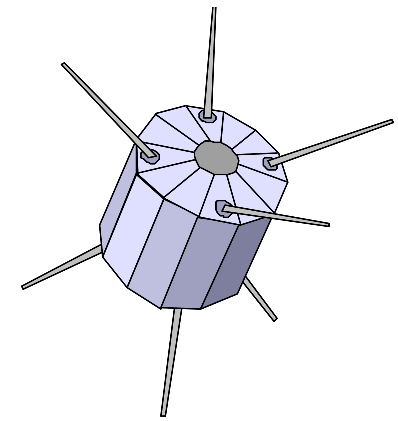
Special Topics



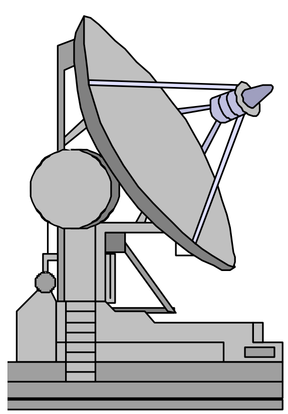
- Data security through encryption
- Spatial, time and satellite diversity
- Frequency hopping
- Interleaving



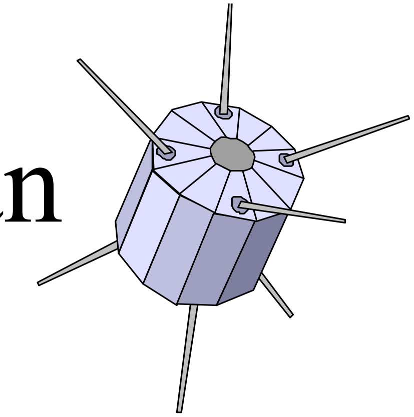
Why Compress Data



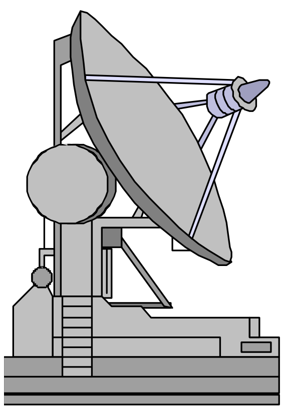
- Need to send more data than bandwidth accommodates
  - Digital image files in particular are very large
- Bandwidth is limited by the link equation and international regulation
- Concept inseparable from data encoding



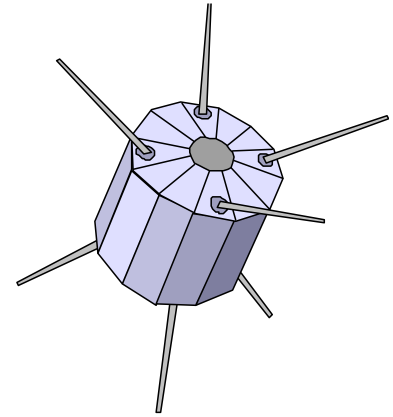
Early Development -- Huffman codes



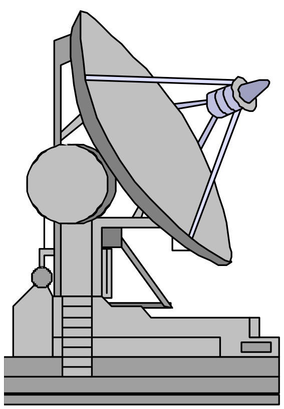
- Assign different number of bits to each possible symbol to minimize total number of bits
  - Example: Encode letters of alphabet
  - 26 symbols, each with equal chance of occurring => 5bits/symbol ($2^5 = 32$ = lowest power of 2 above 26)
  - If R occurs 50% of time, use fewer bits to encode R.



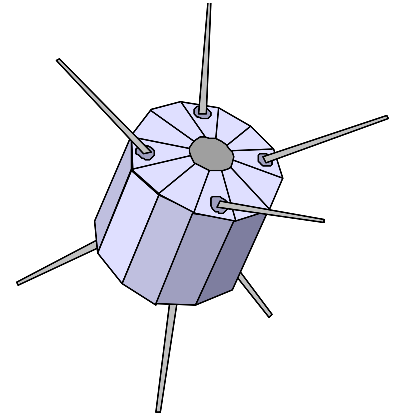
Compression Algorithms



- 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

$$\mathbf{x / B_c + x / (r\ B_n) < x / B_n}$$

Where B_c = data bandwidth through compress/decompressprocess

B_n = network bandwidth for uncompressed data

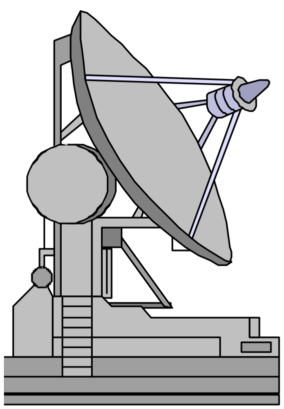
r = average compression ratio

x / B_n = time to send x bytes of uncompressed data

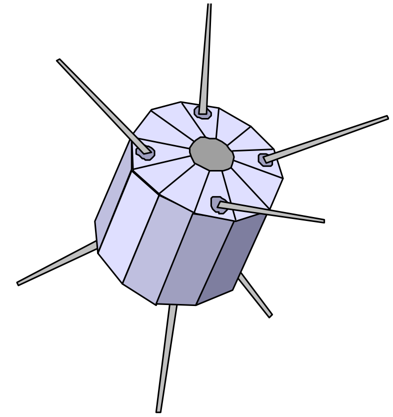
$x / B_c + x / (rB_n)$ = time to compress and send

- Simplified:

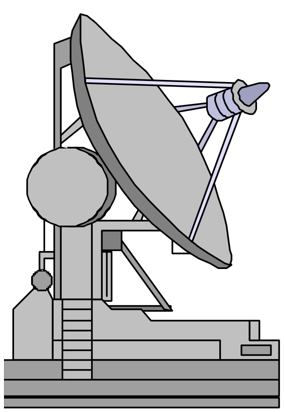
$$B_c > + r / (r - 1) \ * B_n$$



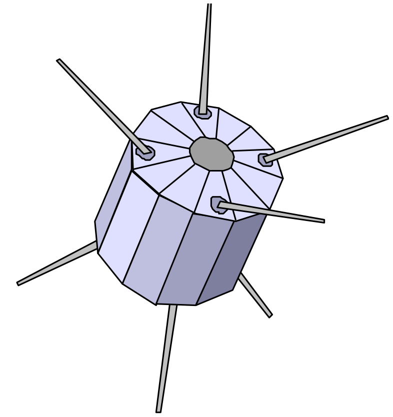
Lossless Compression Algorithms



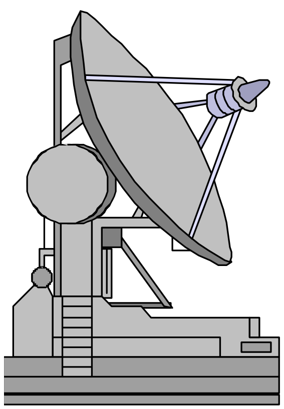
- Run Length Encoding
- Differential Pulse Code Modulation - DPCM
- Dictionary-Based Methods

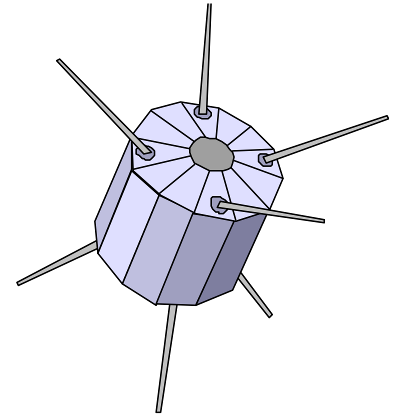


Run Length Encoding



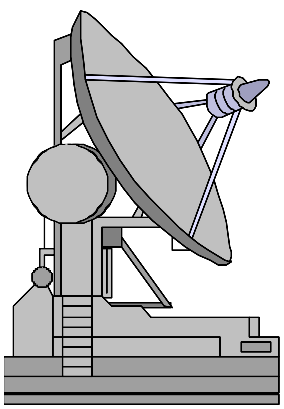
- Replace consecutive occurrences of symbol with 1 copy plus count of how many times symbol occurs:
  AAABBCDDDD => 3A2B1C4D
- Can be used to compress digital imagery
  - Compare adjacent pixel values and encode only changes
- Scanned text can achieve 8-to-1 compression due to large white space
- Key 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



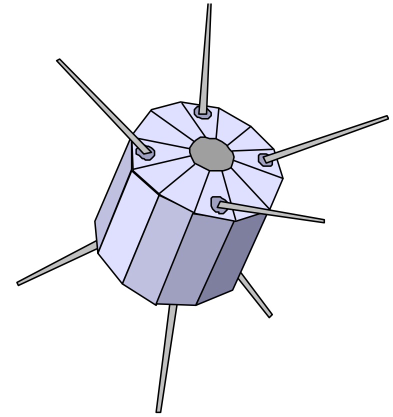


Differential Pulse Code Modulation - DPCM

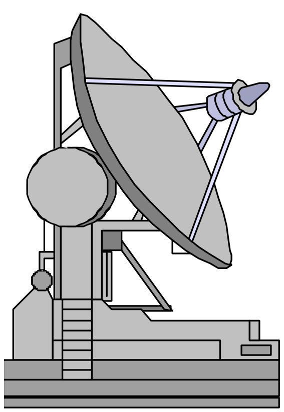
- Represent differences between data
  - Output reference symbol
  - For each symbol in data, output difference between it and reference symbol: AAABBCDDDD -> A0001123333
- When differences are small, encode with fewer bits (2 bits vs 8 bits)
- Takes advantage of fact that adjacent pixels are similar - 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



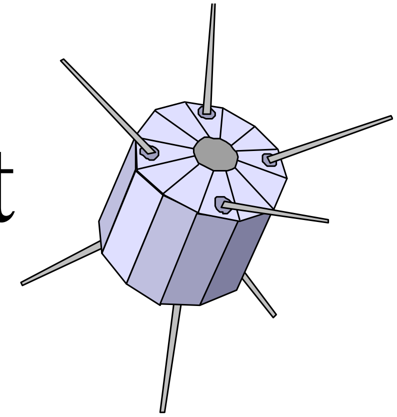
Dictionary-Based Methods



- 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 << 256 colors, can achieve 10-to-1 compression
- If picture contains > 256 colors, Lossy! (e.g., natural scenes)

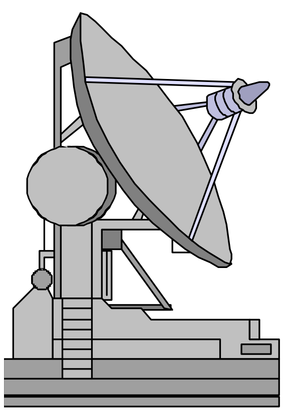
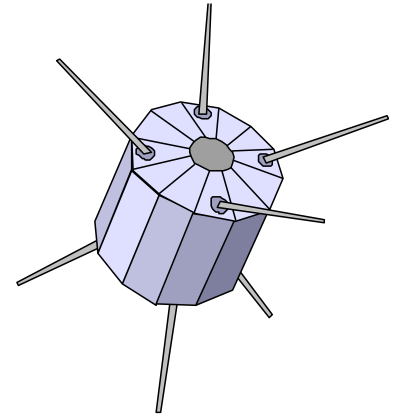
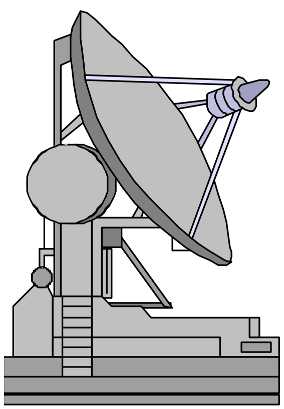


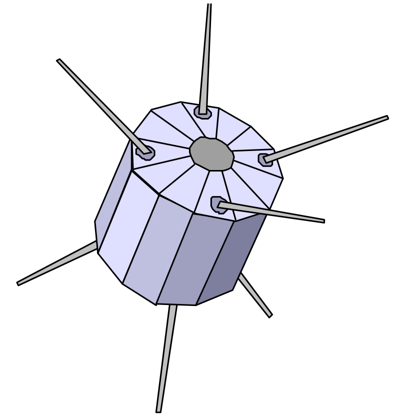
Image Compression



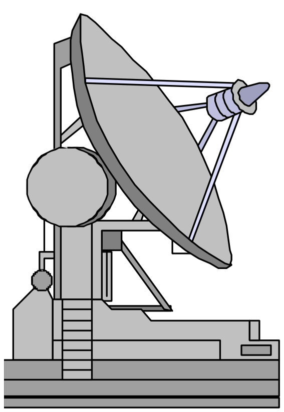
- JPEG (Joint Photographic Experts Group) defines an algorithm and a format
  - Apply discrete cosine transform (DCT) to 8 x 8 block (transform into spatial frequency domain). Lossless.
  - Low frequency = gross features; high frequency = detail
  - Quantize result, losing least significant info. Lossy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



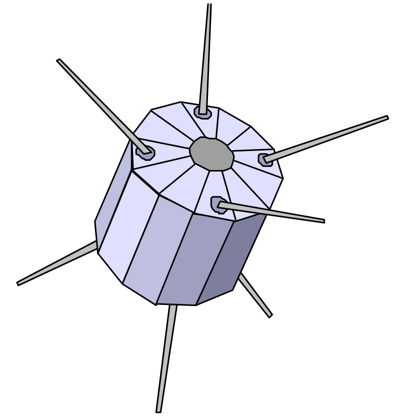
Color Images



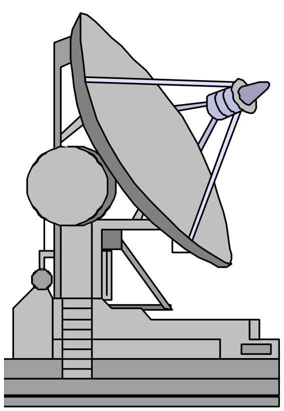
- Three components used to represent each pixel - 3D
  – RGB - red, green, blue
  – YUV - luminance (Y) and two chrominance (U and V)
- To compress, each component is processed independently
- Three components used to represent each pixel - 3D
- JPEG can also compress multi-spectral images
- Compress 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



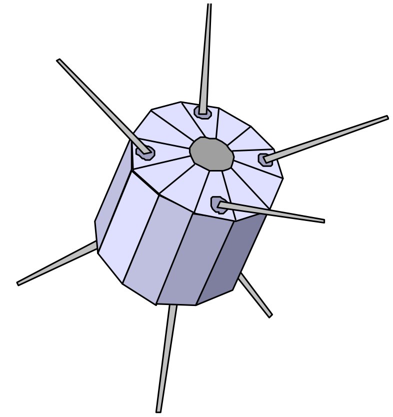
Video Compression



- 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



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