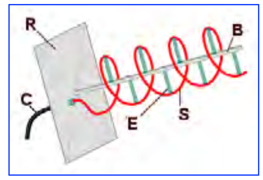
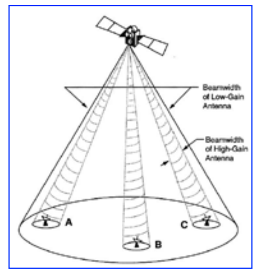
Communications

Space System Design, MAE 342, Princeton University
Robert Stengel

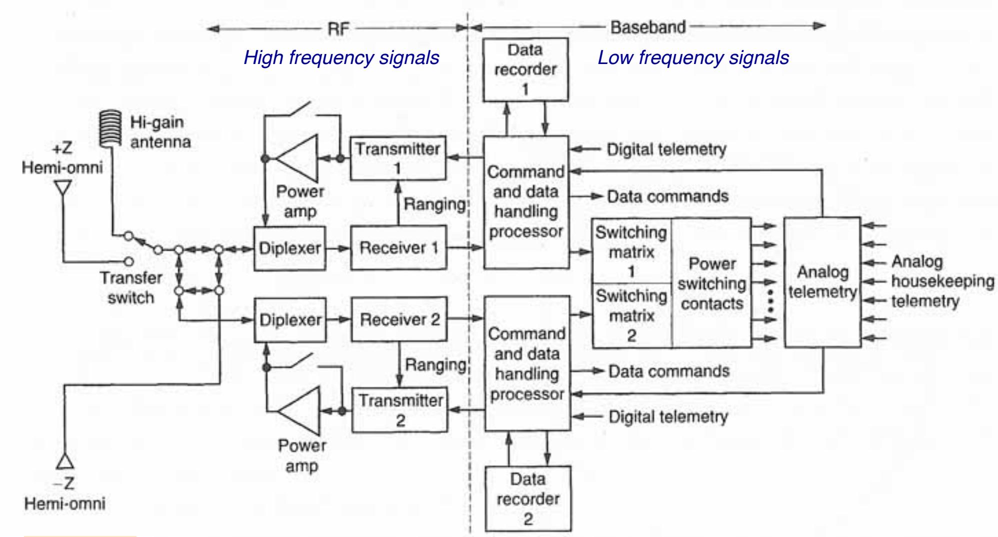
- Antenna characteristics
- Power transmission and reception
- Signals, information, and noise
- Analog and digital modulation
- Communication link budgets
- Laser communications





$$\boxed{C(\text{bits/s}) = BW \log_2\left(\frac{S}{N} + 1\right)}$$

Typical Spacecraft Communications Architecture



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Antenna Gain

- Isotropic (uniform) radiation of power, ***P***, from the center of a sphere of radius, ***r***
- Power per unit area (power density) of the sphere's surface

$$\boxed{p = P/4\pi r^2}$$

- Power received from isotropic radiator over area, ***S***

$$\boxed{P_S = Sp}$$

- Power received over area, ***S***, if all power is focused uniformly on that area by antenna with gain, ***G***

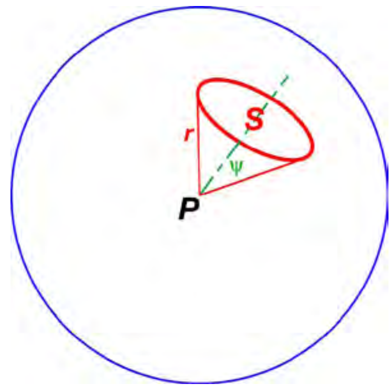
$$\boxed{P_S = GSp_S = P}$$

- Power density in ***S*** with idealized focused antenna

$$\boxed{p_S = P/GS}$$

- **Idealized antenna gain**

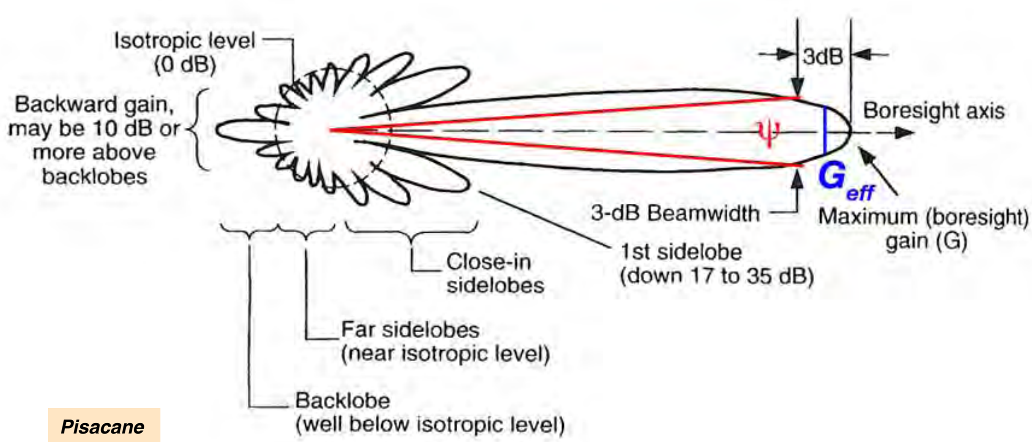
$$\boxed{G = \frac{P}{Sp_S} = \frac{4\pi r^2}{S}}$$



ψ = beamwidth half-angle

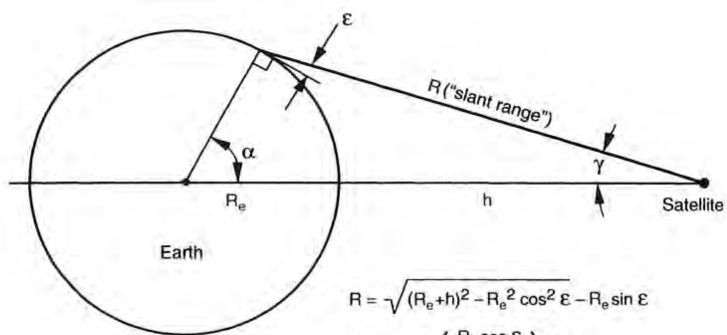
Typical Antenna Pattern

- Gain vs. angle from boresight axis (2-D)
- ***G_{eff}*** is average gain over beamwidth
- Beamwidth variously defined as **–3 dB** cone angle or half-angle



Communications Geometry

- **Ground station communication and tracking limited by its minimum elevation angle, ε**
- **Fixed (non-steerable) antenna must have sufficient beamwidth to transmit or receive**
- **Antenna gains and radiated power must be adequate, given slant range and noise environment**



$$R = \sqrt{(R_e+h)^2 - R_e^2\cos^2\varepsilon} - R_e\sin\varepsilon$$

$$\alpha = \cos^{-1}\left(\frac{R_e\cos\varepsilon}{R_e+h}\right) - \varepsilon$$

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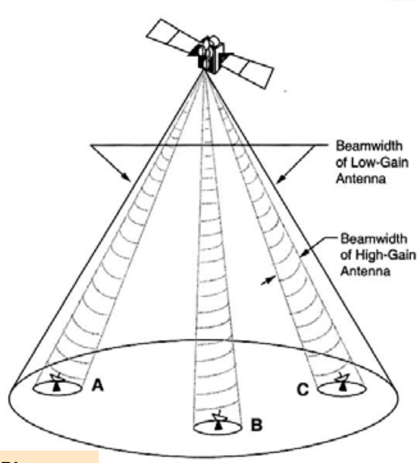
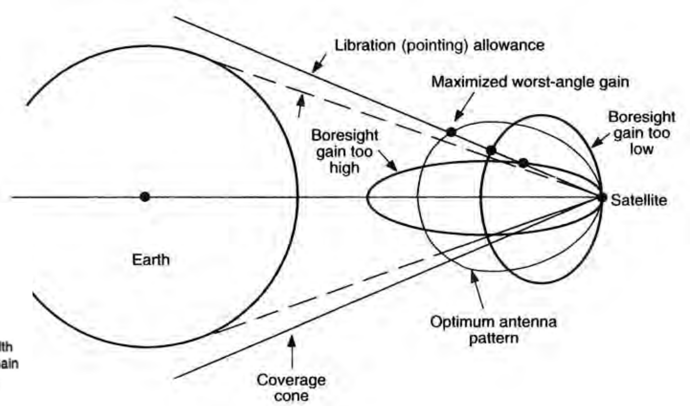
Beamwidth Coverage

- **Broad or narrow coverage may be desired**





Beamwidth of reflector antenna

$$\psi(\text{cone}) \approx \frac{21}{fd},\ \text{deg}$$

$$f = \text{carrier signal frequency, GHz}$$

$$d = \text{reflector diameter, m}$$

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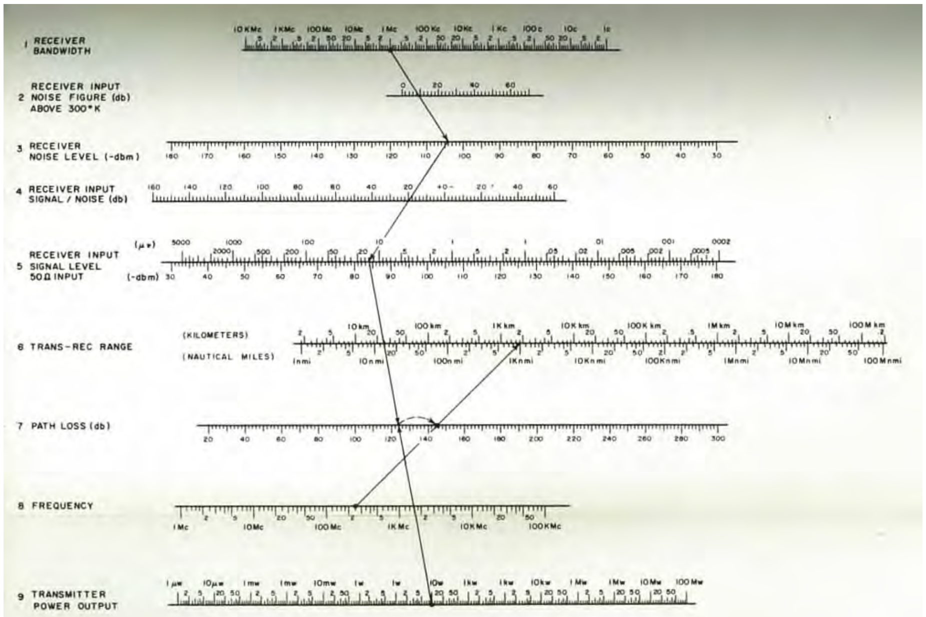
One-Way Radio Communication Calculation Nomogram *(GE, 1960)*



https://en.wikipedia.org/wiki/Nomogram

Relationship of Antenna Area and Signal Wavelength to Antenna Gain

Effective antenna gain (transmitting or receiving)

$$\boxed{G_{eff} = \frac{4\pi A_{eff}}{\lambda^2}}$$

$$A_{eff} = \text{effective antenna area, m}^2$$

$$\lambda = c / f = \text{carrier signal wavelength, m}$$

$$c = \text{speed of light} \approx 3 \times 10^8 \text{ m/s}$$

$$f = \text{carrier signal frequency, Hz}$$

Relationship of Antenna Area and Signal Wavelength to Antenna Gain

Power received from the transmitter

$$P_r = p_r A_r = \frac{G_t P_t A_r}{4\pi r^2}$$

p_r = power density at receiving antenna
A_r = effective area of receiving antenna
G_t = gain of transmitting antenna
P_t = transmitted power
r = distance between transmitting antenna and receiving antenna

Power ratio

$$\frac{P_r(\text{watts})}{P_t(\text{watts})} = \frac{G_t A_r}{4\pi r^2}$$

Antenna Characteristics

Type of Antenna	Typical Gain	Effective Area
Isotropic (reference)	1	$\frac{\lambda^2}{4\pi}$
Halfwave dipole	1.64	$\frac{1.64\lambda^2}{4\pi}$
Horn	$\frac{10A}{\lambda^2}$	$0.81\ A$
Axial mode helix ($\pi D \approx \lambda$)	$\frac{6L}{\lambda^2}$	$\frac{L\lambda}{2}$
Parabolic reflector	$\frac{6.9A}{\lambda^2}$	$0.55\ A$
Broadside array (ideal)	$\frac{4\pi A}{\lambda^2}$	A

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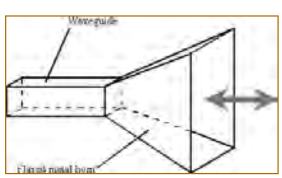
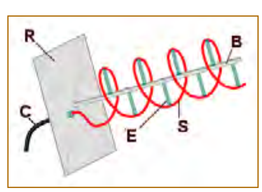
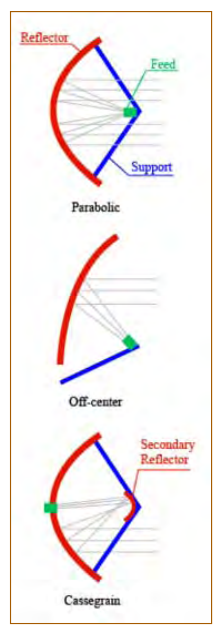
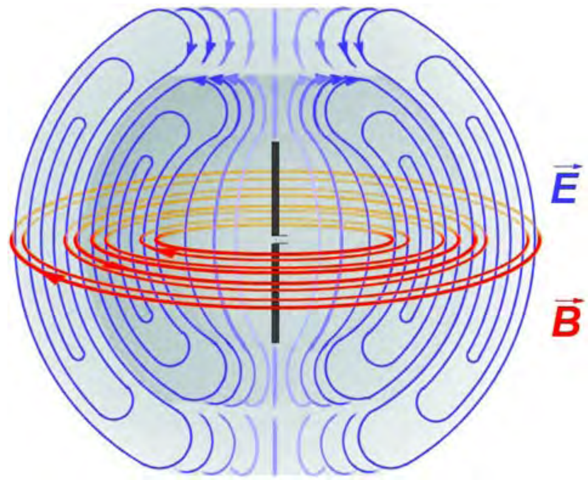






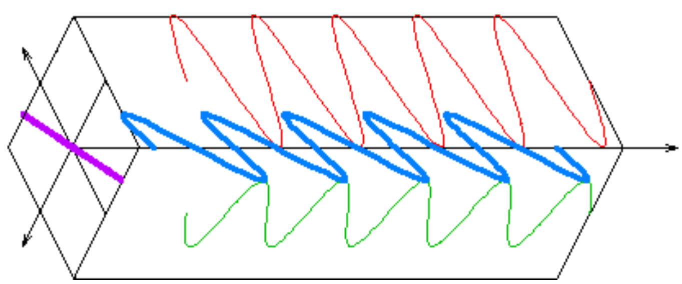
Electric and Magnetic Fields of a Dipole Antenna



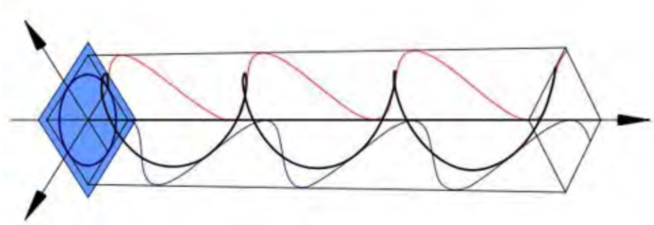
http://en.wikipedia.org/wiki/Antenna_(radio)

Linear and Circular Polarization of Waves

Transmit and receive antennas must be aligned for best communication



Left or right helical rotation of signal

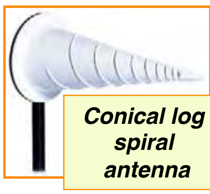


Characteristics of Typical Spacecraft Antennas

Type	Frequency Band (GHz)	Gain (dBi)	Beam-width (deg)	Mass (kg)	Satellite	Size (m)
Quad Helix	L (1.5)	16–19	18	1.8	Intelsat-V	0.4 × 0.4 × 0.47
Conical Log Spiral	S (2.2)	0–3	220	1.2	FLTSATCOM	
Parabola (fixed)	S (1.7)	16–19	18	3.9	GOES I, J, K	0.7 dia
Horn	C (4)	16–19	18	3.1	Intelsat-V	0.3 dia, 0.65L
Parabola w/ Feed Array	C (4)	21–25	*	29.4	Intelsat-V	2.44 dia
Parabola w/ Feed Array	C (6)	21–25	*	15.2	Intelsat-V	1.56 dia
Parabola—Steerable	Ku (11)	36	1.6	5.8	Intelsat-V	1.1 dia
Parabola w/ Feed Array	Ka (20/30)	45–52	*	47.1	SUPERBIRD	1.7 dia

* Beams shaped to illuminate specific land masses

Larson, Wertz



Conical log spiral antenna

$$\text{Gain(dBi)} = 10\log\frac{\text{Antenna Gain}}{\text{Isotropic Antenna Gain}}$$

Alternative Expressions for Power Ratio

$$\frac{P_r(watts)}{P_t(watts)} = \frac{G_t A_r}{4\pi r^2} = \frac{A_t A_r}{(\lambda r)^2} =$$

$$\frac{A_t A_r f^2}{(cr)^2} = \frac{G_t G_r \lambda^2}{4\pi r^2} = \frac{G_r A_t}{4\pi r^2}$$

Power ratio in decibels

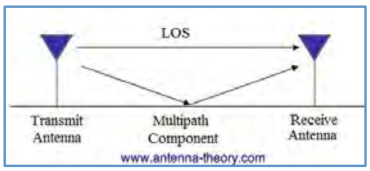
$$10\log_{10}\left(\frac{P_r}{P_t}\right)(dB) =$$

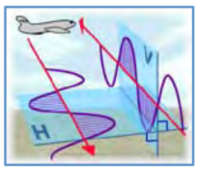
$$G_t(dB) + 10\log_{10} A_r(dB) - 10\log_{10} 4\pi(dB) - 20\log_{10} r(dB)$$

Detected Power

- **Receiver's detected power, P_d, includes components from**
  - transmitter's carrier signal
  - information signal
  - noise

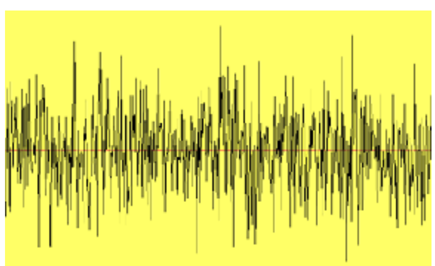
$$\frac{P_r}{P_t}(dB) = \left(\frac{P_r}{P_t}\right)_{ideal}(dB) - Absorption(dB) - Rainfall(dB)$$
$$\pm Multipath(dB) - Cross\,Polarization(dB)$$





$$P_r = P_{carrier} + P_{information} \approx P_{carrier}$$
$$P_d = P_r + P_n$$

Noise Sources



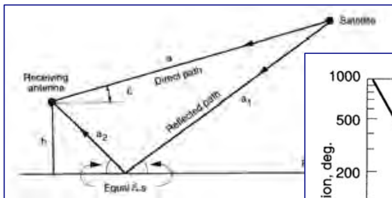
Receiver thermal and "front end" noise

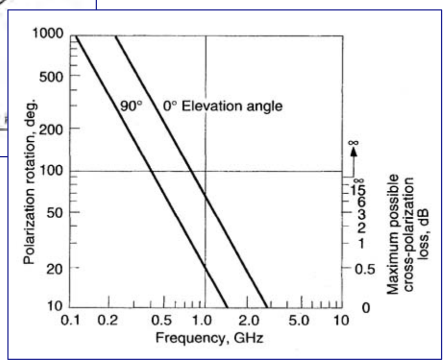
Atmospheric, cosmic, solar, and man-made noise

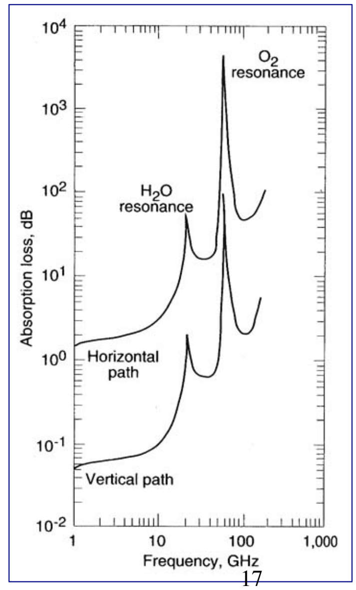
$$P_n =$$
$$P_{n_{atmosphere}} + P_{n_{solar}} + P_{n_{cosmic}} + P_{n_{man-made}} + P_{n_{receiver}}$$

Atmospheric Attenuation, Multipath, and Ionospheric Effects on Space-Earth Communication

$$\frac{P_r}{P_t}(\mathrm{dB}) = \left(\frac{P_r}{P_t}\right)_{ideal}(\mathrm{dB}) - \mathrm{Absorption}(\mathrm{dB}) - \mathrm{Rainfall}(\mathrm{dB})$$
$$\pm\ \mathrm{Multipath}(\mathrm{dB}) - \mathrm{Cross\,Polarization}(\mathrm{dB})$$







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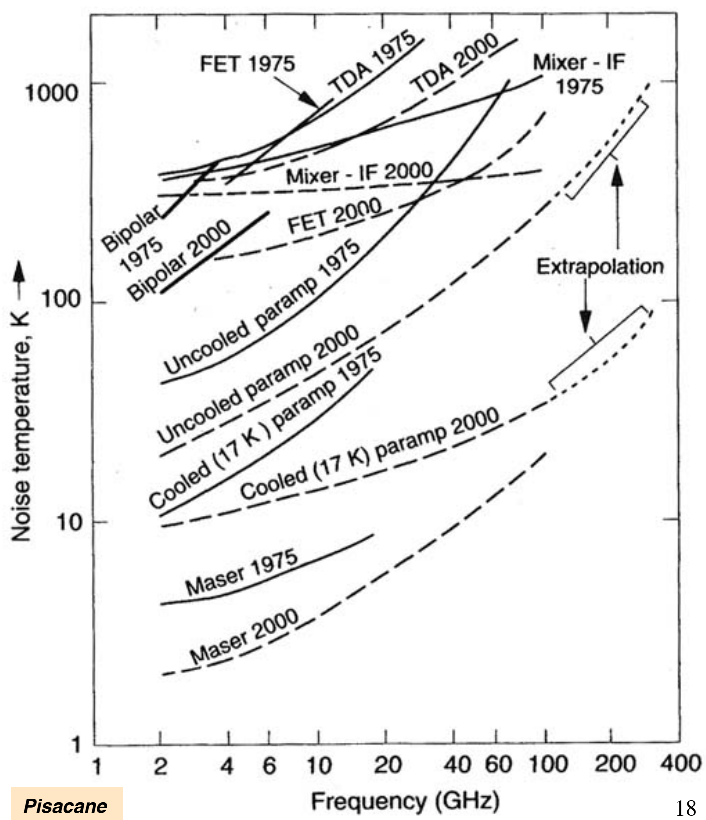
Receiver Noise



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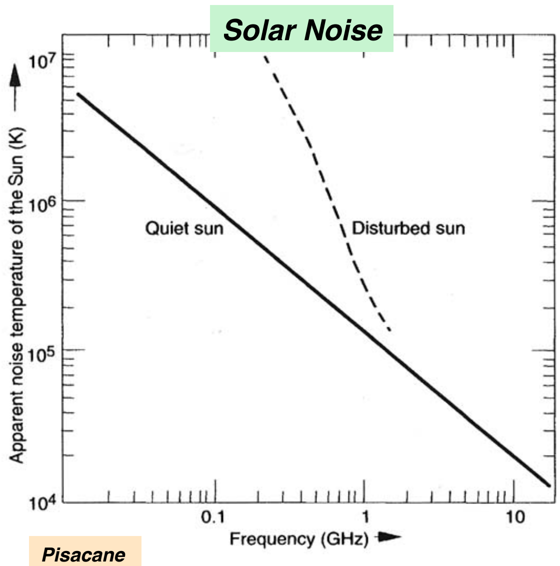
Other Noise Sources

$$\boxed{P_n \propto \lambda^n \quad \text{or} \quad 1/f^n}$$



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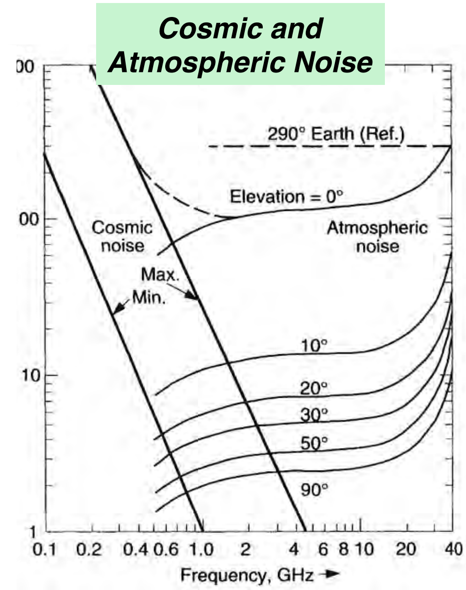


Receiver Noise

Power and temperature

$$P_n = kT\ BW \,(\text{watts})$$
$$T = 290\left(10^{NF(dB)/10} - 1\right)$$
$$= 290\left(F - 1\right)$$

$$k = \text{Boltzmann's constant} = 1.38 \times 10^{-23}\,\text{W-s / K}$$
$$T = \text{effective receiver temperature, K}$$
$$BW = \text{bandwidth, Hz}$$
$$NF = \text{receiver noise figure}$$
$$F = \text{receiver noise factor}$$

Power density

$$N_o = P_n / BW$$
$$= kT \,(\text{watts/Hz})$$

Typical Spacecraft System Noise Temperature

Noise Temperature	Frequency (GHz)					
	Downlink			Crosslink	Uplink	
	0.2	2–12	20	60	0.2–20	40
Antenna Noise (K)	150	25	100	20	290	290
Line Loss (dB)	0.5	0.5	0.5	0.5	0.5	0.5
Line Loss Noise (K)	35	35	35	35	35	35
Receiver Noise Figure (dB)	0.5	1.0	3.0	5.0	3.0	4.0
Receiver Noise (K)	36	75	289	627	289	438
System Noise (K)	221	135	424	682	614	763
System Noise (dB-K)	23.4	21.3	26.3	28.3	27.9	28.8

Signal-to-Noise Ratio and Information Content

$$\frac{S}{N} = \frac{P_r(\text{watts})}{P_n(\text{watts})}$$

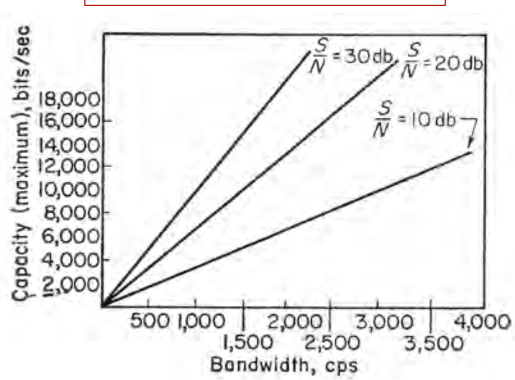
$$\frac{S}{N}(\text{dB}) = P_r(\text{dB}) - P_n(\text{dB})$$

$$P_r(\text{dB}) \equiv 10\log\left(\frac{P_r(\text{watts})}{1\text{ watt}}\right)$$

Channel capacity

$$C(\text{bits/s}) = BW\log_2\left(\frac{S+N}{N}\right) = BW\log_2\left(\frac{S}{N}+1\right)$$

$$BW = \text{bandwidth, Hz}$$



Signal-to-Noise Ratio per Bit, E_b/N_o

E_b : energy per bit
N_o : noise power spectral density

$$\frac{E_b}{N_o} = \frac{S}{N}\frac{BW}{R}$$

S = received signal power
N = received noise power
BW = bandwidth of receiver
R = data bit rate

How would you express this in decibels?

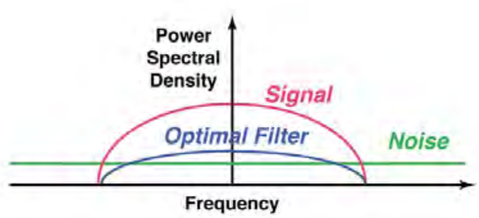
Communication: Separating Analog Signals from Noise

Signal-to-Noise Spectral Density Ratio, *SDR(f)*

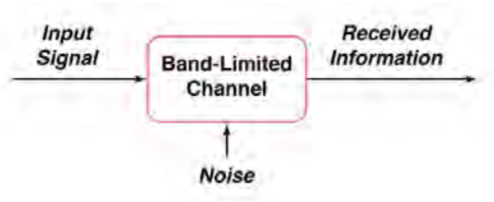
$$SDR\left(\frac{\omega}{2\pi}\right) = SDR(f) = \frac{Signal\ Power\ Spectral\ Density(f)}{Noise\ Power\ Spectral\ Density(f)} \triangleq \frac{PSD_{signal}(f)}{PSD_{noise}(f)}$$

Optimal (non-causal) Wiener Filter, *H(f)*

$$H(f) = \frac{PSD_{signal}(f)}{PSD_{signal}(f) + PSD_{noise}(f)} = \frac{SDR(f)}{SDR(f)+1}$$



Communication: Bit Rate Capacity of a Noisy Channel



Shannon-Hartley Theorem, *C* bits/s

$$C = BW \log_2\left(\frac{S}{N} + 1\right) = BW \log_2\left(SNR + 1\right)$$

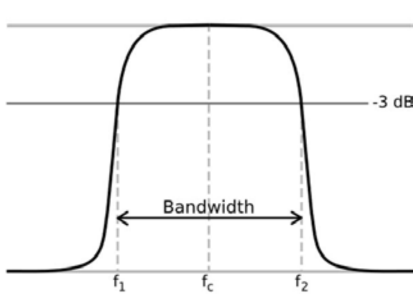
$S =$ Signal Power, e.g., watts
$N =$ Noise Power, e.g., watts
$BW =$ Channel Bandwidth, Hz
$C =$ Channel Capacity, bits/s

Information Bandwidth

$$f_c = \text{carrier frequency, Hz}$$
$$BW = \Delta f = f_2 - f_1 = \text{information signal bandwidth, Hz}$$

- **Low-frequency information signal superimposed on (i.e., *modulates*) high-frequency carrier radio signal for transmission**

Power spectral density of transmitted signal



- **Information signal formats**
  - **Analog (continuous)**
  - **Digital (discrete)**
  - **Digitized analog (i.e., A/D conversion)**

Entropy Measures Information Content of a Signal

- ***H*** **= Entropy of a signal encoding *I* distinct events**

$$\boxed{H = -\sum_{i=1}^{I} \Pr(i) \log_2 \Pr(i)}$$

$$0 \le \Pr(.) \le 1$$
$$\log_2 \Pr(.) \le 0$$
$$0 \le H \le 1$$

- **Entropy is a measure of the signal's uncertainty**
  - ***High entropy connotes high uncertainty***
  - ***Low entropy portrays high information content***
- ***i*** **= Index identifying an event encoded by a signal**
- **Pr(*i*) = Probability of i^{th} event**
- **$\log_2\Pr(i)$ = Number of bits required to characterize the probability that the i^{th} event occurs**

Entropy of Two Events with Various Frequencies of Occurrence

- **$-\Pr(i)\log_2\Pr(i)$ represents the channel capacity (i.e., average number of bits) required to portray the i^{th} event**
- **Frequencies of occurrence estimate probabilities of each event (#1 and #2)**

$$\Pr(\#1) = \frac{n(\#1)}{N}$$
$$\Pr(\#2) = \frac{n(\#2)}{N} = 1 - \frac{n(\#1)}{N}$$

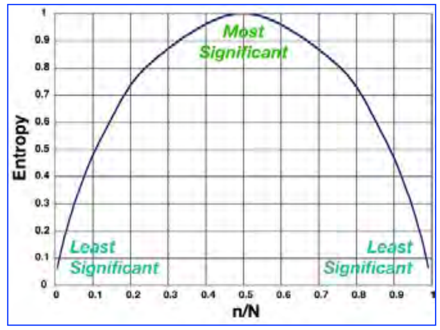
$$\boxed{\log_2 \Pr\left(\#1 \text{ or } \#2\right) \le 0}$$

- **Combined entropy**

$$H = H_{\#1} + H_{\#2}$$
$$= -\Pr(\#1)\log_2\Pr(\#1) - \Pr(\#2)\log_2\Pr(\#2)$$

Entropy of Two Events with Various Frequencies of Occurrence

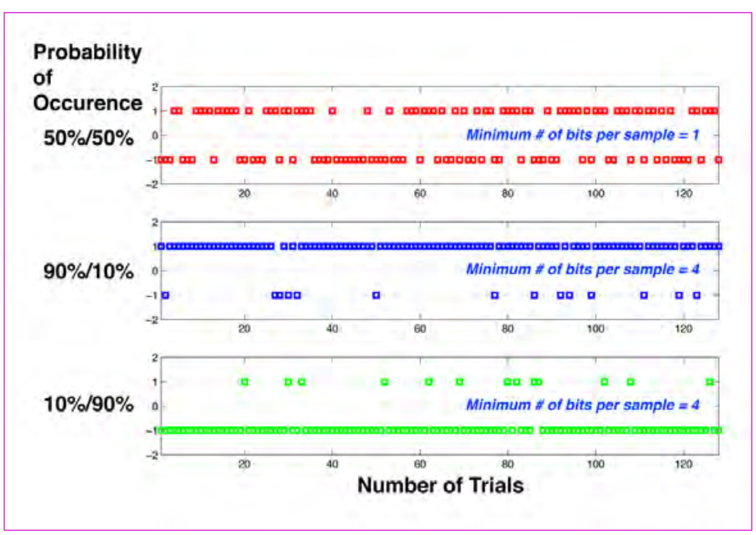
	Entropies for 128 Trials				
	Pr(#1)	- # of Bits(#1)	Pr(#2)	- # of Bits(#2)	Entropy
n	n/N	$\log_2(n/N)$	1 - n/N	$\log_2(1 - n/N)$	*H*
1	0.008	-7	0.992	-0.011	0.066
2	0.016	-6	0.984	-0.023	0.116
4	0.031	-5	0.969	-0.046	0.201
8	0.063	-4	0.938	-0.093	0.337
16	0.125	-3	0.875	-0.193	0.544
32	0.25	-2	0.75	-0.415	0.811
64	0.50	-1	0.50	-1	1
96	0.75	-0.415	0.25	-2	0.811
112	0.875	-0.193	0.125	-3	0.544
120	0.938	-0.093	0.063	-4	0.337
124	0.969	-0.046	0.031	-5	0.201
126	0.984	-0.023	0.016	-6	0.116
127	0.992	-0.011	0.008	-7	0.066



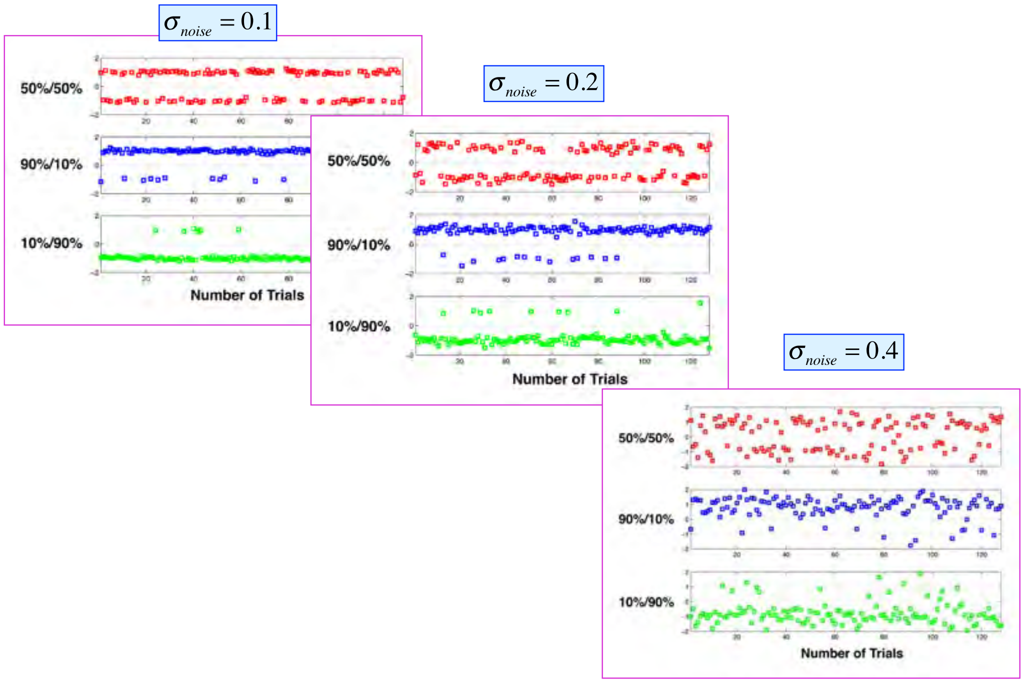
Entropy of a fair coin flip = 1

Accurate Detection of Events Depends on Their Probability of Occurence

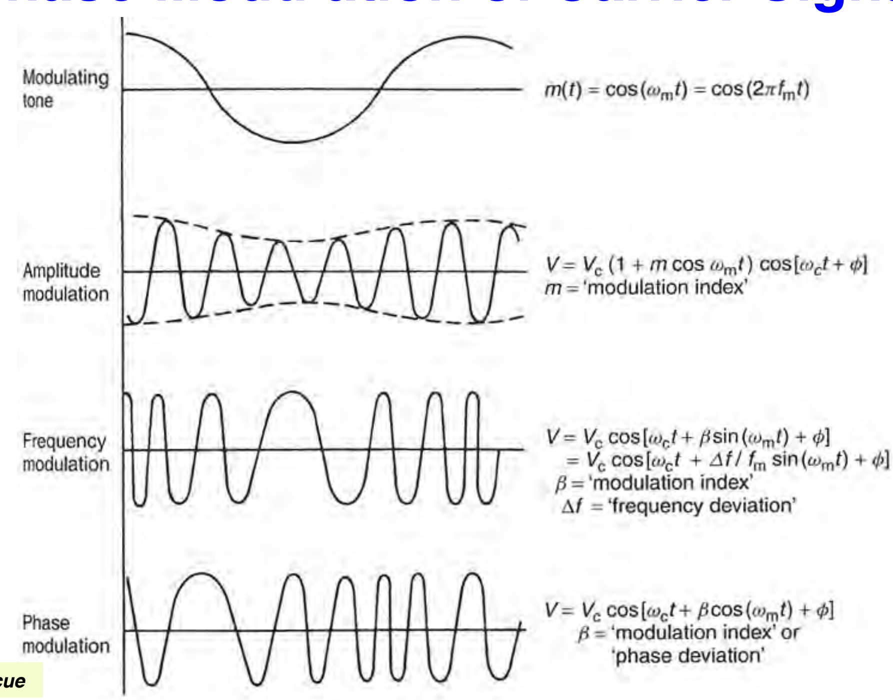
Signals Rounded to Their Intended Values



Accurate Detection of Events Depends on Their Probability of Occurrence

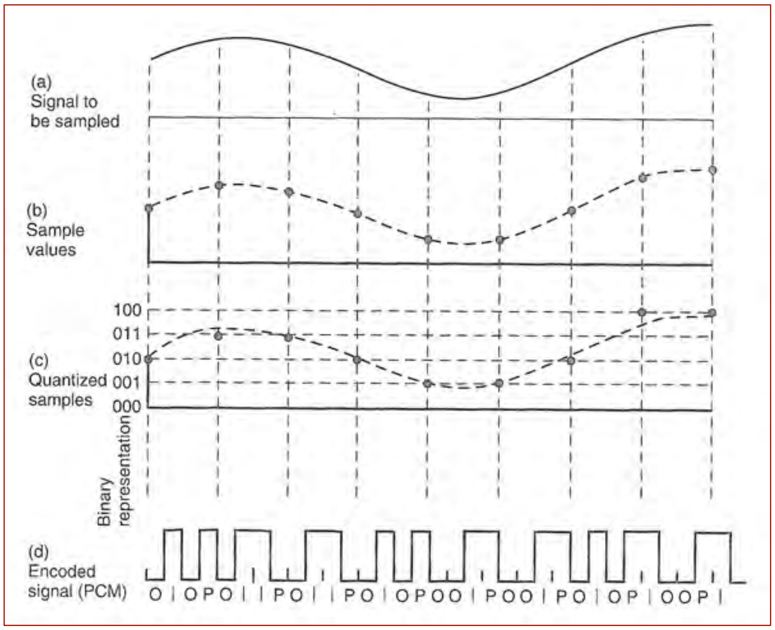


Analog Amplitude, Frequency, and Phase Modulation of Carrier Signal



Fortescue

Sampling and Digitization



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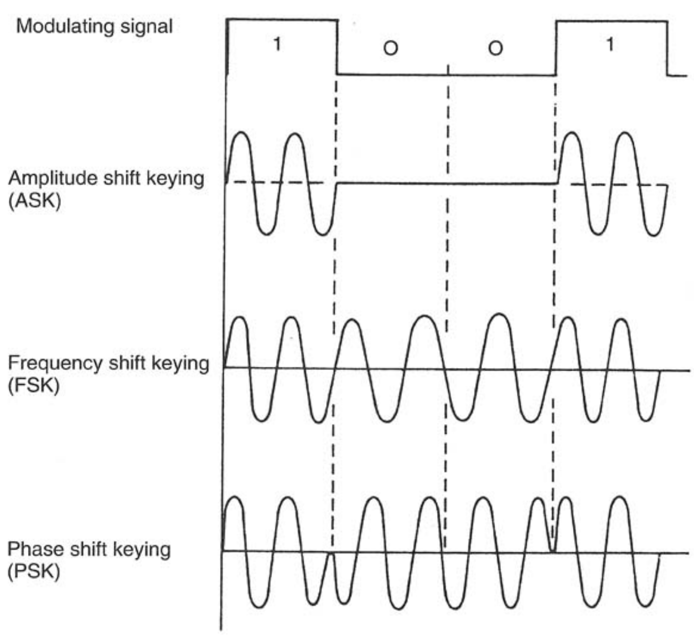
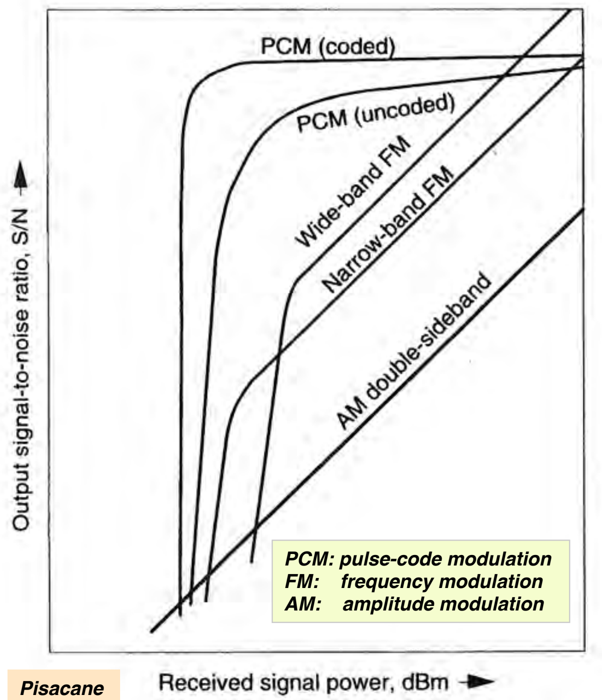
Digital Amplitude-, Frequency-, and Phase-Shift Modulation of Carrier Signal



Fortescue

Digital vs. Analog Modulation



- Analog
  - Amplitude modulation conserves bandwidth
  - Frequency modulation spreads information bandwidth over larger RF bandwidth
- Digital
  - Pulse-code modulation (particularly phase-shift keying) uses RF power most efficiently

Link Budget for a Digital Data Link

$$\frac{E_b}{N_o} = \frac{S}{N}\frac{BW}{R}$$

Link budget design goal is to achieve satisfactory E_b/N_o by choice of link parameters

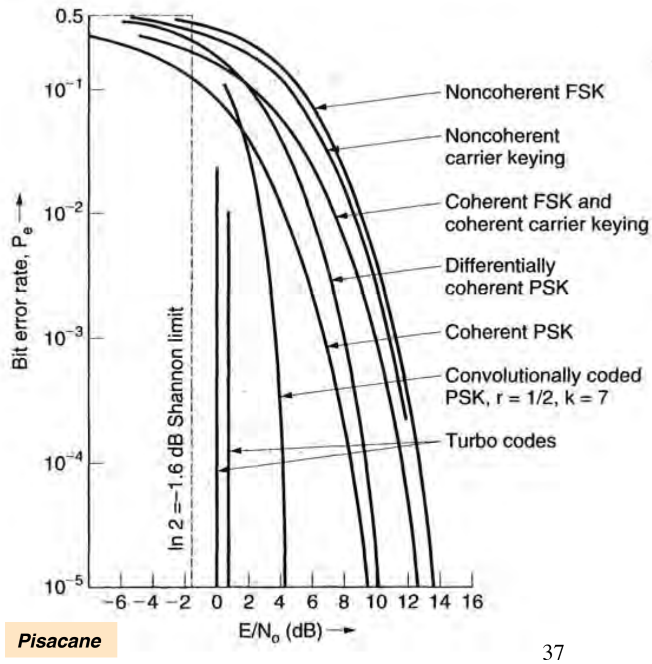
$$\frac{E_b}{N_o} = \frac{P_t L_l G_t L_s L_a G_r}{k T_s R}$$

... in decibels?

P_t = transmitter power
L_l = transmitter-to-antenna line loss
G_t = transmit antenna gain
L_s = space loss
L_a = transmission path loss
G_r = receive antenna gain
k = Boltzmann's constant
T_s = system noise temperature

Bit Error Rate vs. E_b/N_o

- Goal is to achieve lowest bit error rate (BER) with lowest E_b/N_o
- Implementation losses increase required E_b/N_o
- Link margin is the difference between the minimum and actual E_b/N_o
- BER can be reduced by error-correcting codes
  - Number of bits transmitted is increased
  - Additional check bits allow errors to be detected and corrected



Pisacane

Performance of Coding/Decoding Methods

Code	Decoding Method	Coding Gain at $P_e = 10^{-5}$	Complexity
Block	Majority—hard decision	1.5–3.5 dB	Simple
Block BCH	Algebraic	1.5–4 dB	Complex
Convolutional	Threshold—hard decision	1.5–3 dB	Fairly simple
Convolutional	Viterbi—soft decision	4.5–5.5 dB	Fairly complex
Convolutional	Sequential—soft decision	5–7 dB	Fairly complex
Concatenated block-convolutional	Viterbi + algebraic	6.7–7.5 dB	Very complex
Turbo	Maximum à posteriori	8.8–9.4 dB	Fairly complex

Note: Theoretical BPSK requires $E_b/N_0 = 9.6$ dB for $P_e = 10^{-5}$.

P_e = Bit Error Rate (BER)
BPSK = Binary phase-shift keying

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Coding gain is net *S/N* improvement provided by adding check bits

Some Natural Numbering Systems

Natural numbers: non-negative, whole numbers

Denary (*Base 10*)	Binary (*Base 2*)	Unary (*Base 1*)
0	0	?
1	1	1
2	10	11
3	11	111
4	100	1111
5	101	11111
6	110	111111
7	111	1111111
8	1000	11111111
9	1001	111111111
10	1010	1111111111
11	1011	11111111111
Digits	Binary Digits "Bits" (John Tukey)	Marks
Two 5-finger hands One 10-finger hand	True-False Yes-No Present-Absent	Chalk and a rock Abacus "Chisenbop"

- Other number systems
  - Octal (*Base 8*)
  - Hexadecimal (*Base 16*)
  - DNA (*Base 4*) *[ATCG]*

American Standard Code for Information Interchange (ASCII) Code

7 data bits plus parity bit
Widely used in computers

Binary	Oct	Dec	Hex	Glyph
100 0000	100	64	40	@
100 0001	101	65	41	A
100 0010	102	66	42	B
100 0011	103	67	43	C
100 0100	104	68	44	D
100 0101	105	69	45	E
100 0110	106	70	46	F
100 0111	107	71	47	G
100 1000	110	72	48	H
100 1001	111	73	49	I
100 1010	112	74	4A	J
100 1011	113	75	4B	K
100 1100	114	76	4C	L
100 1101	115	77	4D	M
100 1110	116	78	4E	N
100 1111	117	79	4F	O

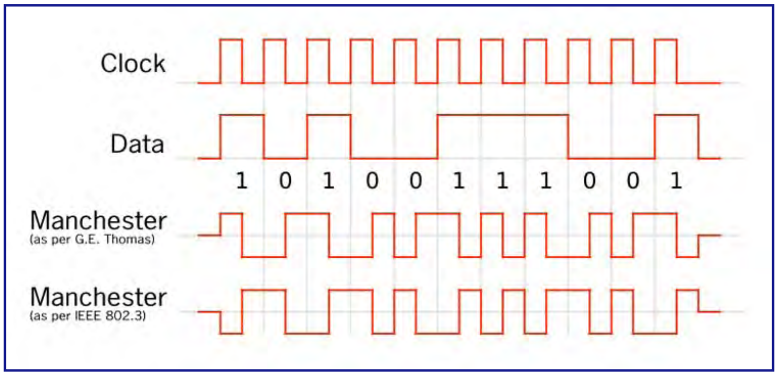
94 printable characters

```
 !"#$%&'()*+,-./
0123456789:;<=>?
@ABCDEFGHIJKLMNO
PQRSTUVWXYZ[\]^_
`abcdefghijklmno
pqrstuvwxyz{|}~
```

http://en.wikipedia.org/wiki/Ascii

Manchester Code for Telecommunication

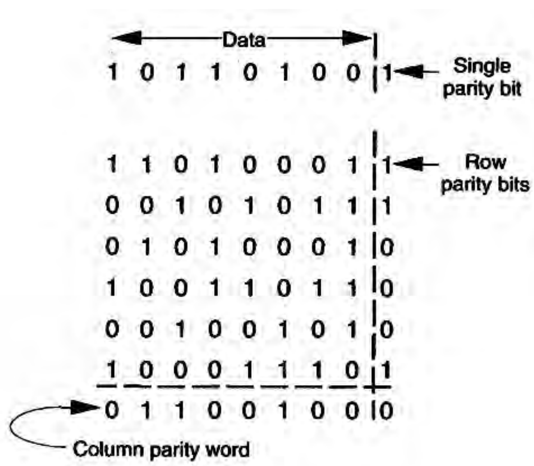
- Each data bit has one transition and occupies the same amount of time
- Self-clocking
- Widely used on Ethernet



http://en.wikipedia.org/wiki/Manchester_code

Error Detection and Correction

- Parity check (simple)
  - Transmitter
    - *n* Data bits added up
    - Parity bit added to make sum even
    - *n*+1 bits transmitted
  - Receiver
    - Check to determine if word is odd or even
    - If odd, odd number of errors has been detected (but not corrected)
  - Column-wise parity check of *m* words determines where bits are corrupted
    - Additional bits must be transmitted
- Turbo code (complex): see



http://en.wikipedia.org/wiki/Turbo_code

Typical Command and Telemetry Characteristics

Network	Command (Uplink) Freq. (GHz)	Command (Uplink) Data Rate (bps)	Telemetry (Downlink) Freq. (GHz)	Telemetry (Downlink) Data Rate (bps)
Air Force SCN (SGLS)	1.76–1.84	1,000 2,000	2.2–2.3	125– 1.024M
NASA DSN	2.025–2.120 7.145–7.190	1.0–2,000	2.2–2.3 8.4–8.5	8–6.6M
Intelsat/ COMSAT	5.92–6.42 14.0–14.5	100–250 100–250	3.9–4.2 12.2 or17.7	1,000–4,800 1,000–4,800
*TDRS*** (user satellite altitude below 12,000 km)*	*MA S-Band 2.1064 **SA S-Band 2.025–2.120 **SA K-Band 13.775	10 kbps max 300k max 25M max	MA S-Band 2.2875 SA S-Band 2.2–2.3 SA K-Band 15.0034	1k to 1.5M 1k to 12M 1k to 300M

Larson, Wertz

*MA—Multiple Access, up to 20 users simultaneously
**SA—Single Access ***Frequencies to and from user satellite

Communications Carrier Frequencies

Frequency Band	Frequency Range (GHz) Uplink	Frequency Range (GHz) Downlink	Service	Downlink Power Flux Density Limit (dBW/m^2)
UHF	0.2 – 0.45	0.2 – 0.45	Military	—
L	1.635 – 1.66	1.535 – 1.56	Maritime/Nav Telephone	–1.44/4 kHz
S	2.65 – 2.69	2.5 – 2.54	Broadcast, Telephone	–137/4 kHz
C	5.9 – 6.4	3.7 – 4.2	Domestic, Comsat	–142/4 kHz
X	7.9 – 8.4	7.25 – 7.75	Military, Comsat	–142/4 kHz*
Ku	14.0 – 14.5	12.5 – 12.75	Domestic, Comsat	–138/4 kHz
Ka	27.5 – 31.0	17.7 – 19.7	Domestic, Comsat	–105/1 MHz
SHF/EHF	43.5 – 45.5	19.7 – 20.7	Military, Comsat	—
SHF/EHF	49	38	Internet Data, Telephone, Trunking	–135/1 MHz
V	-60		Satellite Crosslinks	—

*No limit in exclusively military band of 7.70–7.75 GHz.

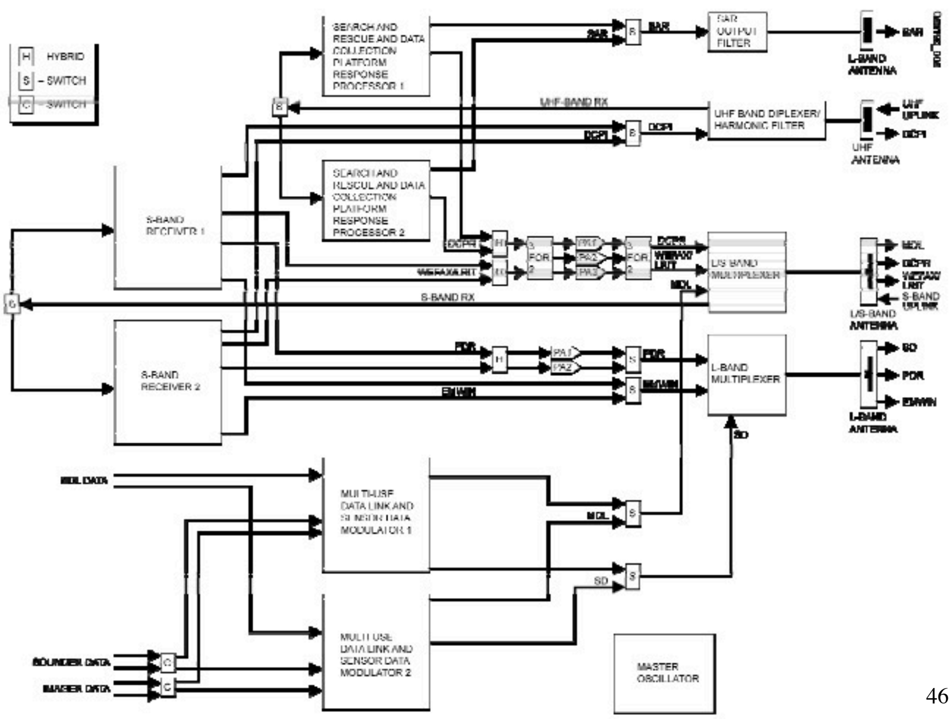
Larson, Wertz

Typical Communication Satellite Transponder Characteristics

Satellite	Band	Transponder Bandwidth (MHz)	Number Transponders	Total Relay Bandwidth (MHz)
Intelsat-V	C Ku	36/41 72/77 72/77 241	4/1 12/4 2/2 2	2,137
DSCS-III	X	50 60 85	1 4 1	375
Globalstar	L, S, C	16.5	16	264
Generic Internet	Ka	100–1,000	20	4,000

Larson, Wertz

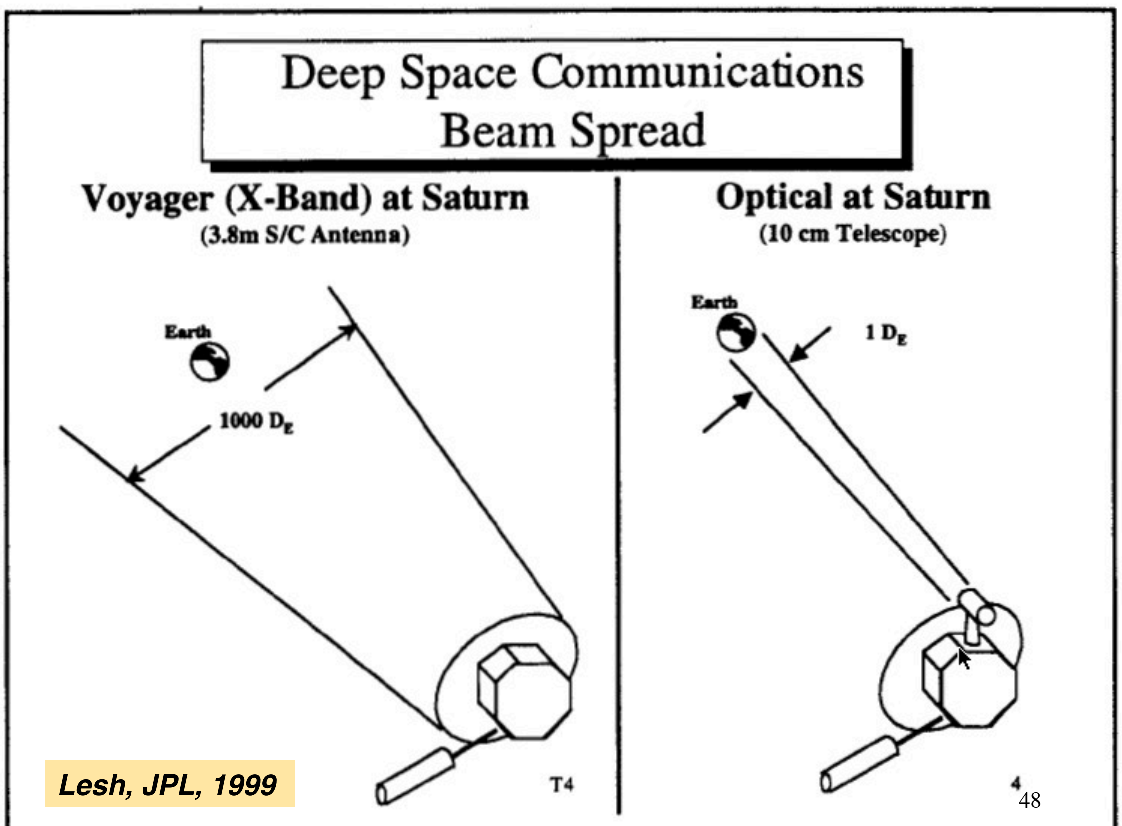
GOES Communication Sub-System



Free-Space Laser Communication

- Diffraction limit of electro-magnetic beam is proportional to ***λ/d***
  - ***λ*** = Wavelength
  - ***d*** = aperture (diameter) of beam source
  - Radio frequency wavelengths: ***cm – m***
  - Optical wavelengths: ***μm***
  - Up to 10^6 less beam spread for optical communication

Lesh, JPL, 1999



Lesh, JPL, 1999

Optical Communication Advantage Compared to Ka-Band RF

(One-Way Pluto example, same power input)

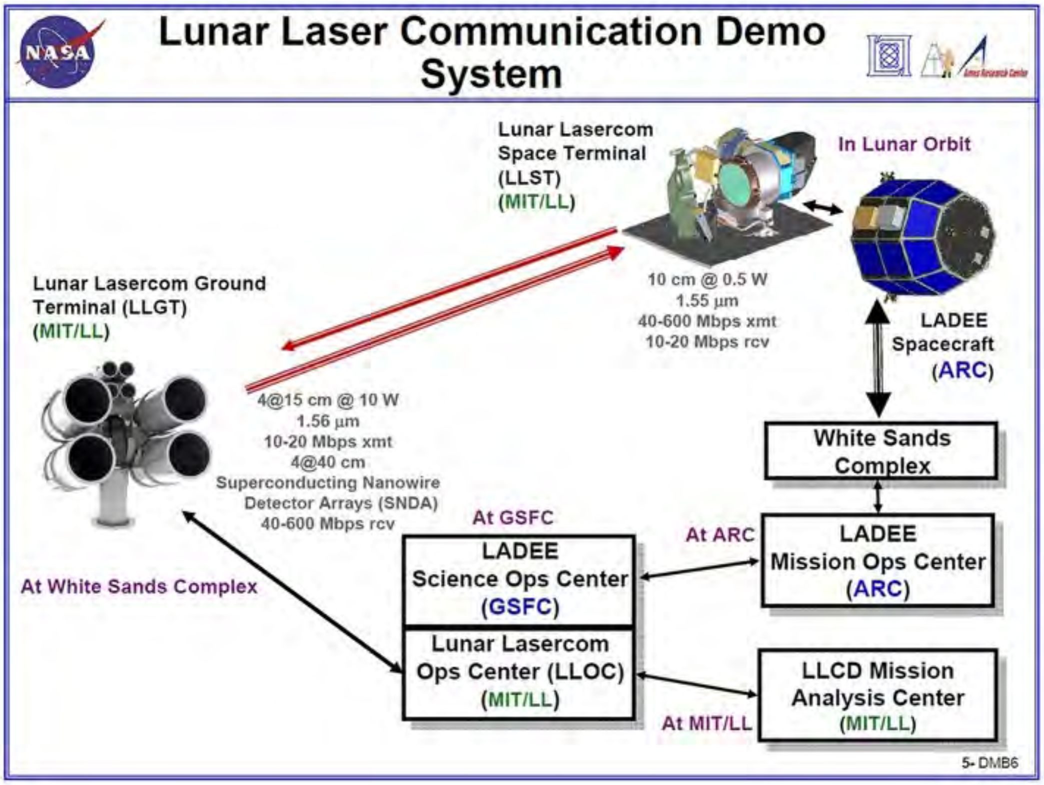
dB	Factor	Comparison
13	Data Rate Increase	4.9 kbs vs. 270 bps
26	Smaller Spacecraft Aperture	10 cm vs. 2 m
4	Less Transmitted Power Required	1 W vs. 2.7 W
7	Lower Transmitter Efficiency	5% vs. 28%
2	Lower System Efficiencies	24% vs. 40%
3	Atmospheric Loss	-
10	Smaller Ground Station	10 m vs. 34 m

Lesh, JPL, 1999

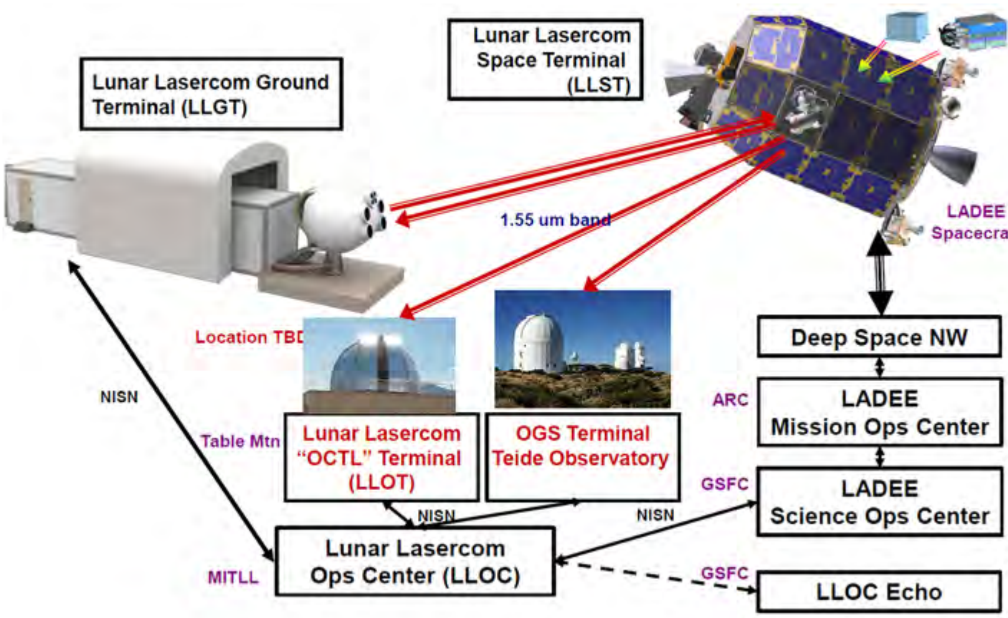
Good News/Bad News for Optical Communication

- **Good news**
  - Higher bit rates possible
  - Optical beams are narrower
  - Energy concentrated on receiver
- **Bad News**
  - Optical beams are narrower
  - Narrow beams must pointed more precisely
  - Must track intended receiver
  - RF may be preferred for acquisition, command, and tracking
  - Effects of cloud cover

Lesh, JPL, 1999

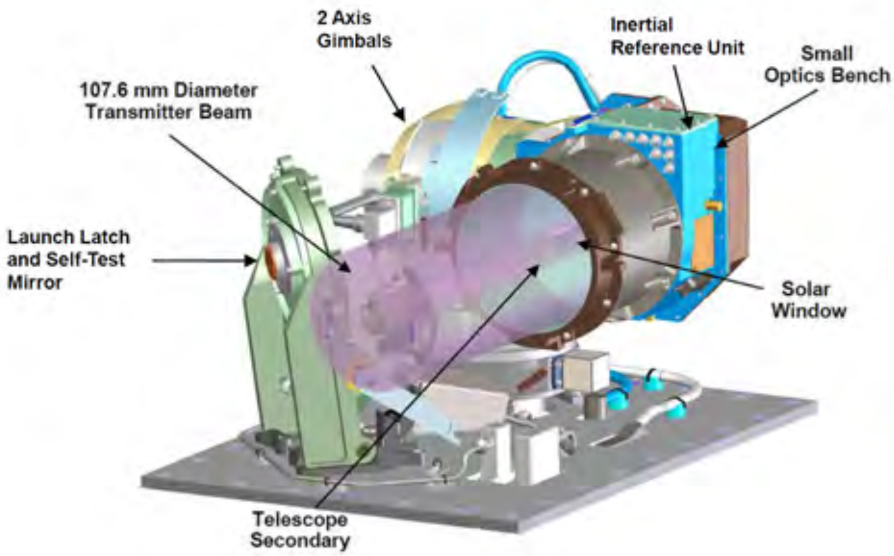


Lunar Laser Communication Demo System
Lunar Lasercom Space Terminal (LLST) (MIT/LL)
In Lunar Orbit
Lunar Lasercom Ground Terminal (LLGT) (MIT/LL)
10 cm @ 0.5 W
1.55 μm
40-600 Mbps xmt
10-20 Mbps rcv
LADEE Spacecraft (ARC)
4@15 cm @ 10 W
1.56 μm
10-20 Mbps xmt
4@40 cm
Superconducting Nanowire Detector Arrays (SNDA)
40-600 Mbps rcv
White Sands Complex
At GSFC
At ARC
LADEE Science Ops Center (GSFC)
LADEE Mission Ops Center (ARC)
At White Sands Complex
Lunar Lasercom Ops Center (LLOC) (MIT/LL)
LLCD Mission Analysis Center (MIT/LL)
At MIT/LL
5- DMB6

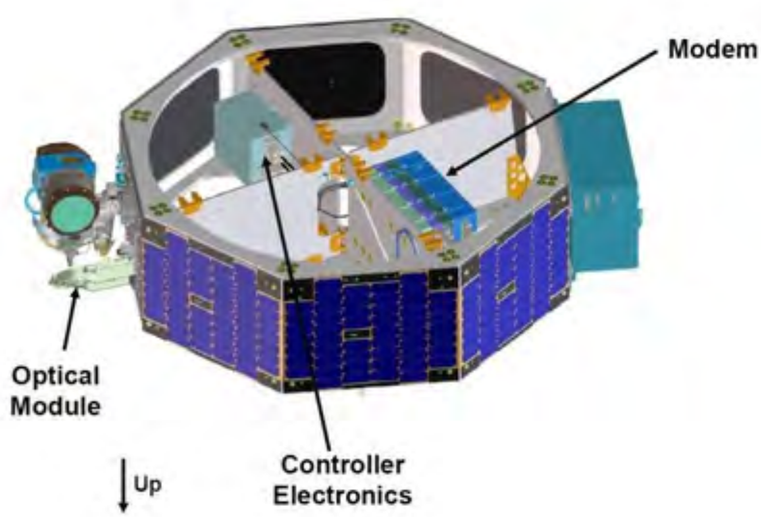


Lunar Lasercom Space Terminal (LLST)
Lunar Lasercom Ground Terminal (LLGT)
1.55 um band
LADEE Spacecraft
Location TBD
Deep Space NW
NISN
ARC
LADEE Mission Ops Center
Table Mtn
Lunar Lasercom "OCTL" Terminal (LLOT)
OGS Terminal Teide Observatory
GSFC
LADEE Science Ops Center
NISN
NISN
Lunar Lasercom Ops Center (LLOC)
MITLL
GSFC
LLOC Echo

LADEE Lunar LaserCom Space Terminal



LADEE LaserCom Components

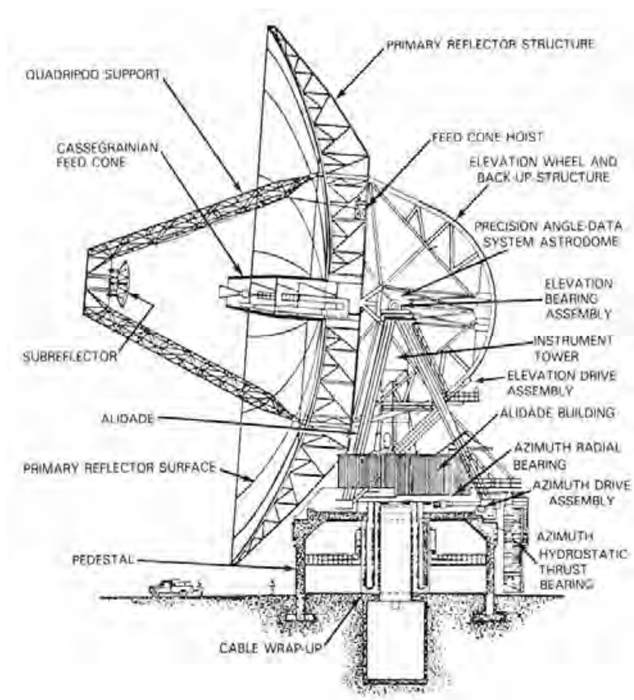


Deep Space Network

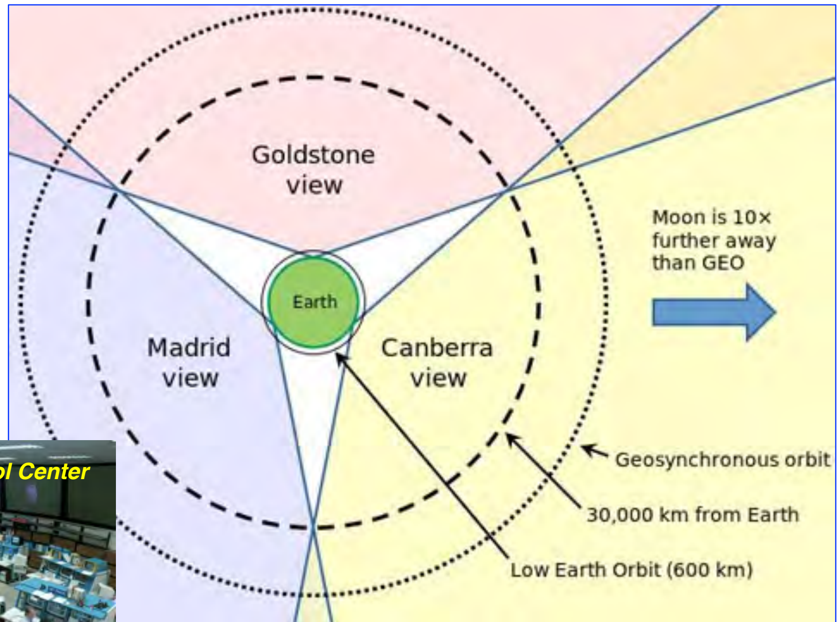
- Command and telemetry
- Radar tracking (range, elevation, and azimuth)
- Radiated signal power drops off as $1/r^2$
- Reflected return signal power drops off as $1/r^2$
- "Skin track" return signal power drops off as $1/r^4$
- Beacon (or transponder) on cooperative target
  - Receives radiated signal
  - Re-transmits fresh signal
    - Known time delay
    - Different frequency
  - Return signal power drops off as $1/r^2$

Goldstone 70-m Antenna

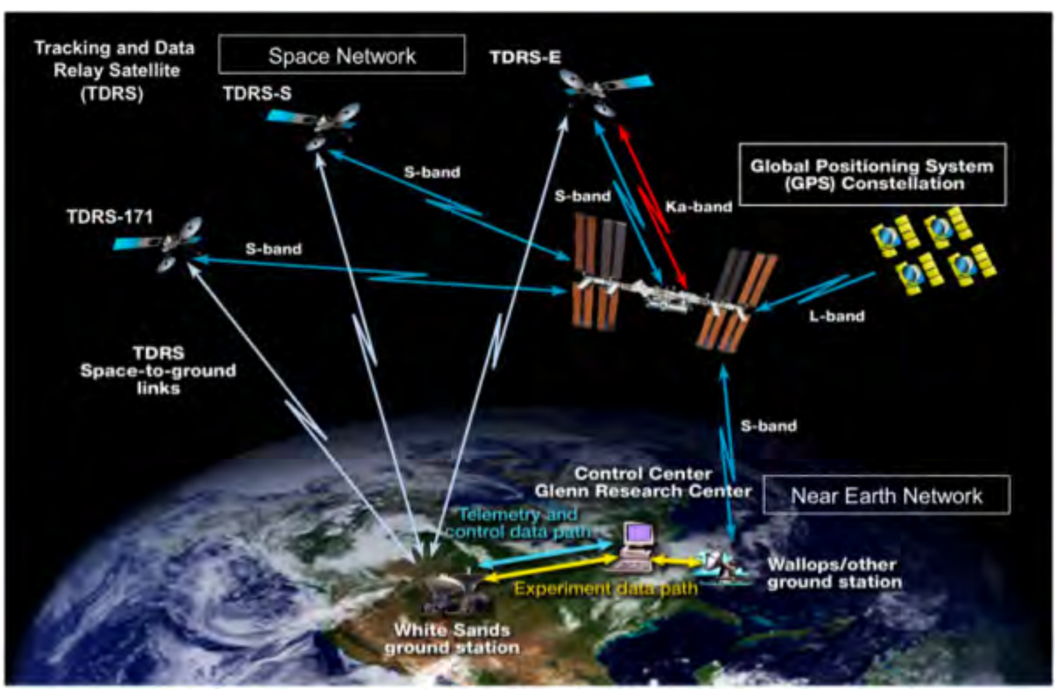
DSN 64-m Antenna

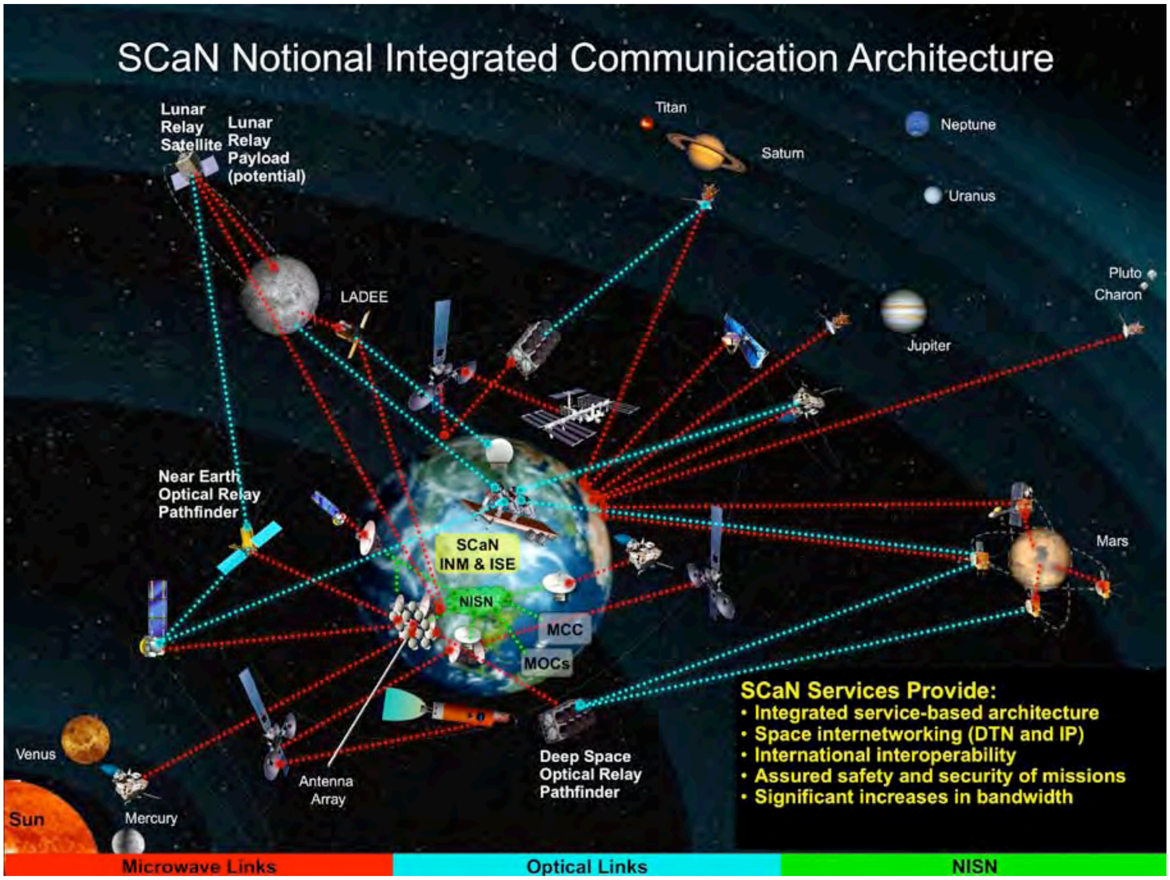


Deep Space Network Coverage



Tracking and Data Relay Satellites





Next Time:
Telemetry, Command, Data Handling & Processing

Supplemental Material

Signal-to-Noise Ratio per Bit, E_b/N_o

$$\boxed{\frac{E_b}{N_o} = \frac{S}{N}\frac{BW}{R}}$$

E_b : energy per bit

N_o : noise power spectral density

S = received signal power

N = received noise power

BW = bandwidth of receiver

R = data bit rate