Spacecraft Communications

- Lecture #25 - November 28, 2023
- Antennas
- Orbits
- Modulation
- Noise
- Link Budgets

Decibels

- Parameters range across many orders of magnitude (~10^{18} – 10^{-23})
- In the olden days, tended to lose precision with multiplications
- To make life easier, convert everything to dB

$$dB = 10 \log_{10} X$$

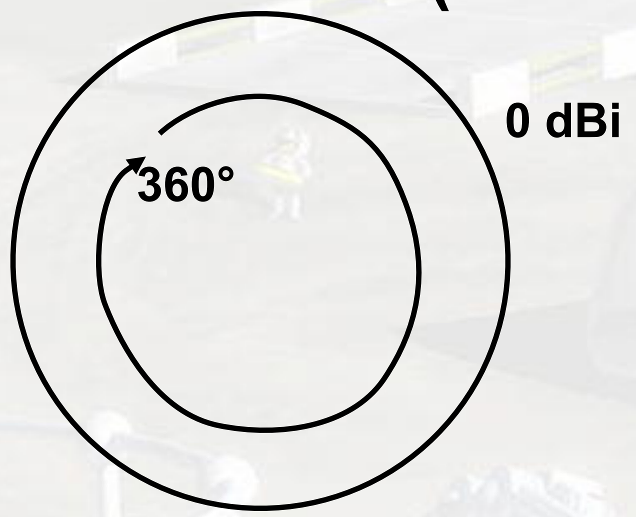
- Doubling of value = 3 dB
- Can have dB(units) – dBW, dBm, etc.
- Calculate link budgets by adding dB rather than multiplying base values

Antennas

- Receive & transmit RF (radio frequency) energy
- Size/type selected directly related to frequency/required gain

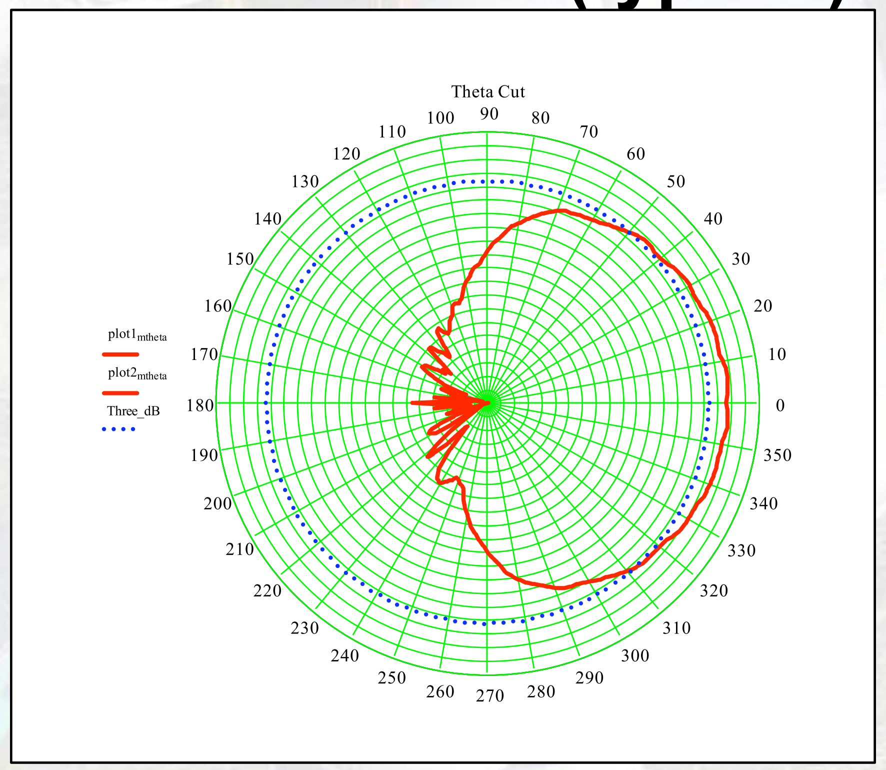
Gain Pattern

Omni Antenna (idealized)

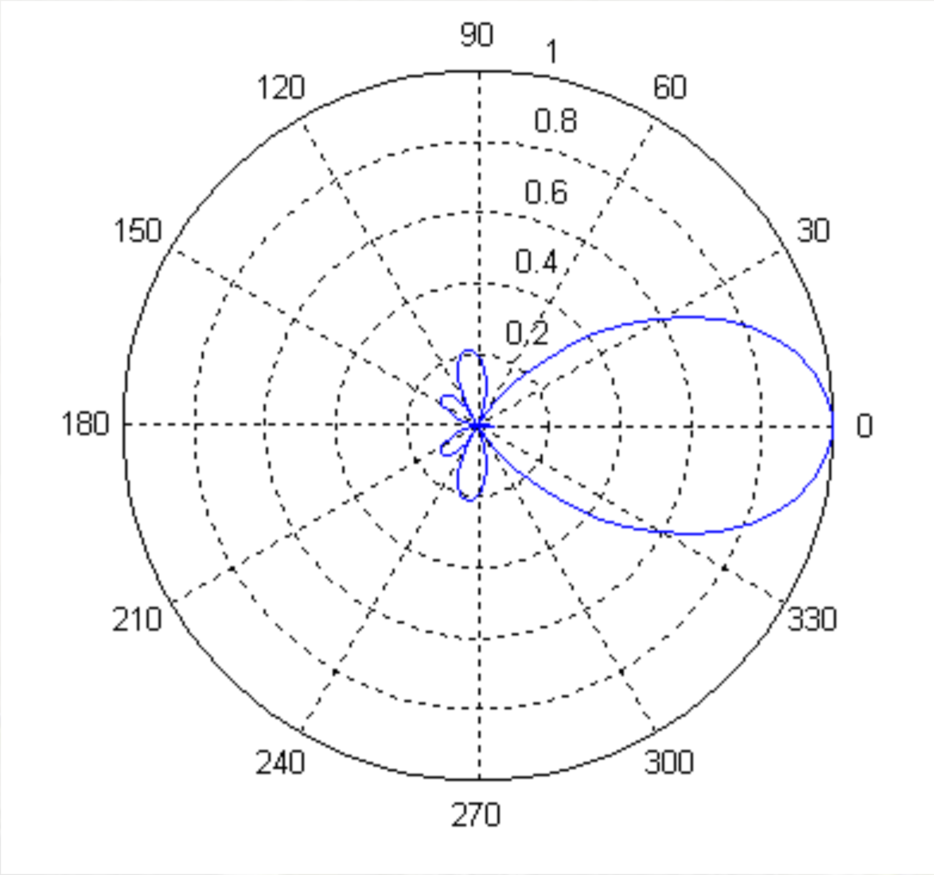


Isotropic antenna

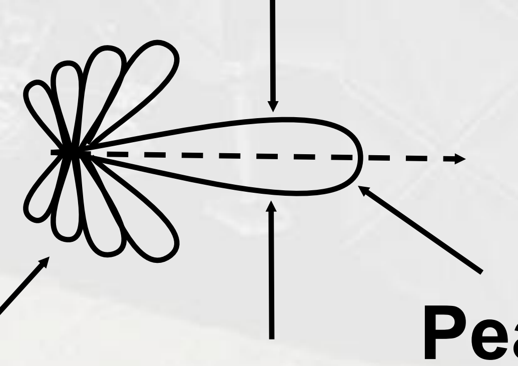
Omni Antenna (typical)



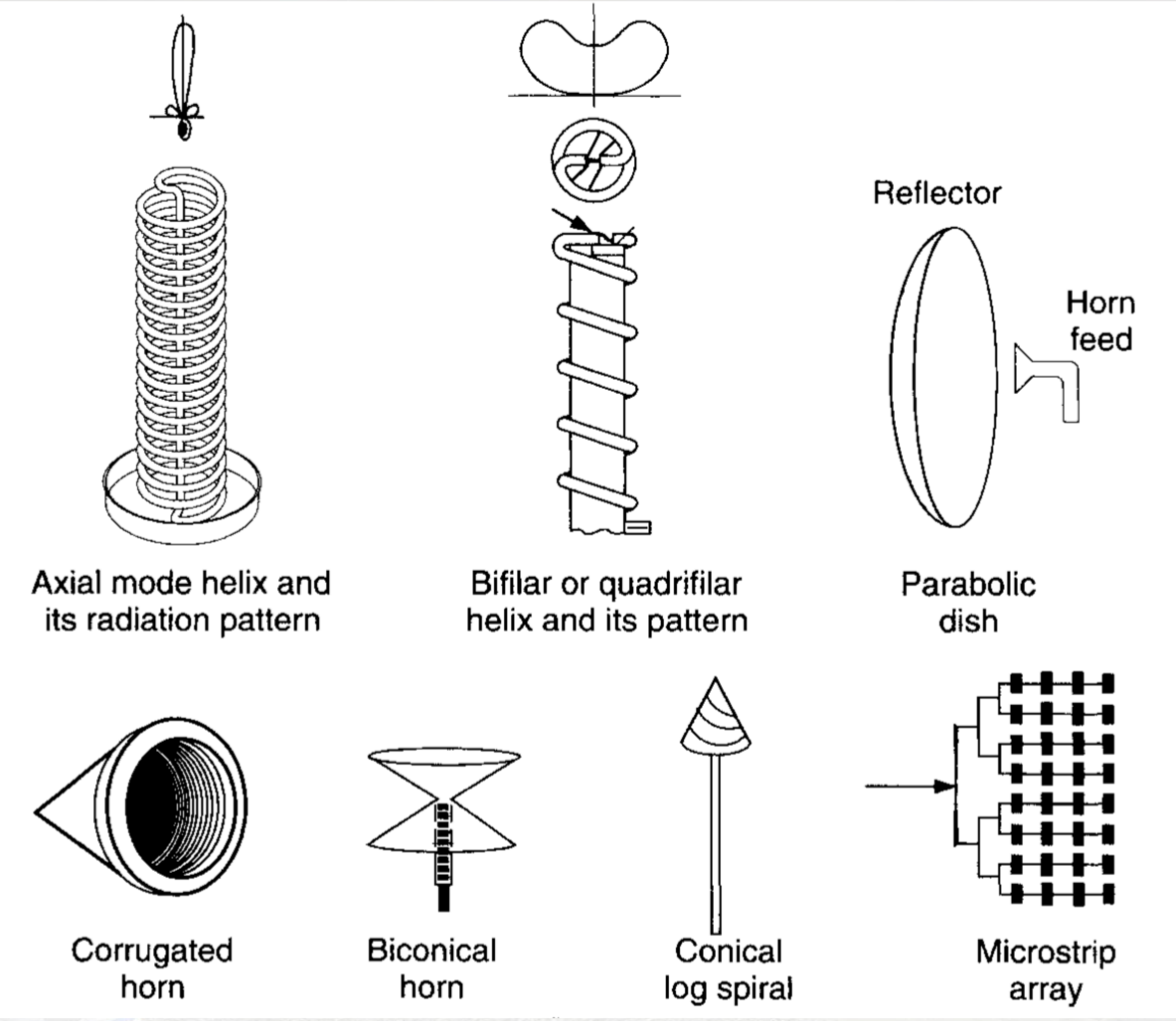
Directional (Hi-Gain) Antenna



Gain is relative to isotropic with units of dBi



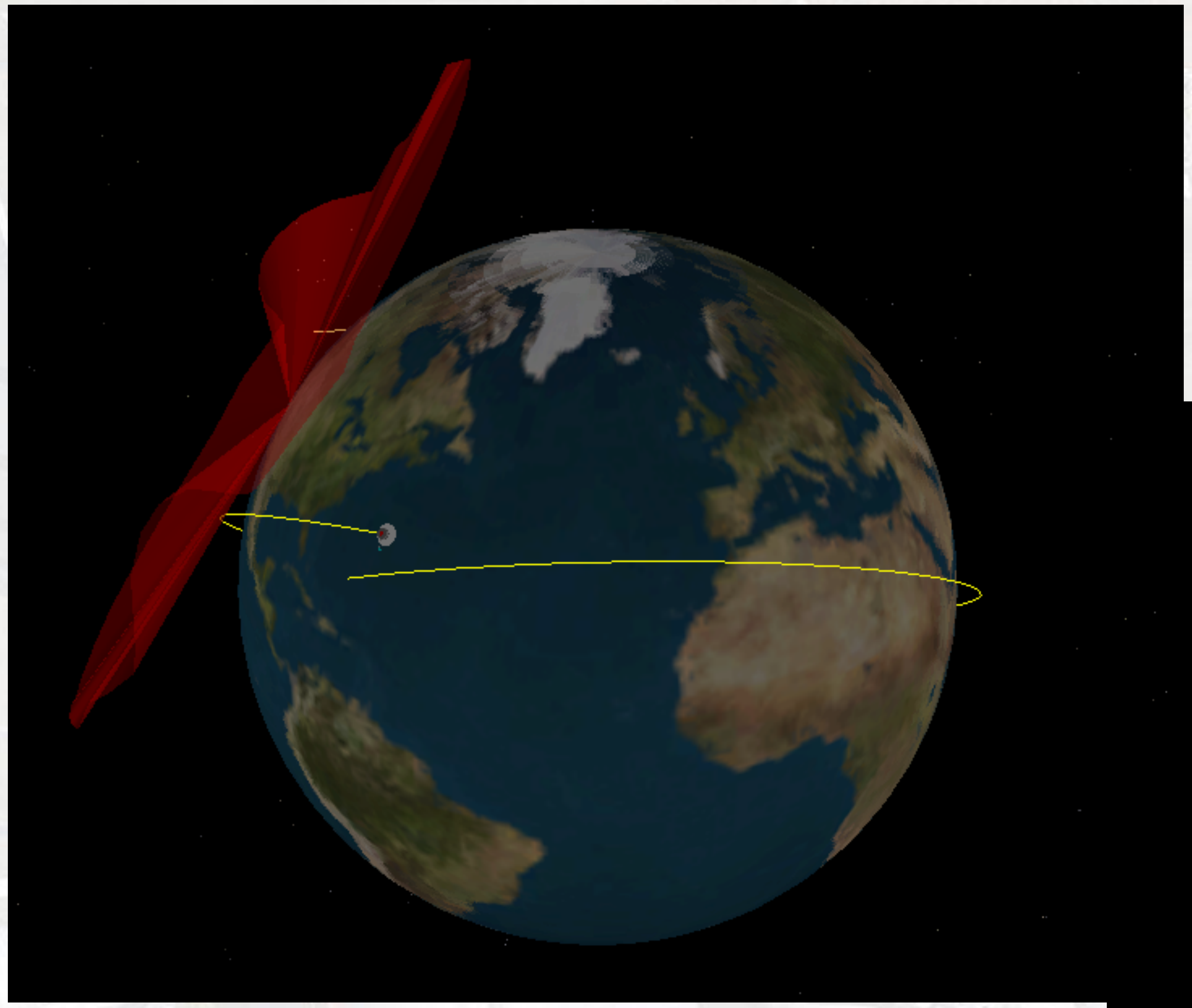
Representative Antenna Types

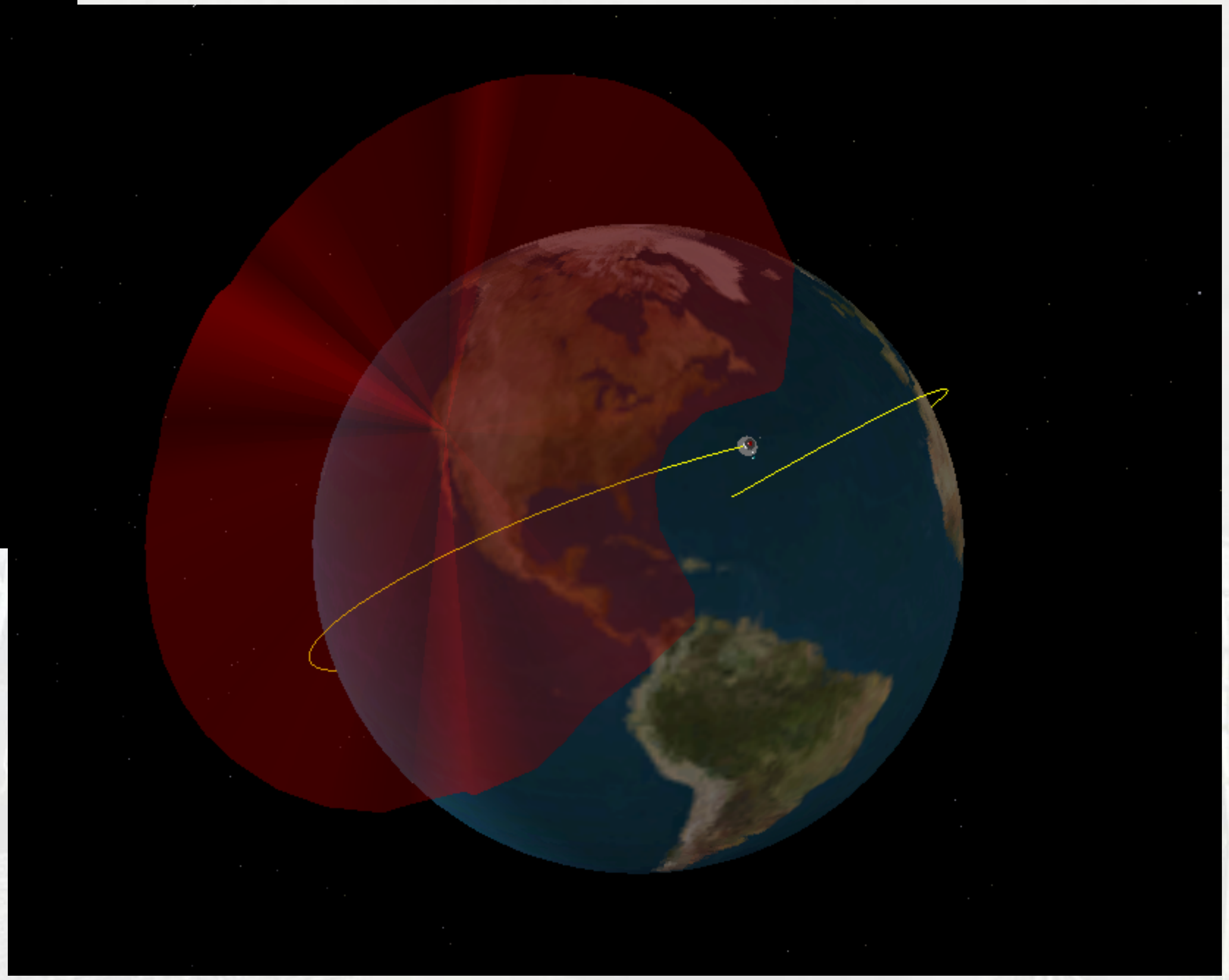


from Pisacane, Fundamentals of Space Systems, 2nd ed., Oxford Univ. Press, 2005

Orbit Considerations – Line of Sight

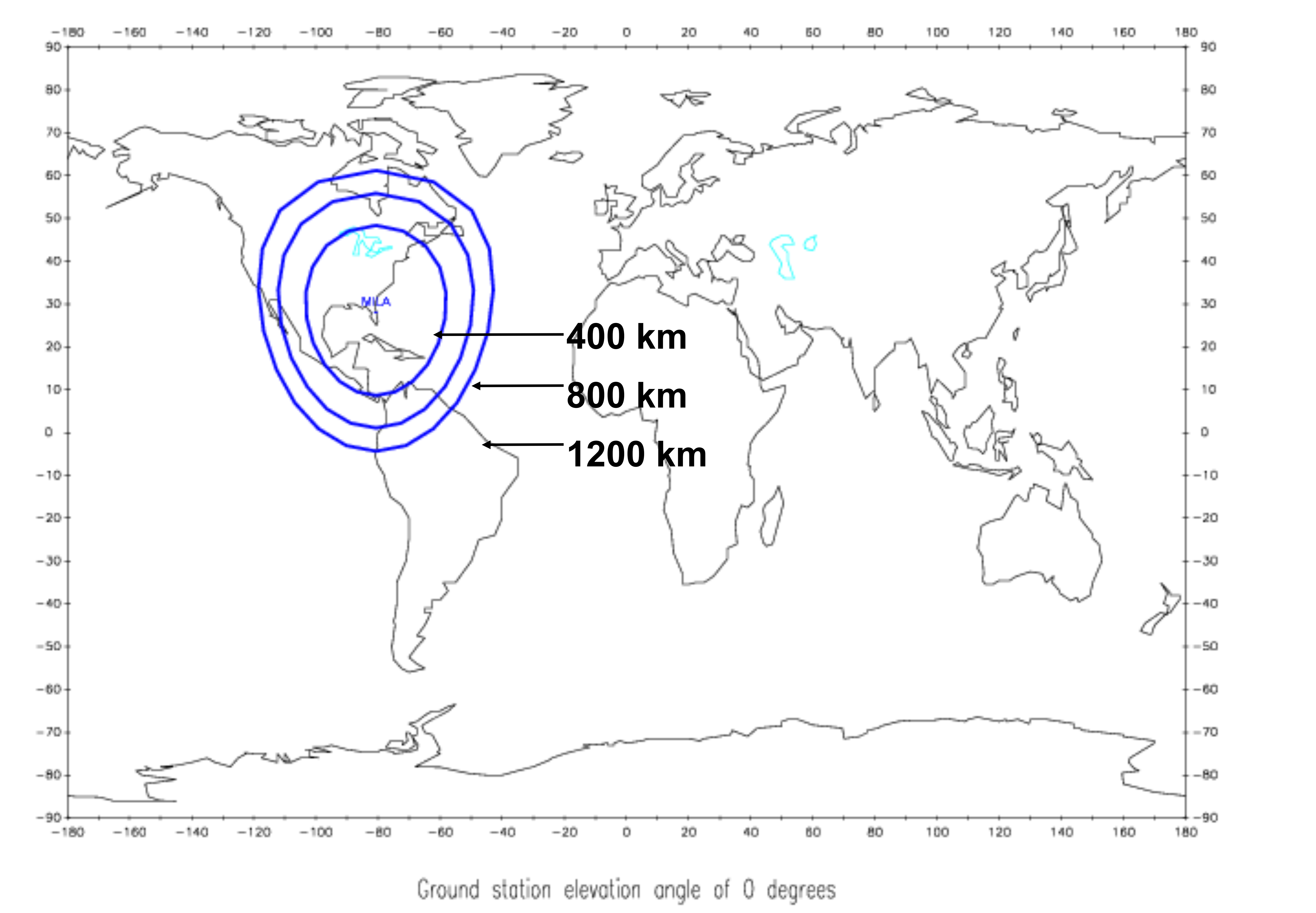
Ground Station Coverage





Ground Station Coverage

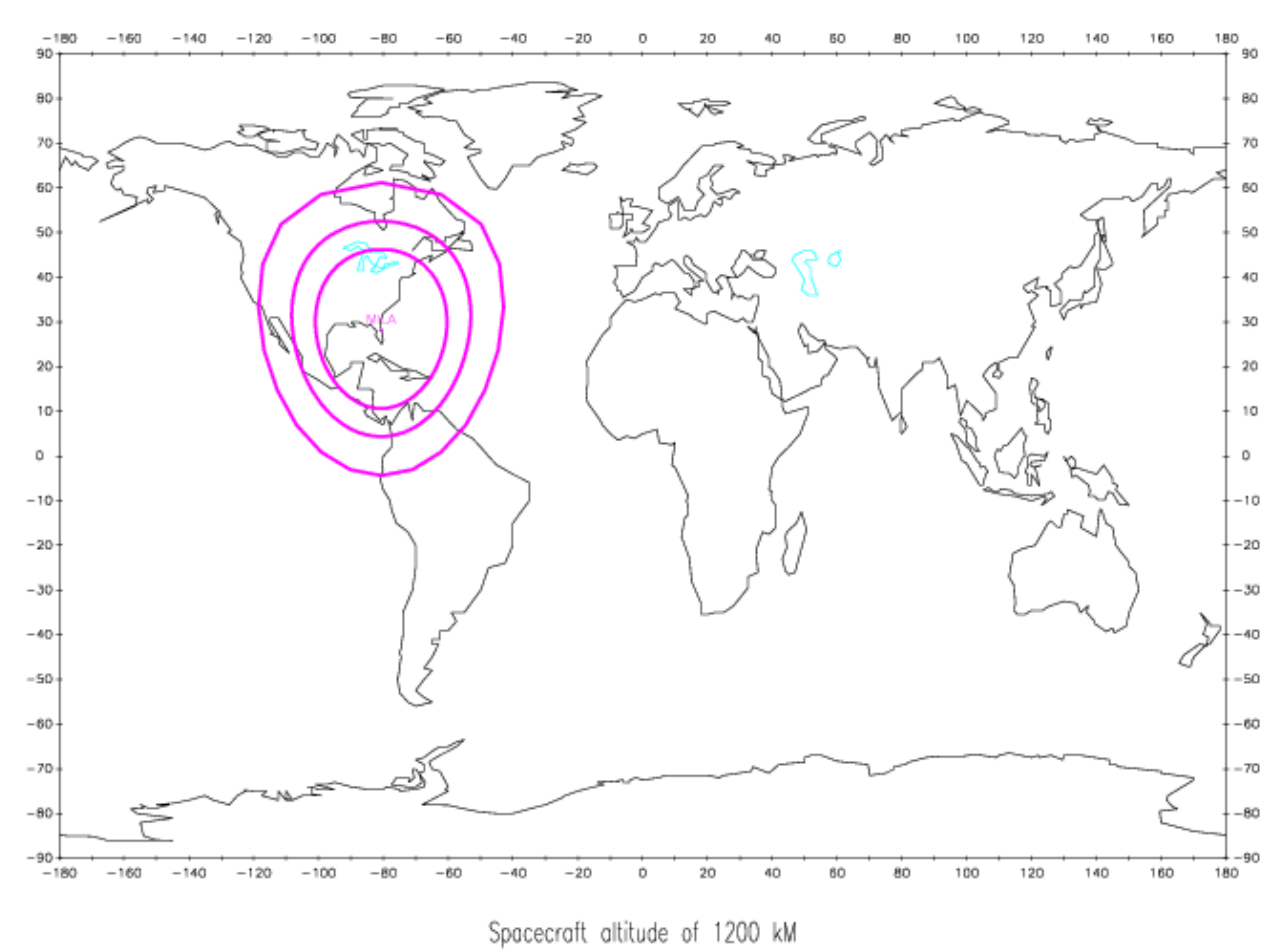
Florida ground station with spacecraft altitudes 400, 800, and 1200 km



Merritt Island

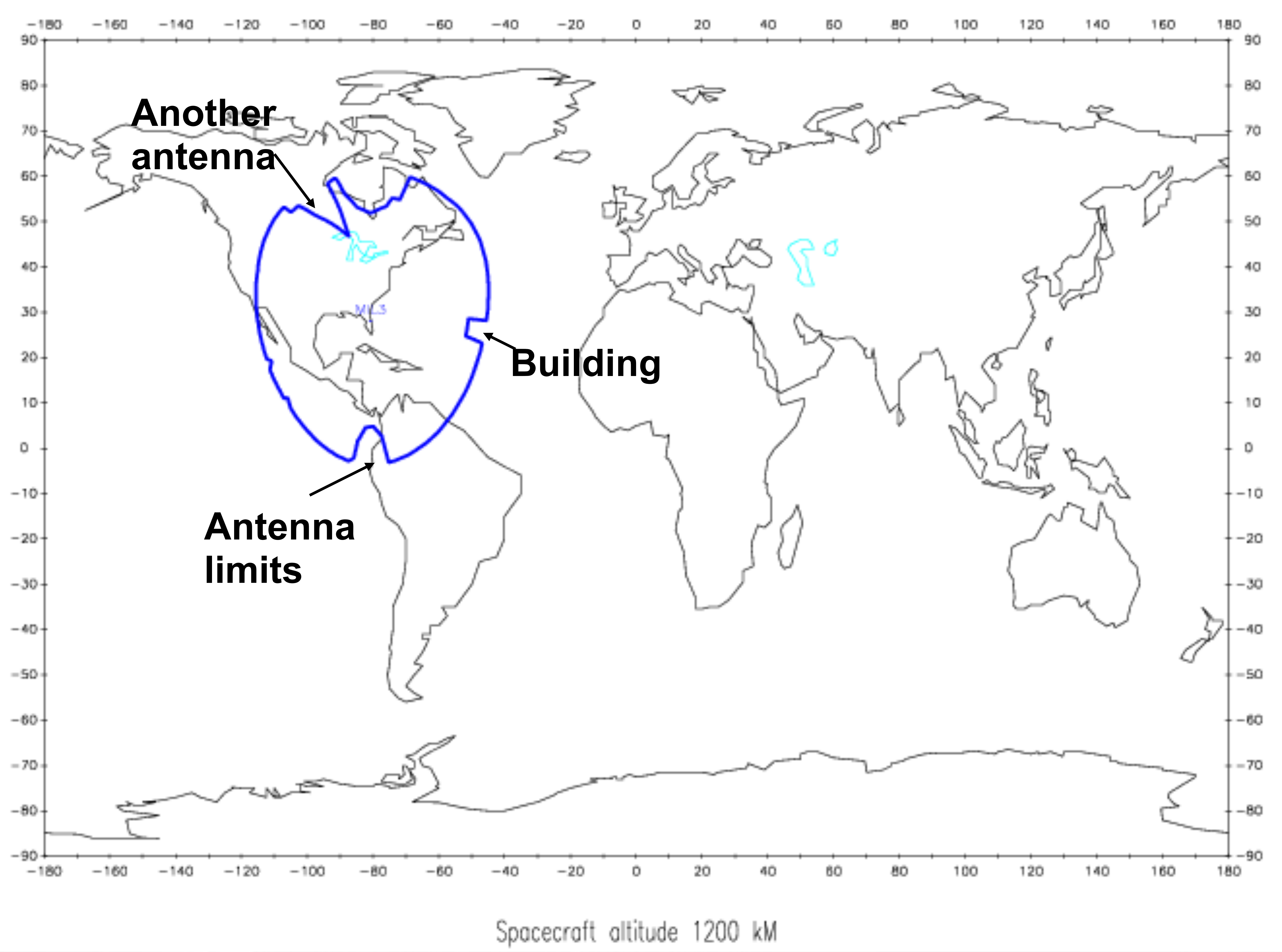
Ground Station Coverage

Ground station elevation angles of 0, 10, and 20 degrees



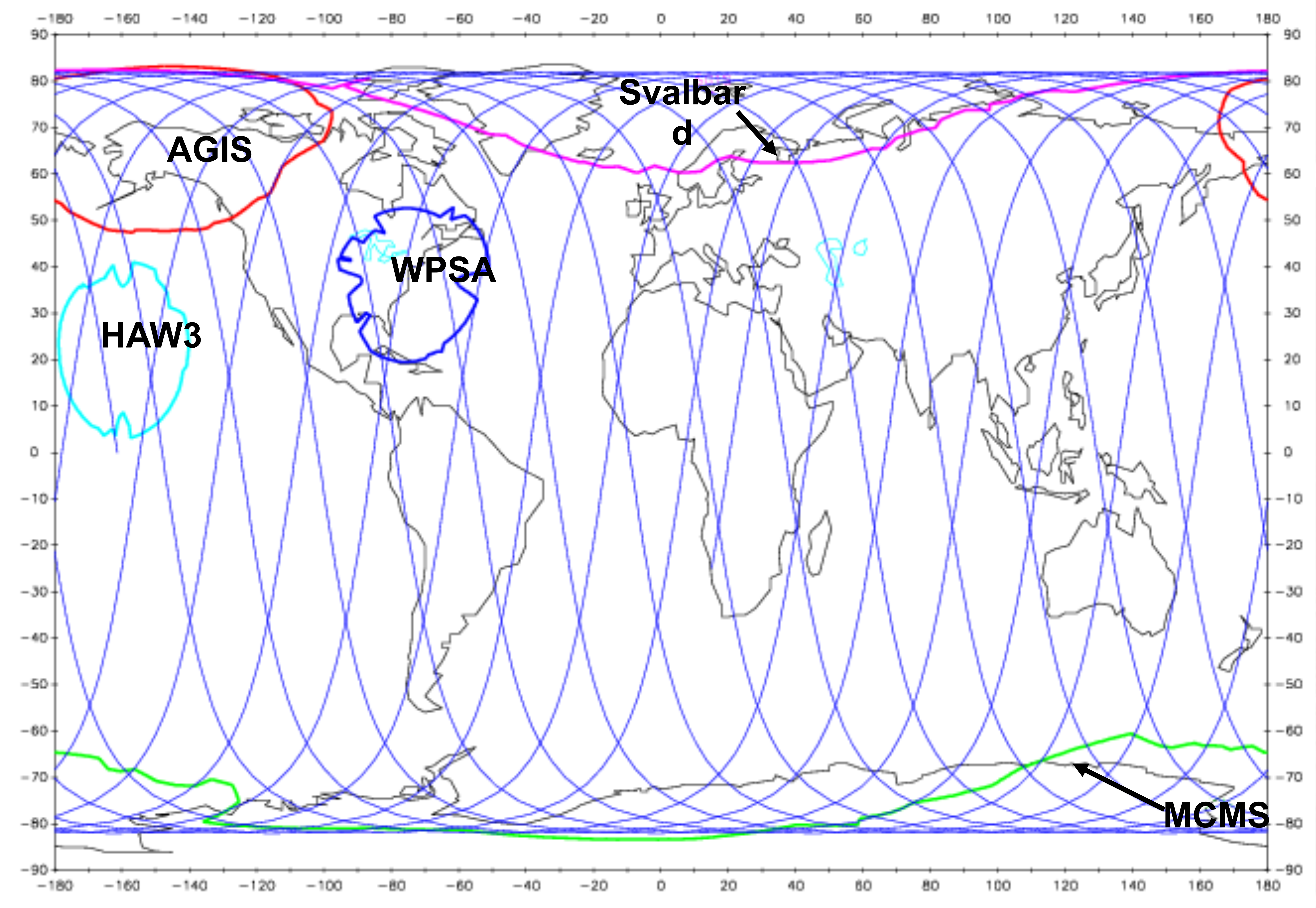
Ground Station Coverage

Effects of terrain and antenna limitations



Ground Station Coverage

Hawaii (HAW3), Alaska (AGIS), Wallops Island (WPSA), Svalbard (SGIS), McMurdo (MCMS)

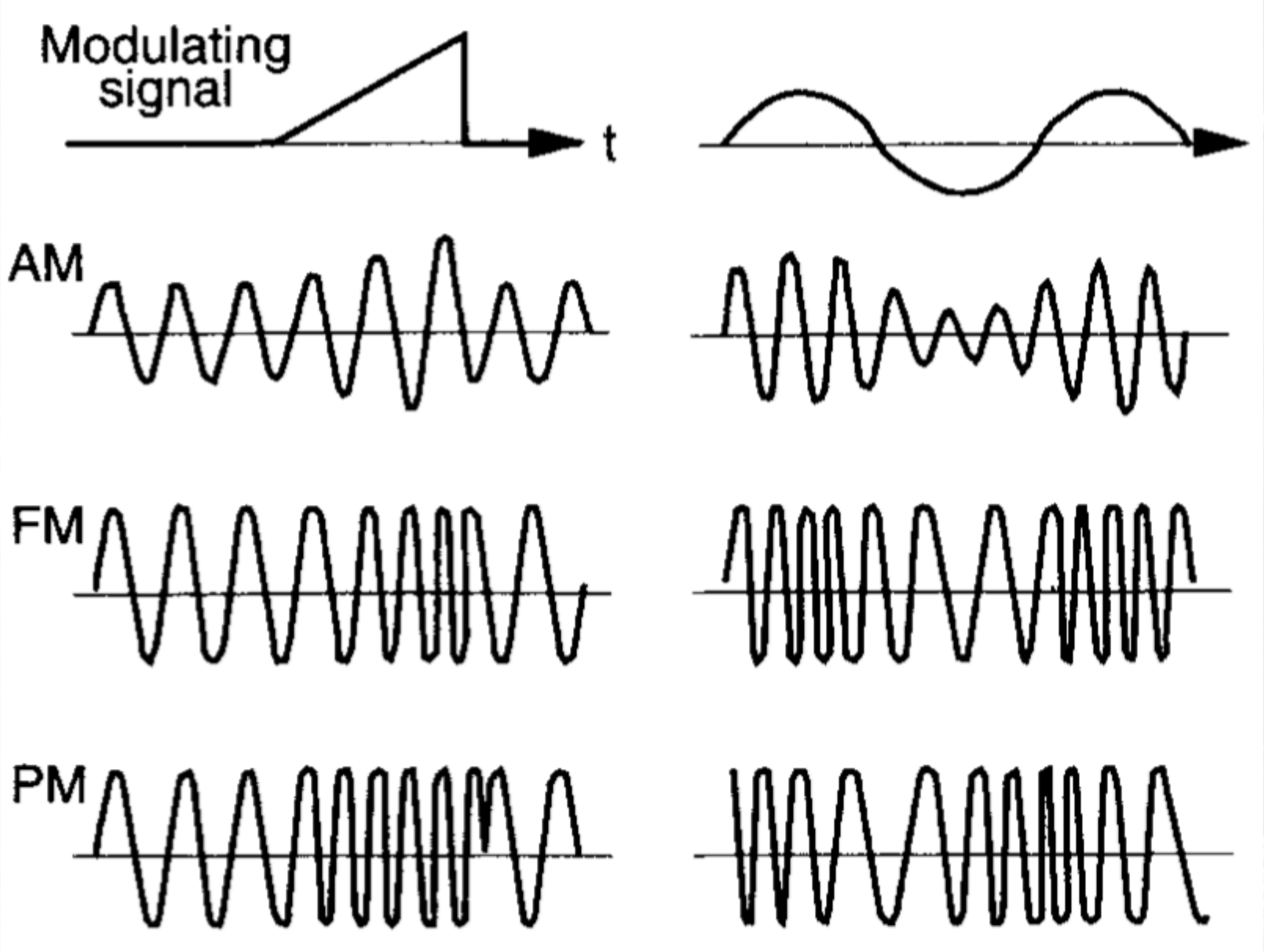


Frequency Bands

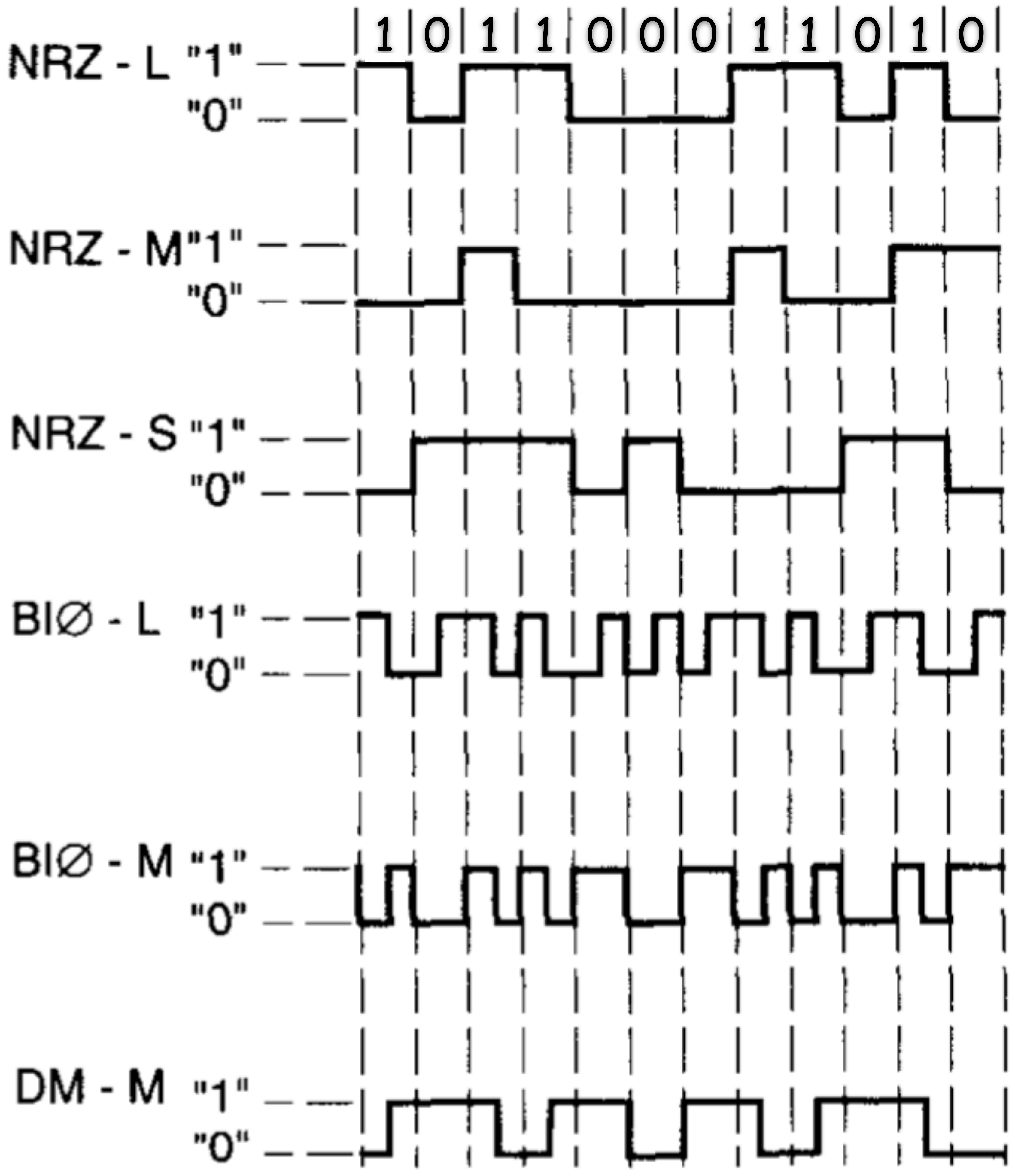
- S-Band — 2-3 GHz
  - Space operation, Earth exploration, Space research
- X-Band — 7-8 GHz
  - Earth exploration, Space research
- Ku-Band — 13-15 GHz
  - Space research
  - Loss from rain
- Ka-Band — 23-28 GHz
  - Inter-satellite, Earth exploration

Types of Modulation

- Amplitude Modulation
  - $s(t) = A\,[1 + m(t)]\cos(2\pi f_c t)$
  - Easy to implement
  - Poor noise performance
- Frequency Modulation
  - $x(t) = A\cos[2\pi\int_{0\text{->}t}(f_c + f_\Delta m(\tau))d\tau]$
  - Requires frequency lock loop
- Phase Modulation
  - $s(t) = A\cos[2\pi f_c t + \beta m(t)]$
  - Requires phase lock loop
  - Most digital modulation techniques involve PM



Pulse Code Modulation Protocols



Non-return-to-zero-level
"One" is represented by one level.
"Zero" is represented by the other level.

Non-return-to-zero-mark
"One" is represented by a change in level.
"Zero" is represented by no change in level.

Non-return-to-zero-space
"One" is represented by no change in level.
"Zero" is represented by a change in level.

Bi-phase level (split phase)
Level change occurs at center of every bit period.
"One" is represented by a "one" level with the transition to the "zero" level.
"Zero" is represented by a "zero" level with the transition to the "one" level.

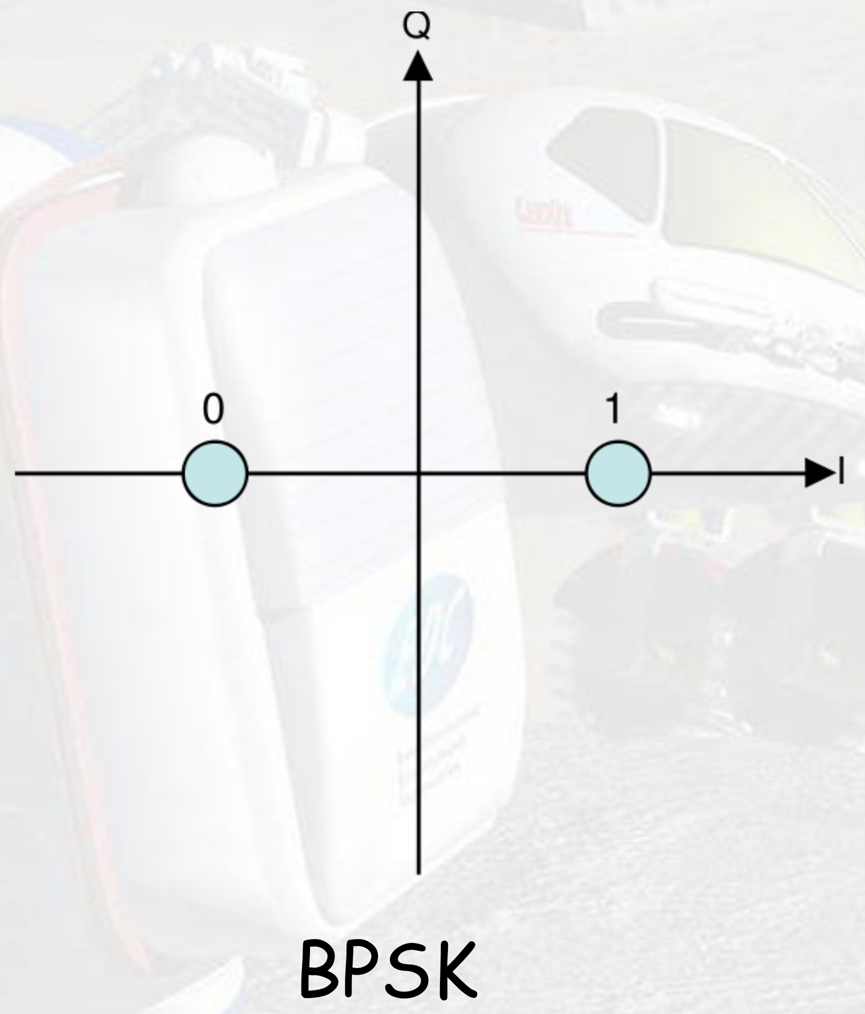
Bi-phase mark
Level change occurs at the beginning of every bit period.
"One" is represented by a midbit level change.
"Zero" is represented by no midbit level change.

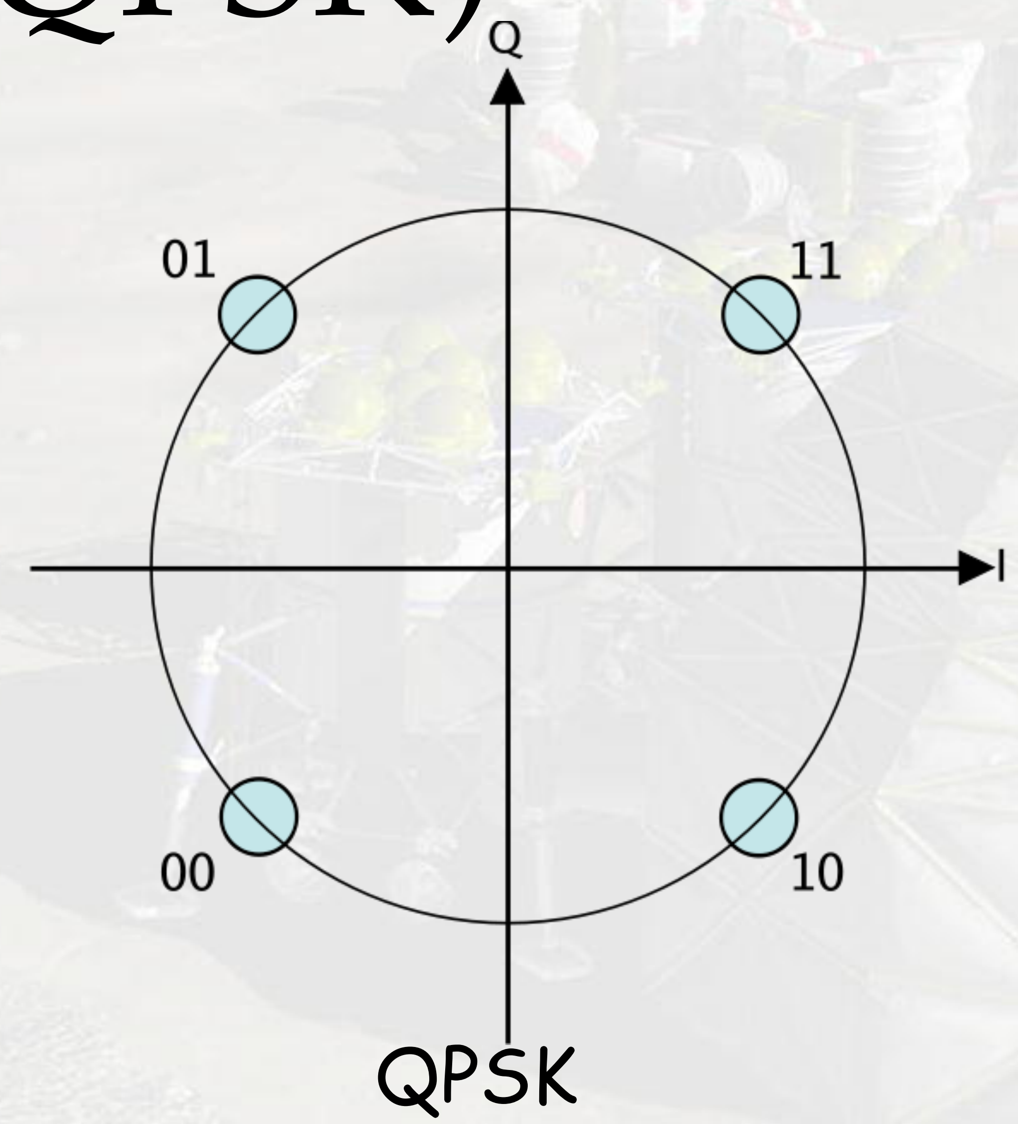
Delay modulation-mark (Miller code)
"One" is represented by a level change midbit time.
"Zero" followed by a "zero" is represented by a level change at the end of the first "zero" bit. No level change occurs when a "zero" is preceded by a "one."

from Pisacane, Fundamentals of Space Systems, 2nd ed., Oxford Univ. Press, 2005

Digital Modulation Techniques

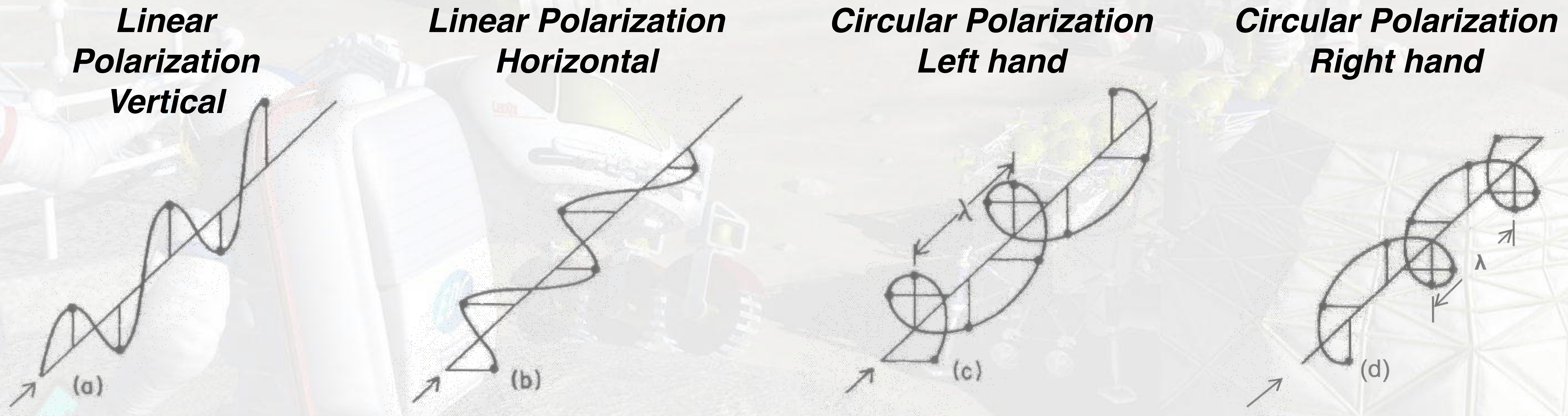
- On-Off Keying (OOK)
- Frequency Shift Keying (FSK)
- Bi-Phase Shift Keying (BPSK)
- Quadrature Phase Shift Keying (QPSK)



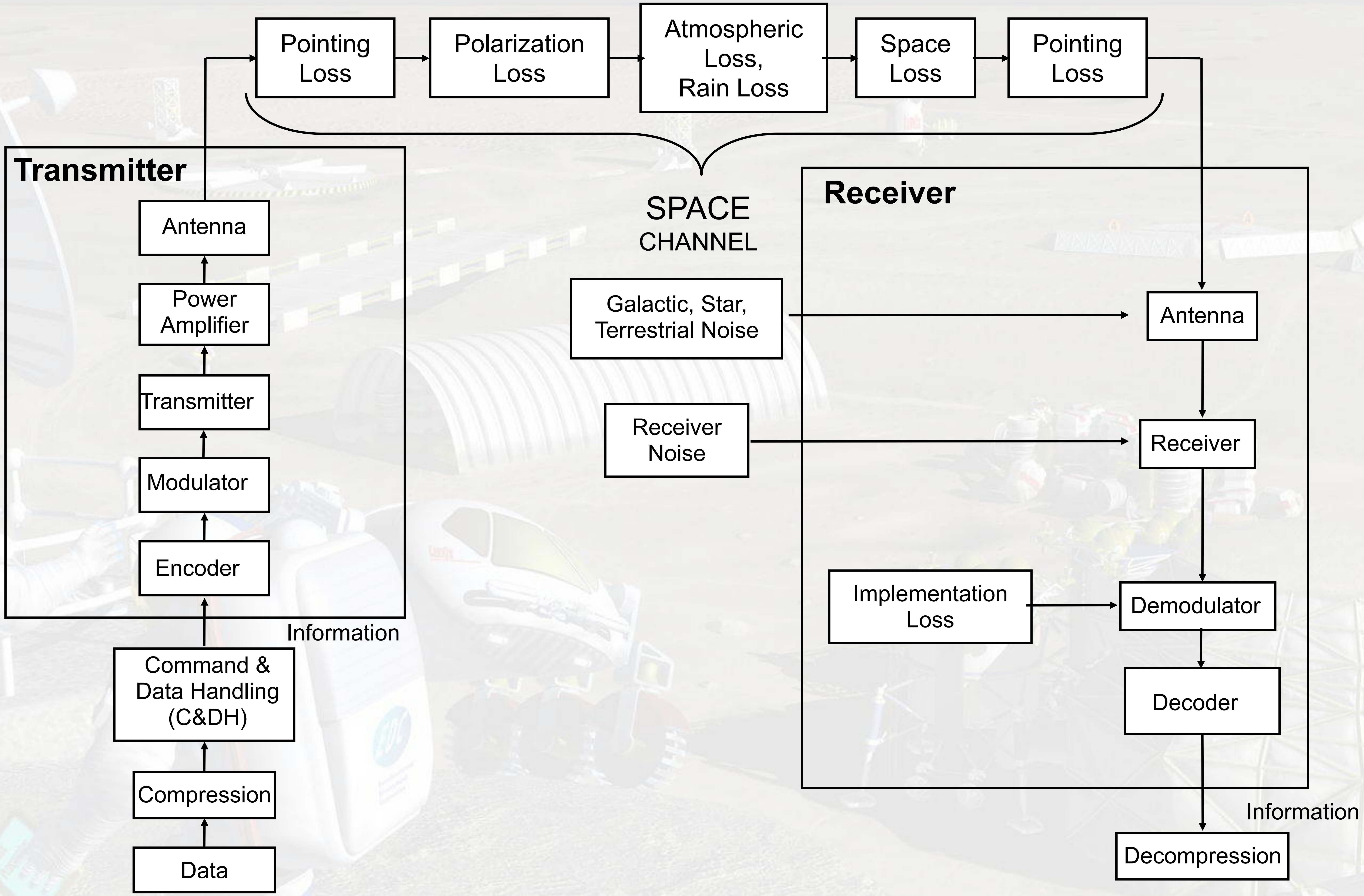


Polarization

- Orientation of electric field vector
- Shape traced by the end of the vector at a fixed location, as observed along the direction of propagation
- Some confusion over left hand/right hand conventions



The Problem: Verify the Link



Satellite transmitter-to-receiver link with typical loss and noise sources

Definition of Variables

$[\ ]_t \equiv$ refers to transmitting system

$[\ ]_t \equiv$ refers to receiving system

$A_e \equiv$ Effective area of the antenna (m^2)

$c \equiv$ Speed of light (2.998×10^8 m/sec)

$f \equiv$ Frequency ($2\pi/\lambda$)

$G_r \equiv$ Gain of the component

$P \equiv$ Power at the antenna (W)

$R \equiv$ Free-space distance between antennas (m)

$\eta \equiv$ Efficiency of the component

$\lambda \equiv$ Wavelength (m)

Radio-Frequency Propagation

$$P_r = \frac{P_t G_t A_e}{4\pi R^2}$$

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

$$P_r = \frac{P_t G_t \lambda^2 G_r}{4\pi R^2 4\pi} = \frac{P_t G_t G_r}{(4\pi)^2 R^2} \times \frac{c^2}{f^2}$$

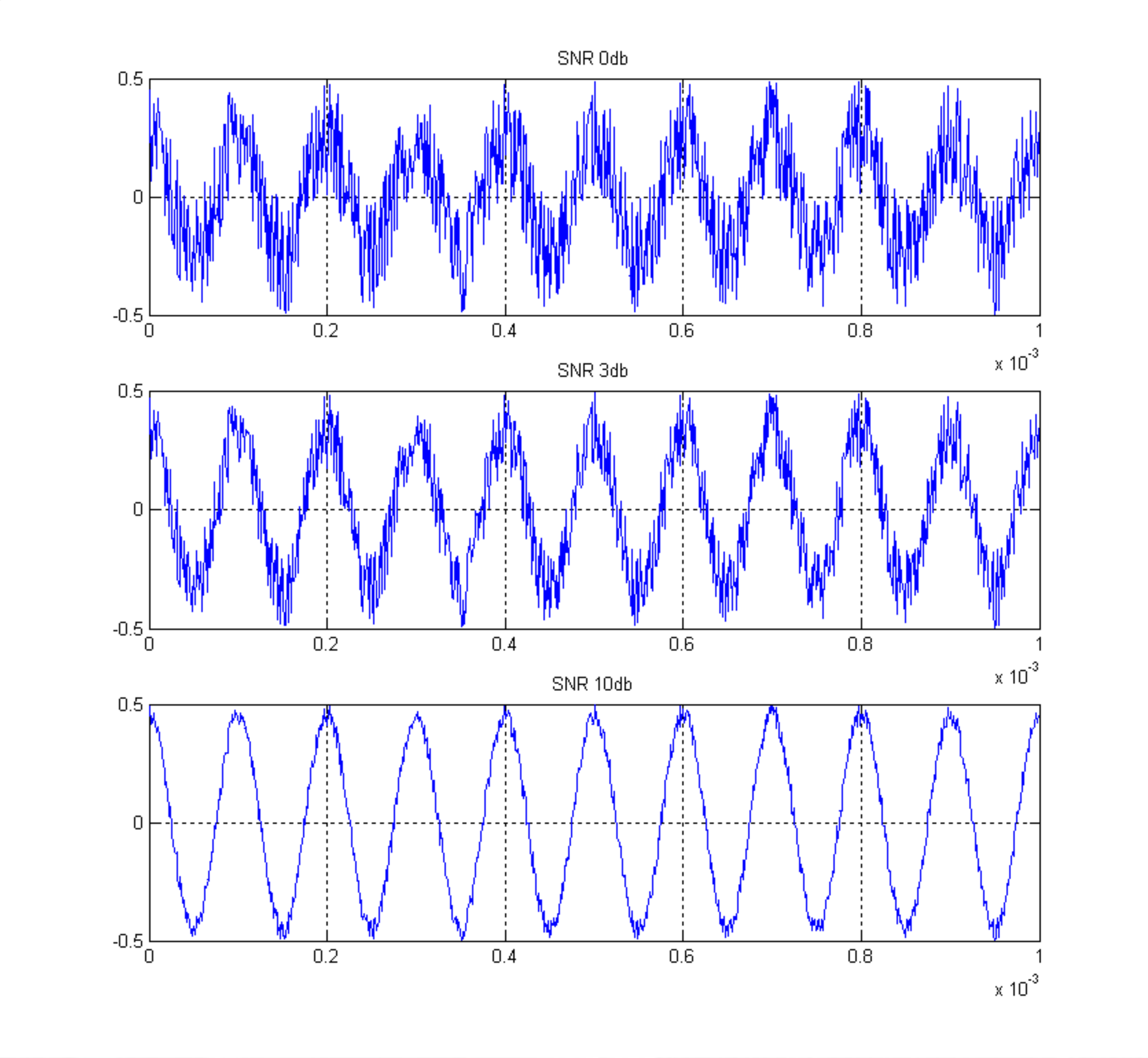
$$P_r = \frac{P_t 4\pi A_{e_t} A_{e_r}}{\lambda^2 4\pi R^2} = \frac{P_t A_{e_t} A_{e_r}}{R^2} \times \frac{f^2}{c^2}$$

Noise

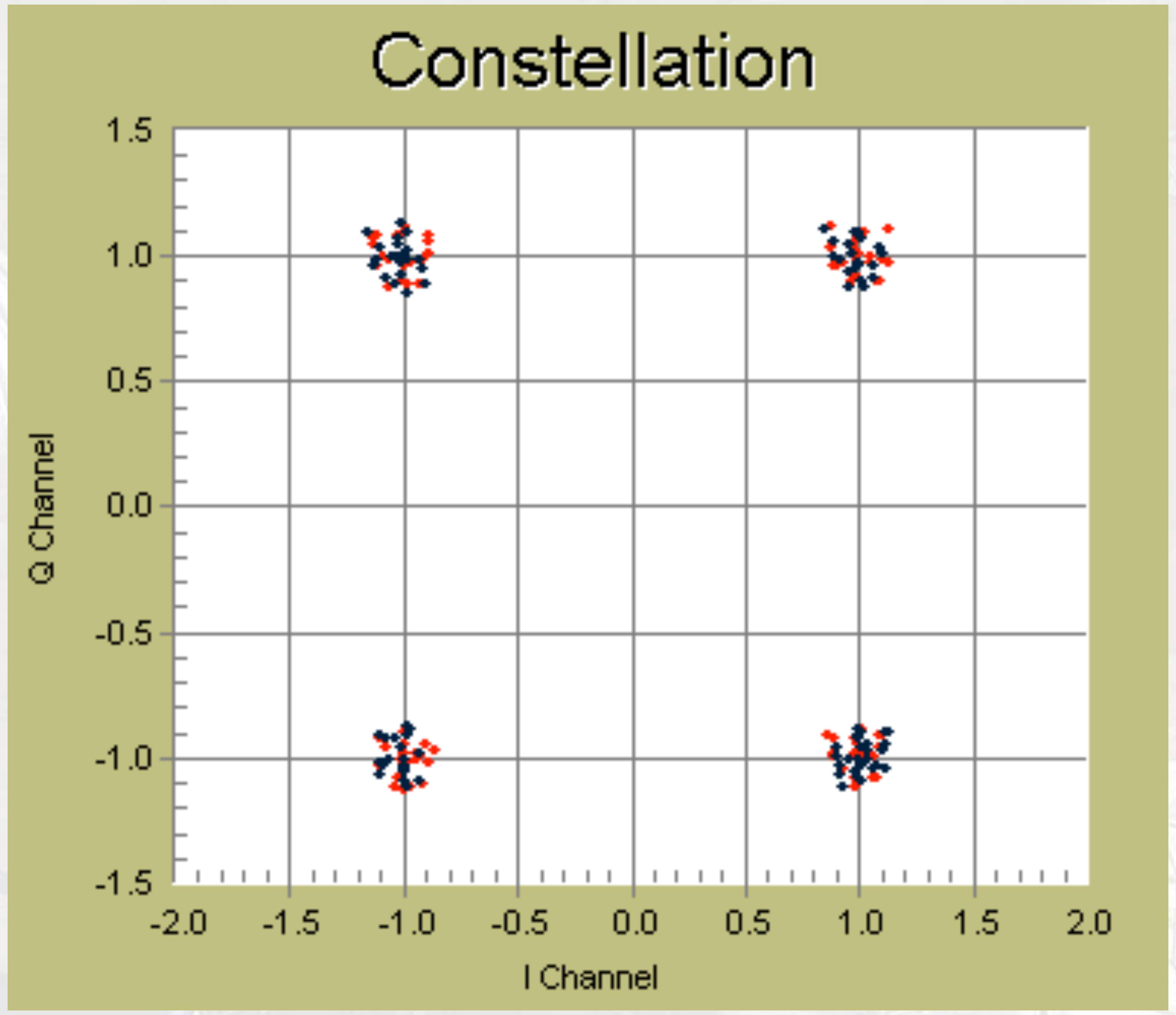
- Any signal that isn't part of the information sent
- Signal noise
  - Amplitude noise – error in the magnitude of a signal
  - Phase noise – error in the frequency / phase modulation
- System Noise
  - Component passive noise
  - Component active noise (amplifiers, mixers, etc…)
- Environmental Noise
  - Atmospheric noise
  - Galactic noise
  - Precipitation

Signal Noise

Amplitude Noise



Phase Noise



System Noise

- All real components generate “thermal noise” due to the random motion of atoms
- Passive devices’ thermal noise is directly related to the temperature of the device, its bandwidth, and the frequency of operation
- Noise is generated by thermal vibration of bound charges
- A moving charge generates an electromagnetic signal
- Passive components include
  - Resistive loads (power loads)
  - Cables & other such things (like waveguides)

Environmental Noise

- Rain loss, particularly in the Ku band
- Snow is not a problem
- Lightning
- Stars, galaxies, planets
- Human interference

Noise Temperature

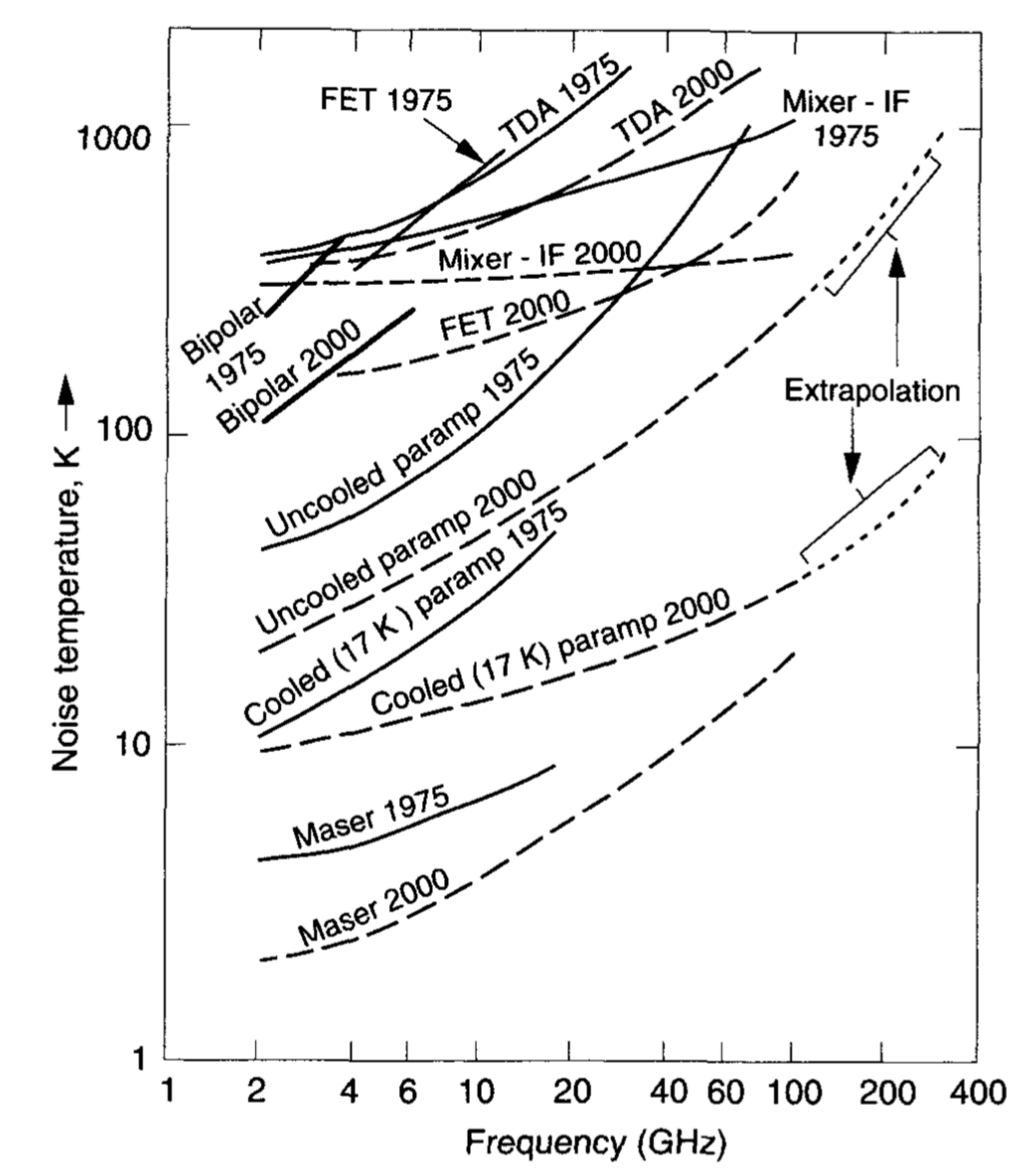
- Noise temperature provides a way of determining how much thermal noise is generated in the receiving system
  - The physical noise temperature of a device, T_n, results in a noise power of $P_n = KT_nB$

    K = Boltzmann's constant = 1.38×10^{-23} J/K; K in dBW = -228.6 dBW/K

    T_n = Noise temperature of source in Kelvin

    B = Bandwidth of power measurement device in hertz
- Satellite communications systems work with weak signals, so reduce the noise in the receiver as far as possible
  - Generally the receiver bandwidth is just large enough to pass the signal
  - Liquid helium can hold the physical temperature down

Typical Receiver Noise Performance



from Pisacane, Fundamentals of Space Systems, 2nd ed., Oxford Univ. Press, 2005

S/N and NF

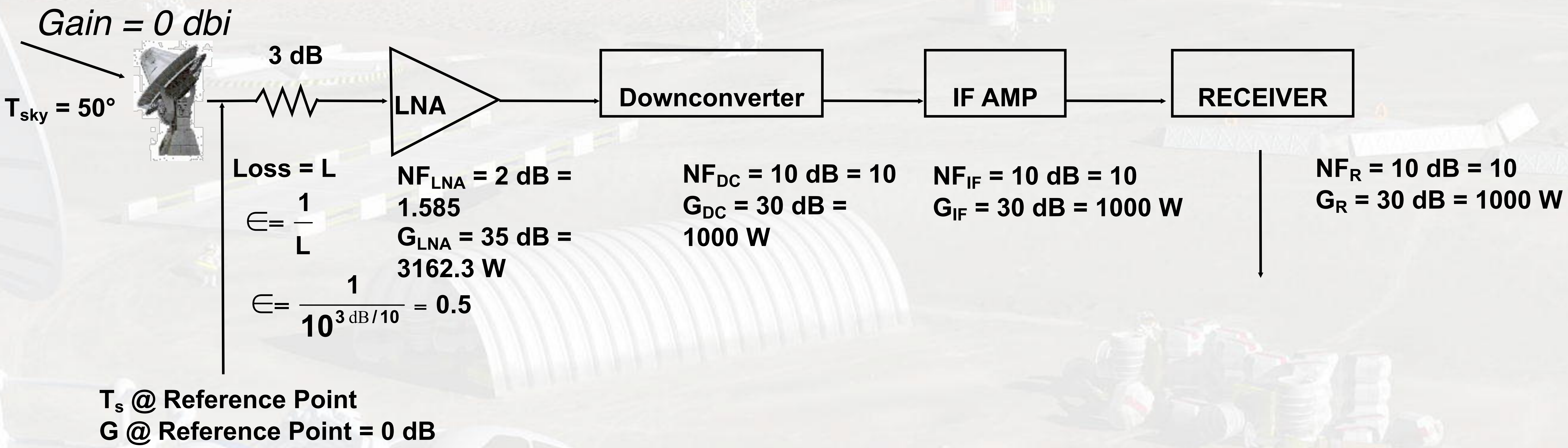
- Signal to Noise Ratio
  - Most common description of the quantity of noise in a transmission
- Noise Figure
  - S/N of input divided by S/N of output for a given device (or devices) in a communications system
  - Related to the noise temperature of a device:

$$T_d = T_0(NF - 1)$$

T_0 = reference temperature, usually 290 K

System Noise Temperature

Example:



System Noise Temperature ≡ T_s °K

T_o is reference temperature of each device = 290°K (assumed)

$$T_s \approx T_{sky} + \frac{(1-\in)T_o}{\in} + \frac{(NF_{LNA}-1)T_o}{\in} + \frac{(NF_{PC}-1)T_o}{\in G_{LNA}} + \frac{(NF_{IF}-1)T_o}{\in G_{LNA} G_{DC}} + \ldots$$

T_s = 50° + 290° + 2*0.585*290° + (2*10*290°/3162.3) * (1 + 1/1,000 + 1/1,000,000)

T_s = 681.136°K = 28.33 dB

BER and E_b/N_o

- The rate at which bits are corrupted beyond the capacity to reconstruct them is called the BER (Bit Error Rate).
  - A BER of less than 1 in 100,000 bits (a BER of 10^{-5}) is generally desired for an average satellite communications channel.
  - For some types of data, an even smaller BER is desired (10^{-7}).
- The BER is directly dependent on the E_b/N_o, which is the ratio of Bit Energy to Noise Density.
  - Since noise density is difficult to control, this means that BER can be reduced by using a higher power signal, or by controlling other parameters to increase the energy transmitted per bit.
- The BER will decrease (fewer errors) if the E_b/N_o increases.

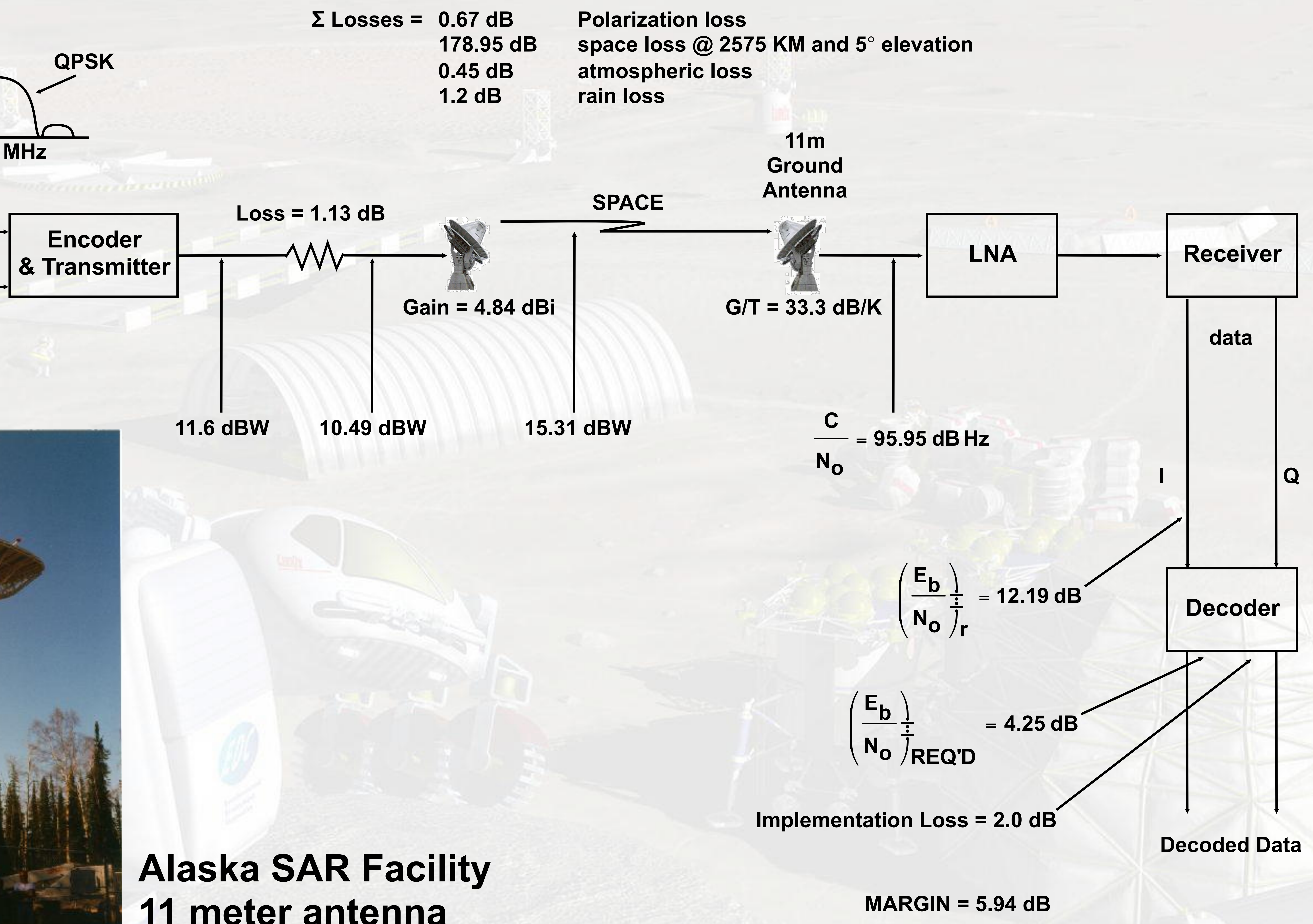
Link Margin

- Received E_b/N_o minus required E_b/N_o (in dB)
- Required E_b/N_o found by adding losses to the expected E_b/N_o for the BER (which varies with encoding scheme used)

$$\left(\frac{E_b}{N_o}\right)_{\text{Req©d dB}} = \left(\frac{E_b}{N_o}\right)_{\text{Theoretical for BER}} + \sum \text{Other System Losses}_{\text{dB}}$$

$$\text{Margin} = \left(\frac{E_b}{N_o}\right)_{\text{recieved}_{\text{dB}}} - \left(\frac{E_b}{N_o}\right)_{\text{Req©d dB}}$$

Diagram of a Link Budget



Alaska SAR Facility
11 meter antenna

Standard Link Budget Analysis

from David G. MacDonnell, "Communications Analysis of Potential Upgrades of NASA's Deep Space Network

and numerous other sources

Note: Only change values in boxed cells!

				dB
Speed of light	m/sec	c	3.00E+08	84.77
Frequency	Hz	f	2.50E+09	93.98
Wavelength	m	λ	0.1200	-9.21
Diameter of Transmitting Antenna	m	d(t)	0.04	-14.18
Area of Transmitting Antenna	m^2	A(t)	0.00	-29.41
Efficiency of Transmitting Antenna		η(t)	0.63	-2.04
Transmitter Gain		G(t)	6.25E-01	-2.04
Transmitter Power	W	P	11.47	10.60
EIRP	W	EIRP	7.17E+00	8.55
slant range	m	D	5.00E+07	76.99
Power flux density	W/m^2	Φ	2.28E-16	-156.42
Diameter of Receiving Antenna	m	d(r)	4.50	6.53
Area of Receiving Antenna	m^2	A(r)	15.90	12.02
Efficiency of Receiving Antenna		η(r)	0.55	-2.60
Receiver Gain		G(r)	7.63E+03	38.83
Carrier Power Received	W	C	2.00E-15	-147.00
Receiver System Noise Temp	degK	T(s)	100.00	20.00
Boltzmann Constant	J/degK	k	1.38E-23	-228.60

Transmitter Gain		G(t)	6.25E-01	-2.04
Transmitter Power	W	P	11.47	10.60
EIRP	W	EIRP	7.17E+00	8.55
slant range	m	D	5.00E+07	76.99
Power flux density	W/m^2	Φ	2.28E-16	-156.42
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Receiver Gain		G(r)	7.63E+03	38.83
Carrier Power Received	W	C	2.00E-15	-147.00
Receiver System Noise Temp	degK	T(s)	100.00	20.00
Boltzmann Constant	J/degK	k	1.38E-23	-228.60
Noise Spectral Density	J/degK	N(o)	1.38E-21	-208.60
Figure of Merit Gr/Ts		Gr/Ts	7.63E+01	18.83
Free Space Loss		L(fs)	2.74E+19	194.38
Total System Loss		L(ts)	2.75	4.40
Receiver C/No Available	Hz	C/No(rcv)	5.25E+05	57.20
Bit Error Rate		BER	1.00E-05	-50.00
C/No Required	Hz	C/No(req)	2.63E+05	54.20
Data Rate	bits/sec	R(b)	2.80E+04	44.47
Eb/No Received		Eb/No(rcv)	18.76	12.73
Eb/No Required		Eb/No(req)	9.40	9.73
Link Margin			1.99526	3.00