Professional Development Short Course On:

Satellite RF Communications and Onboard Processing

Instructor:

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Eric Hoffman

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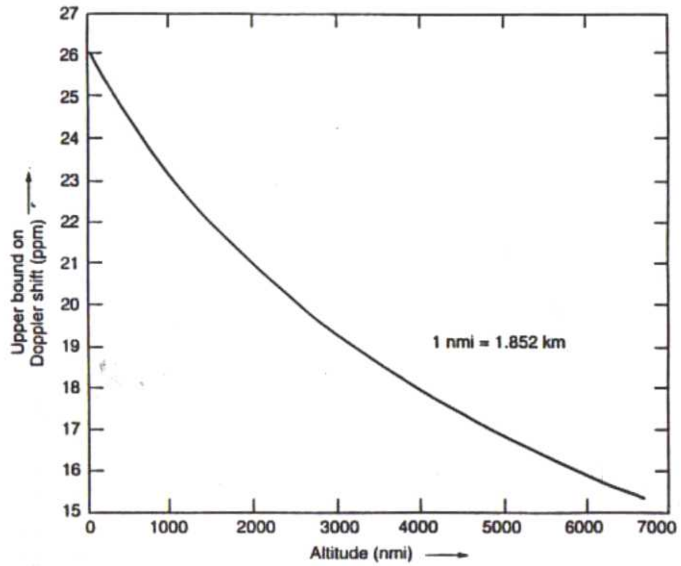
Special Characteristics of Space Links (2)

The satellite is constantly moving -



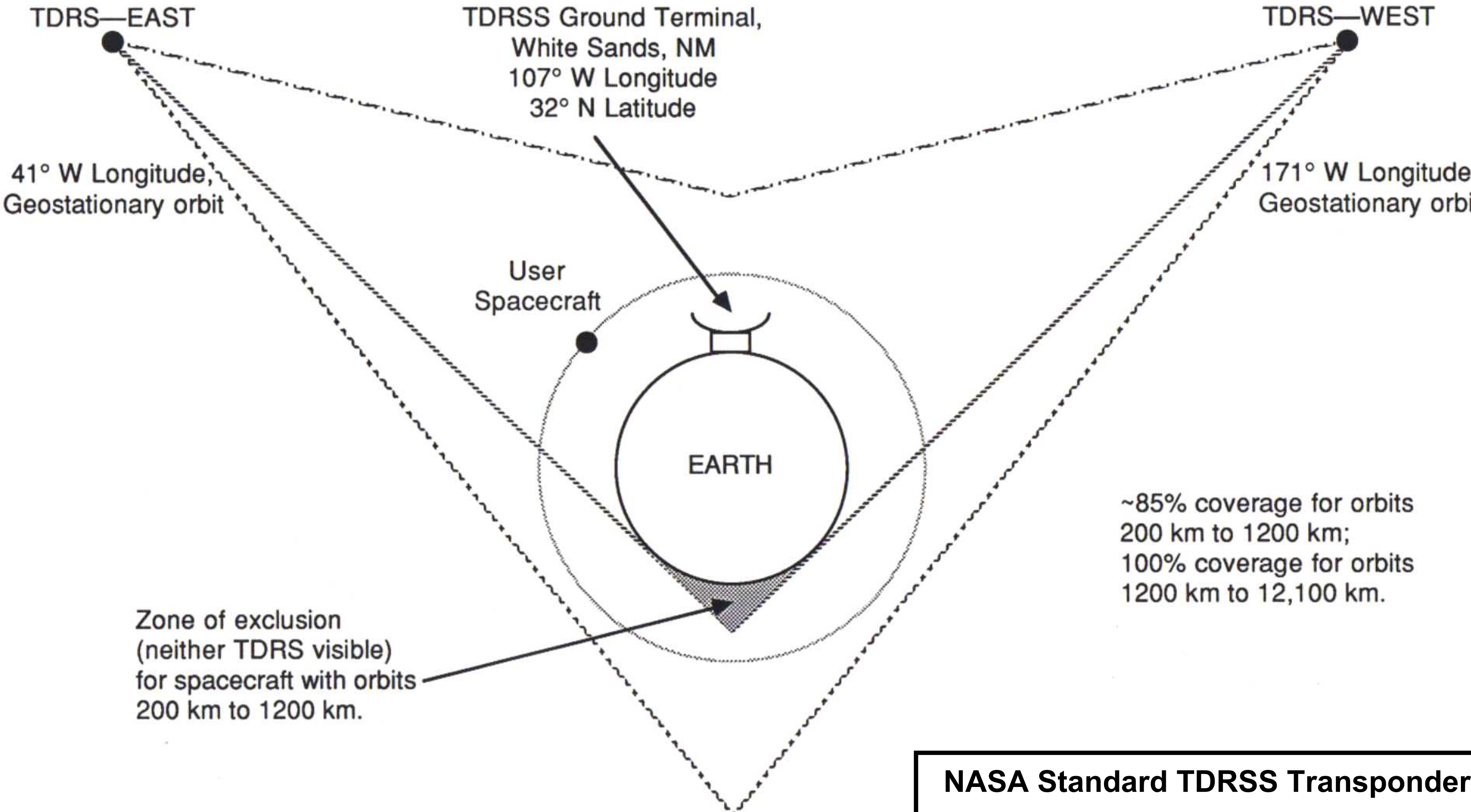
- Antennas must be constantly pointed
- Doppler shift complicates receiver design

  Example:

  Δf/f can be ± 25 ppm for LEO satellites (± 50 kHz at S-band).

- Poor station coverage, short pass times
  - continuous coverage would require hundreds of ground stations
  - may need data storage
  - special communications orbits (geostationary, Molniya)
  - data relay satellite

Tracking and Data Relay Satellite System (TDRSS)



NASA Standard TDRSS Transponder

5.9 x .5 x 4.5 inches, 5 kg

5 W output, 40 W DC input

Source: "Space Network Users' Guide," NASA GSFC, 1988

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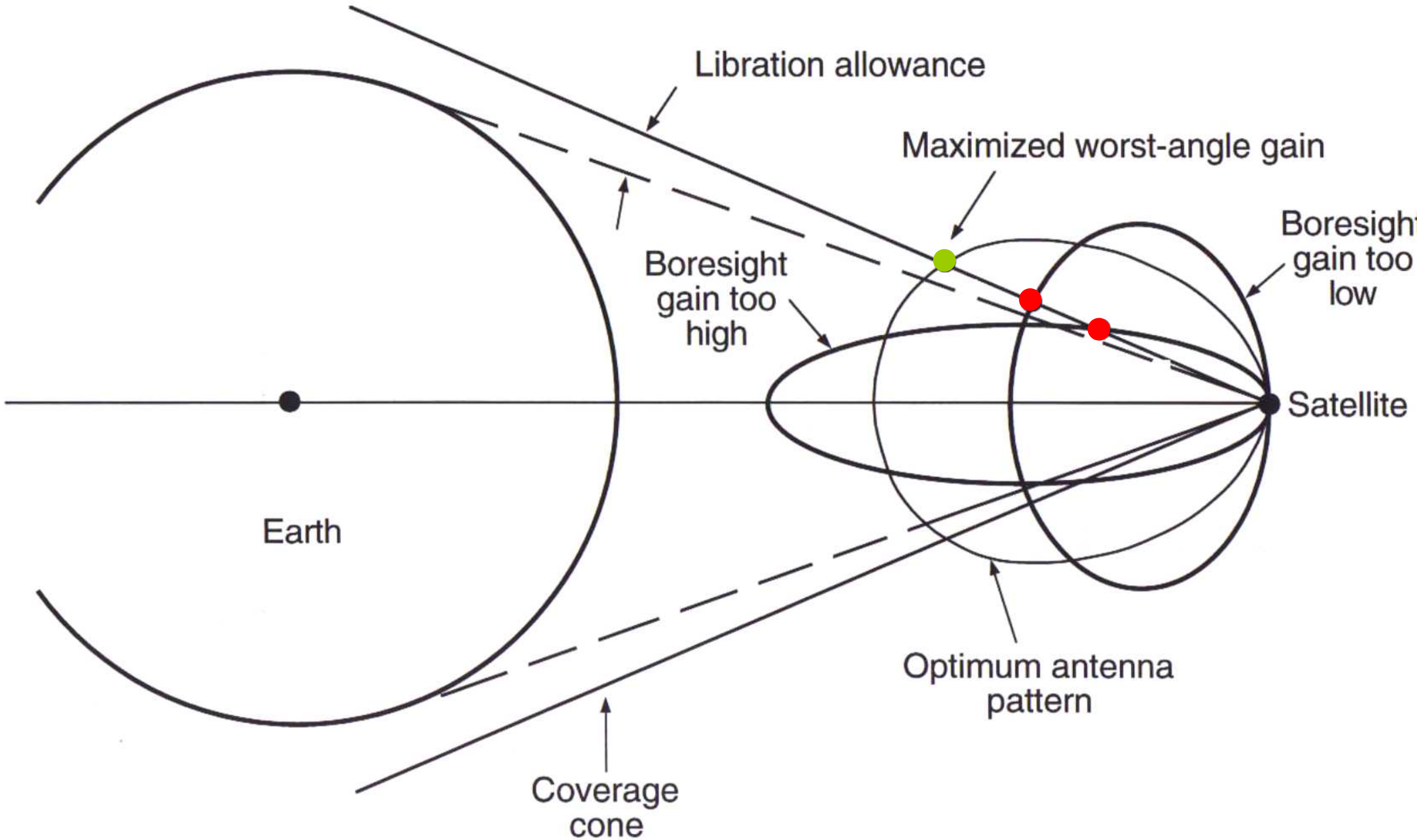
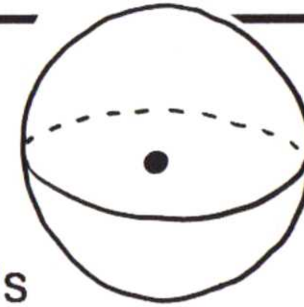
Optimizing the Beamwidth to Cover a Given Cone

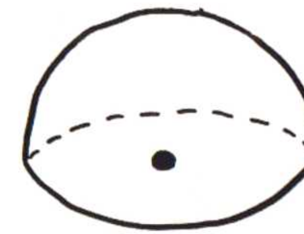


Antenna Considerations for Spacecraft

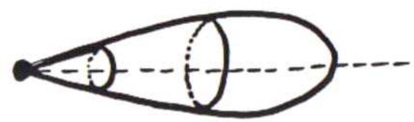
- Omnidirectional antennas



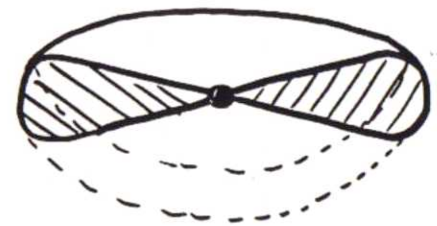
- Hemi – omni antennas, paired hemi – omni's



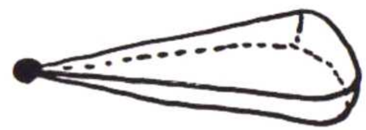
- Pencil beam antennas



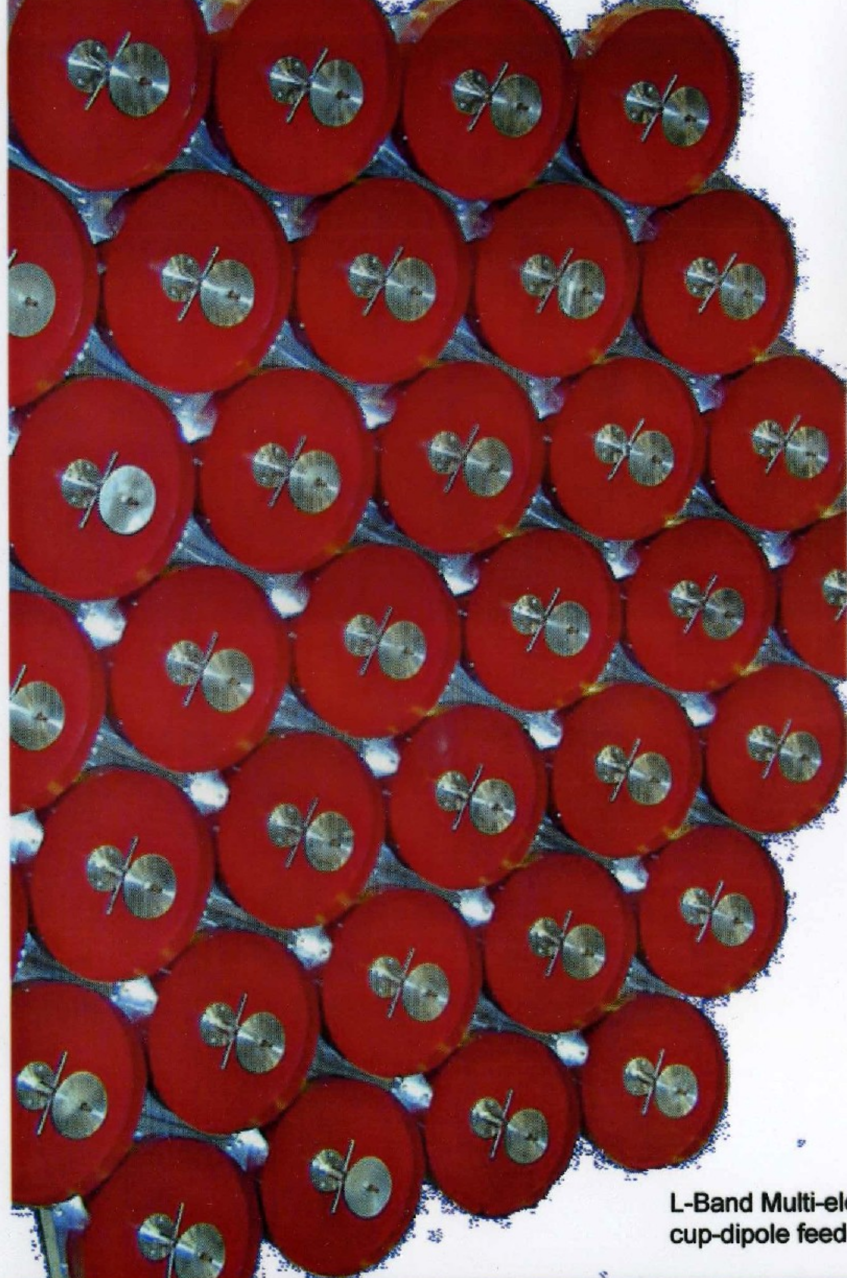
- Toroidal beam antennas



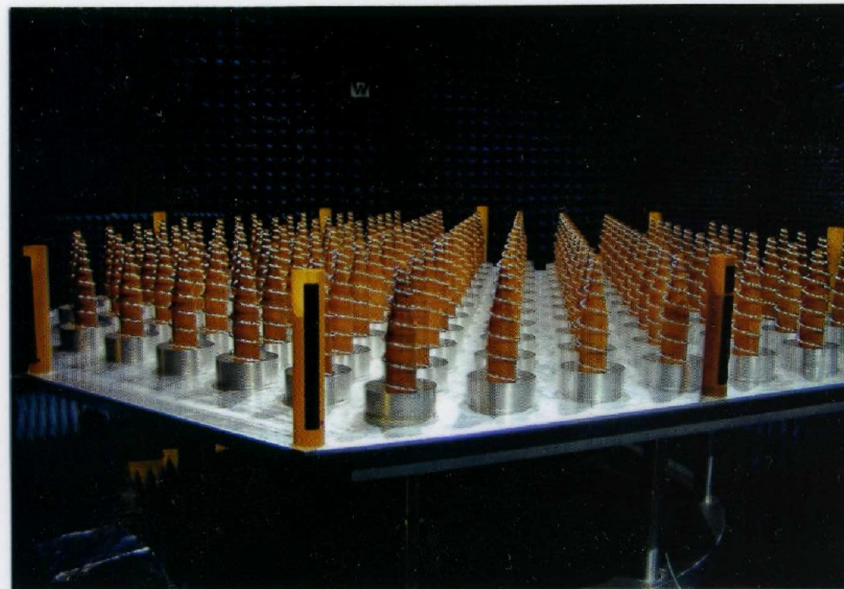
- Fan beam antennas



- Despun antennas
- Antennas are often large, delicate structures that must be stowed for launch, then deployed.
- Antennas are outside the spacecraft: extreme heat and cold, atomic oxygen erosion, ionizing and ultraviolet radiation.



L-Band Multi-element cup-dipole feed array

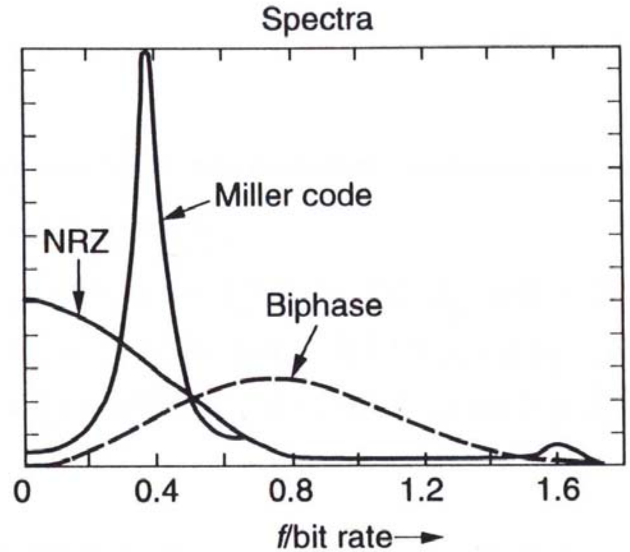


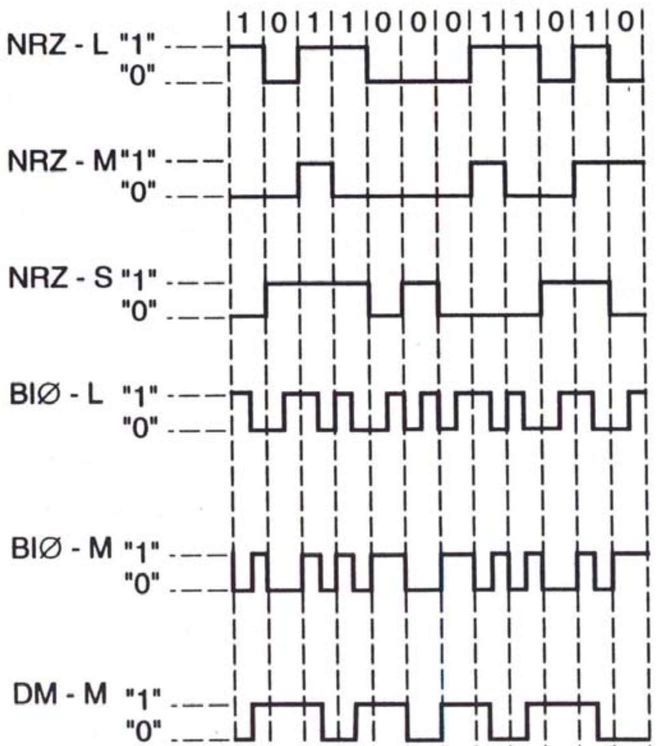
L-Band Multi-element TX/RX cup-helix feed

Space Station Ku-Band HGA

Antennas

Standard PCM Formats





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.

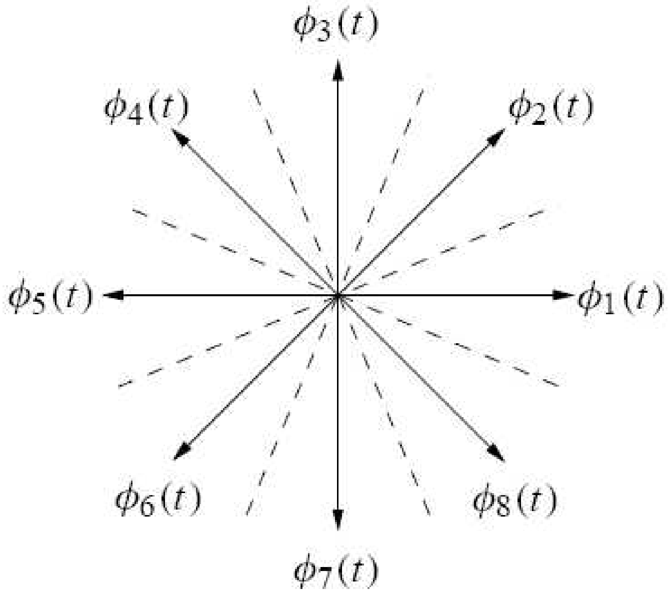
Non-return-to-zero-space
"One" is represented by no change in level.
"Zero" is represented by a change in level.

Biphase 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.

Biphase 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.

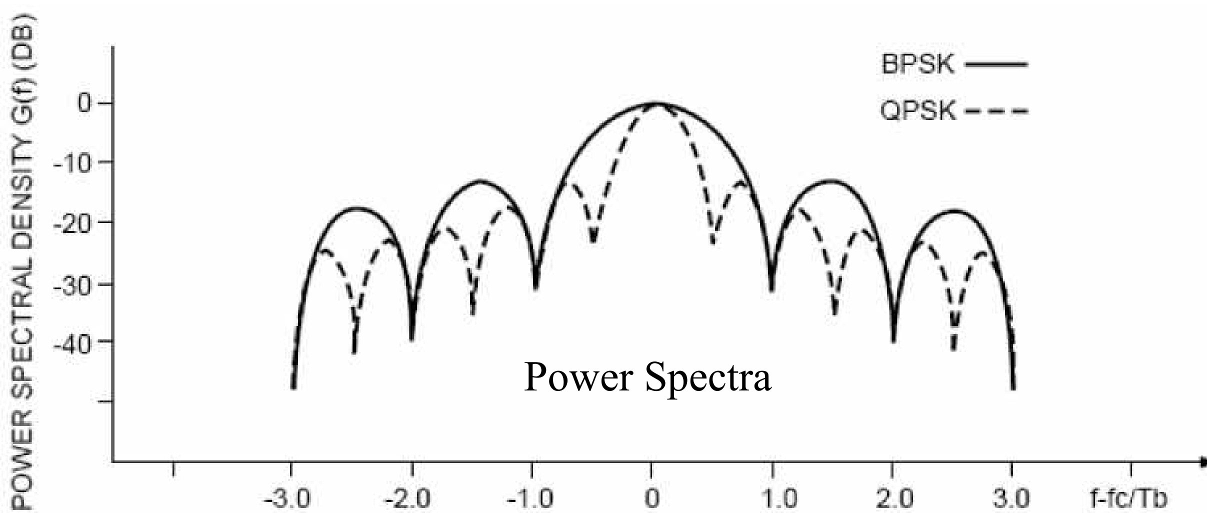
Delay modulation-mark (Miller code)
"One" is represented by a level change midbit time.
"Zero" followed by a "zero" is represented by a level change at the end of the first "zero" bit. No level change occurs when a "zero" is preceded by a "one."

M-ary Phase Shift Keying (m = 8)



For P_ε small,

$$P_\epsilon \approx 2\mathrm{erfc}\sqrt{\frac{2E_s}{\eta}\sin^2\frac{\pi}{M}}, \qquad M > 2$$



Power Spectra

Properties of Gaussian Noise

- Probability density of amplitude $$p(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2}}$$
- Average value, mean square value
- Time behavior, autocorrelation function $$R_v(\tau) = \int_{-\infty}^{\infty} v(t)v(t+\tau)dt$$
- Power spectral density, "white" noise $$G_v(f) = \int_{-\infty}^{\infty} R_v(\tau)e^{-j2\pi f\tau}d\tau$$
- Noise temperature $$T = \frac{N_o}{k} \frac{\text{(W/Hz)}}{\text{(W/Hz K)}}$$

where k is Boltzmann's constant = 1.38×10^{-23} W/Hz/K

Receiving System Figure of Merit - G/T

- The receiving system antenna gain divided by the system noise temperature provides a convenient "figure of merit" to compare receiving stations.

Example: G_r = + 50.0 dBi = 100,000

T_s = 200 K

$$\boxed{G/T = \frac{100{,}000}{200} = 500 = +\,27.0\ \text{dB/K}}$$

- Two systems having the same G/T will (to first order) have the same link performance.

State of the art!

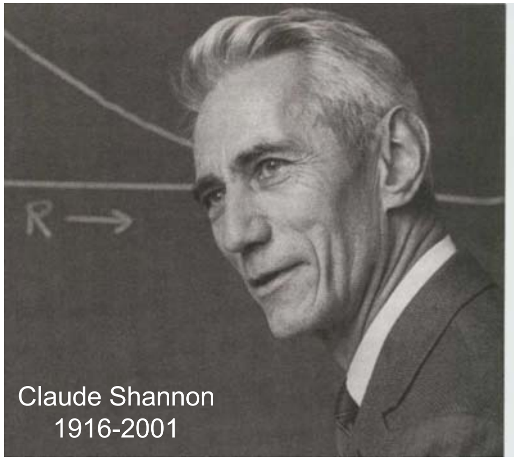
DSN Configuration	Typical G/T
Single 70 m	59 dB/K
Single 34 m	53 dB/K
Array of two 34 m	55.8 dB/K
Array of 1 70 m & 3 34 m	61.2 dB/K

Shannon's Channel Capacity

- Consider a channel with bandwidth W and signal-to-noise ratio S/N.

- In 1948 Claude Shannon proved "there exist" codes and modulations which permit error-free communication, provided the bit rate does not exceed

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



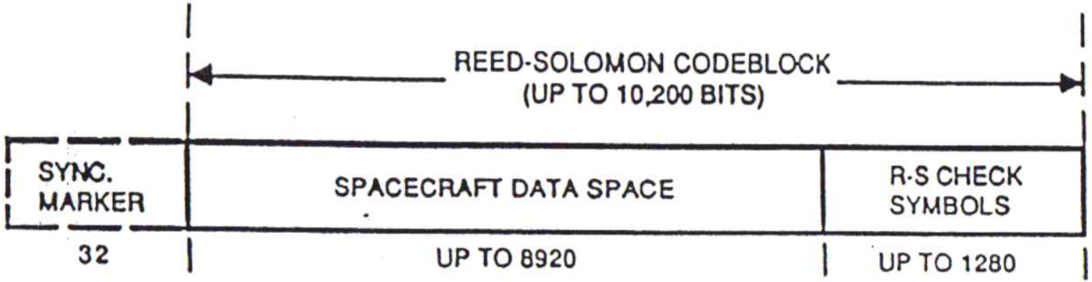
Claude Shannon
1916-2001

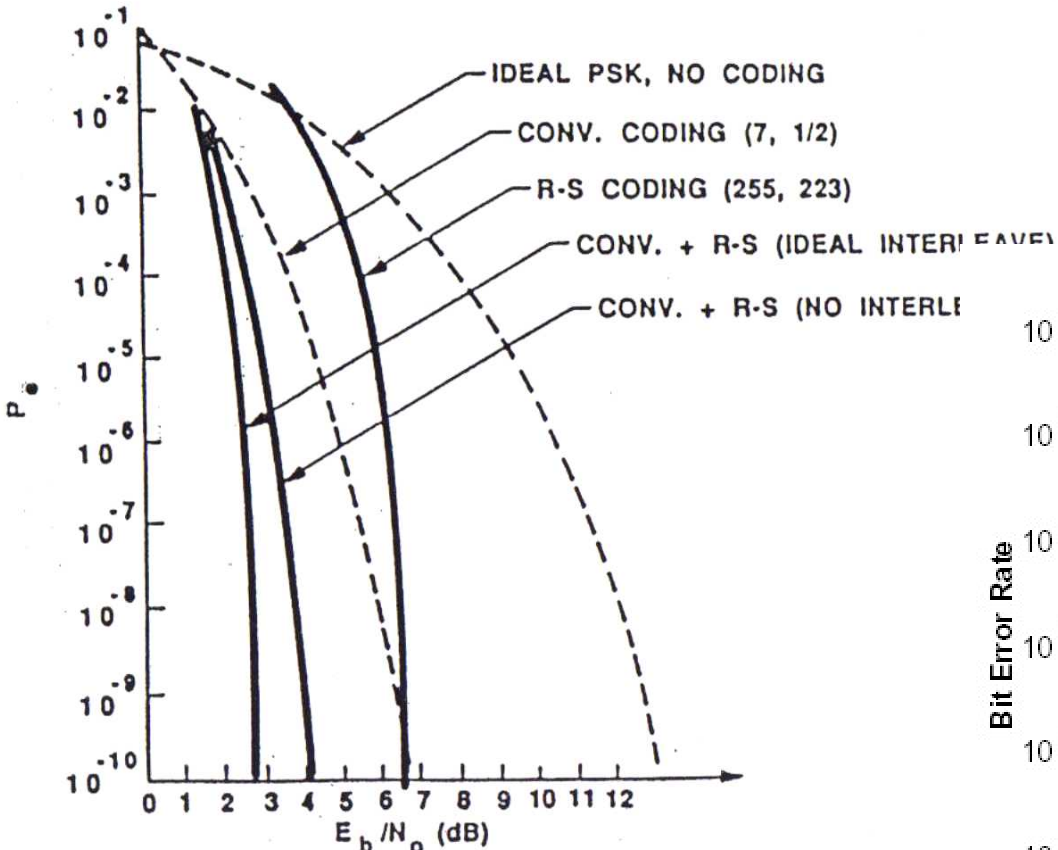
- Do not use this upper bound for design!

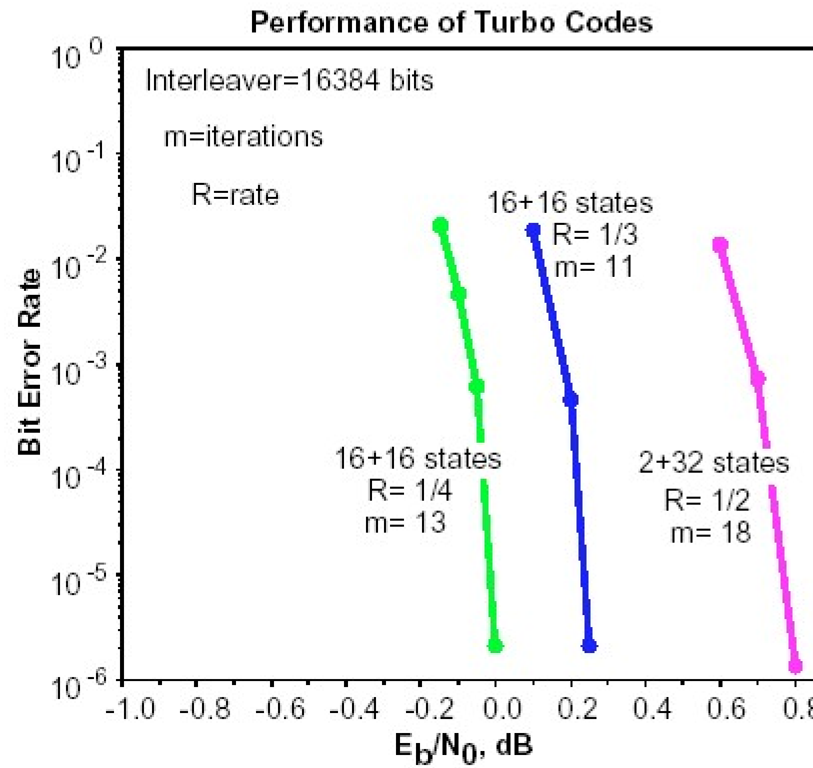
- By letting $N = N_o W$ and $W \longrightarrow \infty$, can show that error-free digital communication cannot take place below $E/N_o =$ -1.6 dB ($\ln 2$)

- High performance exacts a price: bandwidth spreading, abrupt thresholds, complex coding/decoding equipment, computational delays

REED-SOLOMON CODEBLOCK







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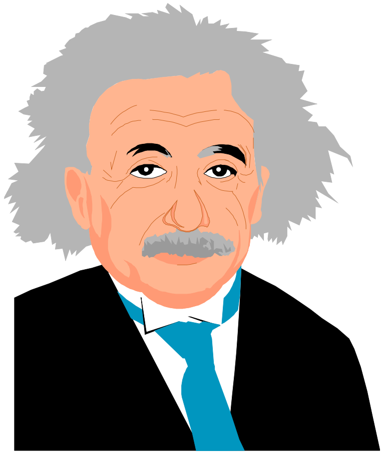
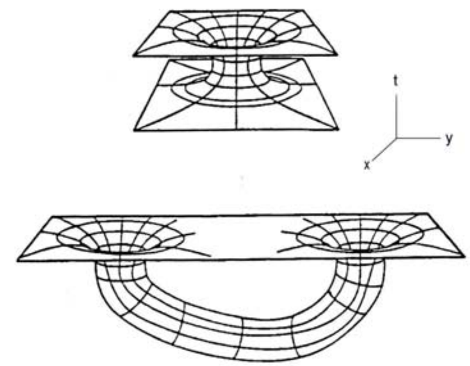
Supraluminal (faster-than-c) Communications



- Can a particle be accelerated to c?
- Can a particle have a velocity > c?
  - Tachyons: how generate, modulate, detect?



- Wormholes. Spacewarps through higher dimensions.
- Would supraluminal communications violate the Causality Principle?

References:

"Particles That Go Faster Than Light," Gerald Feinberg, *Sci. Amer*., 222, 2, Feb. 1970

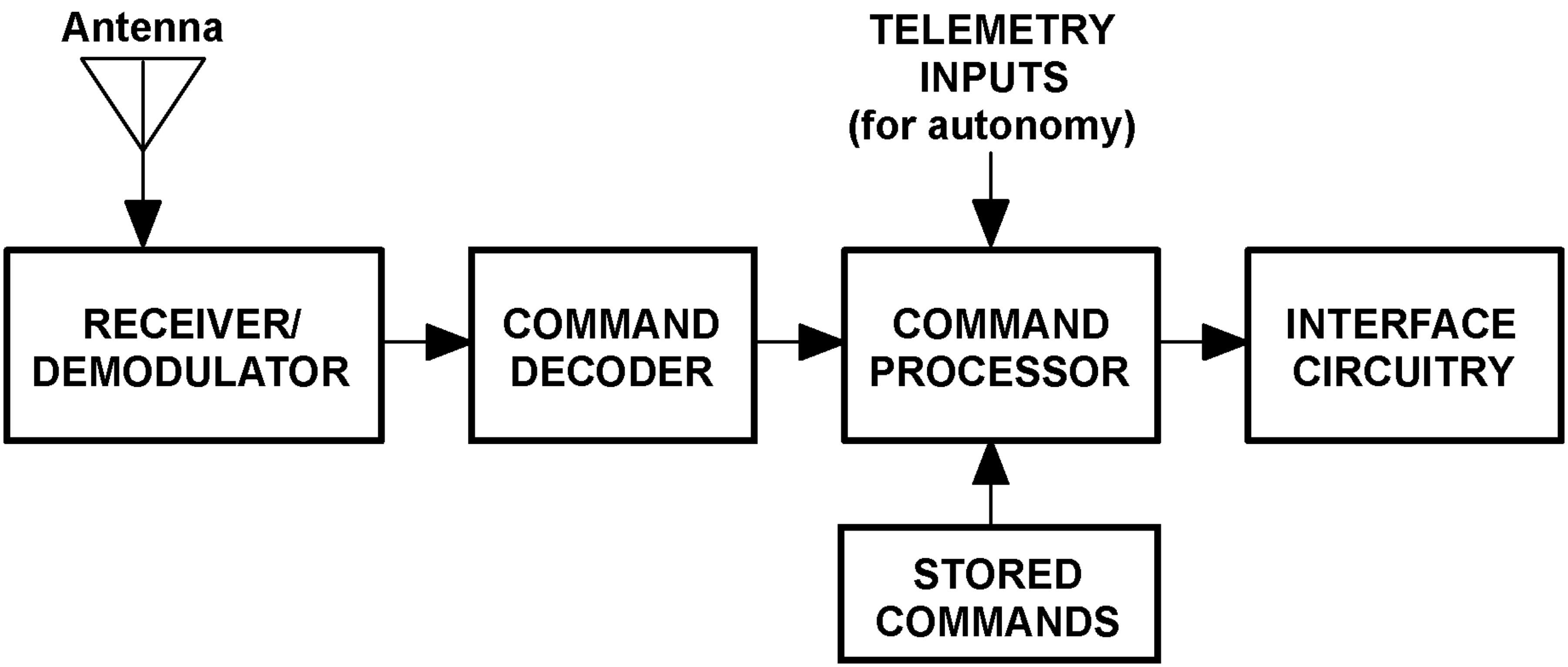
Timescape, Gregory Benford, Simon & Schuster, 1980

A Brief History of Time, Steven W. Hawking, Bantam, 1988

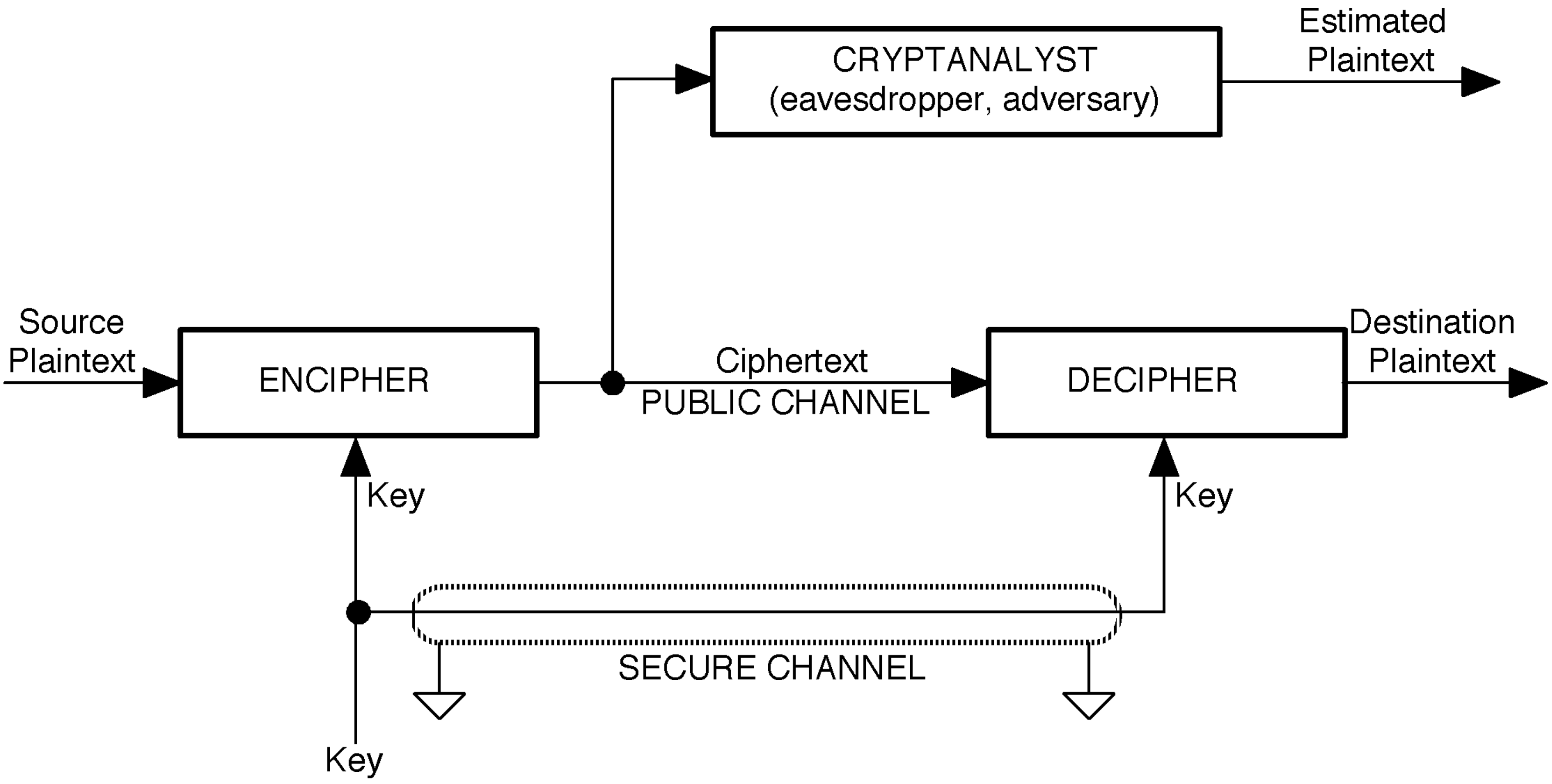
"Faster than Light?" R. Y. Chiao et al, *Sci Amer*., Aug. 1993

Nine Crazy Ideas in Science, Robert Ehrlich, Princeton Univ. Press, 2001

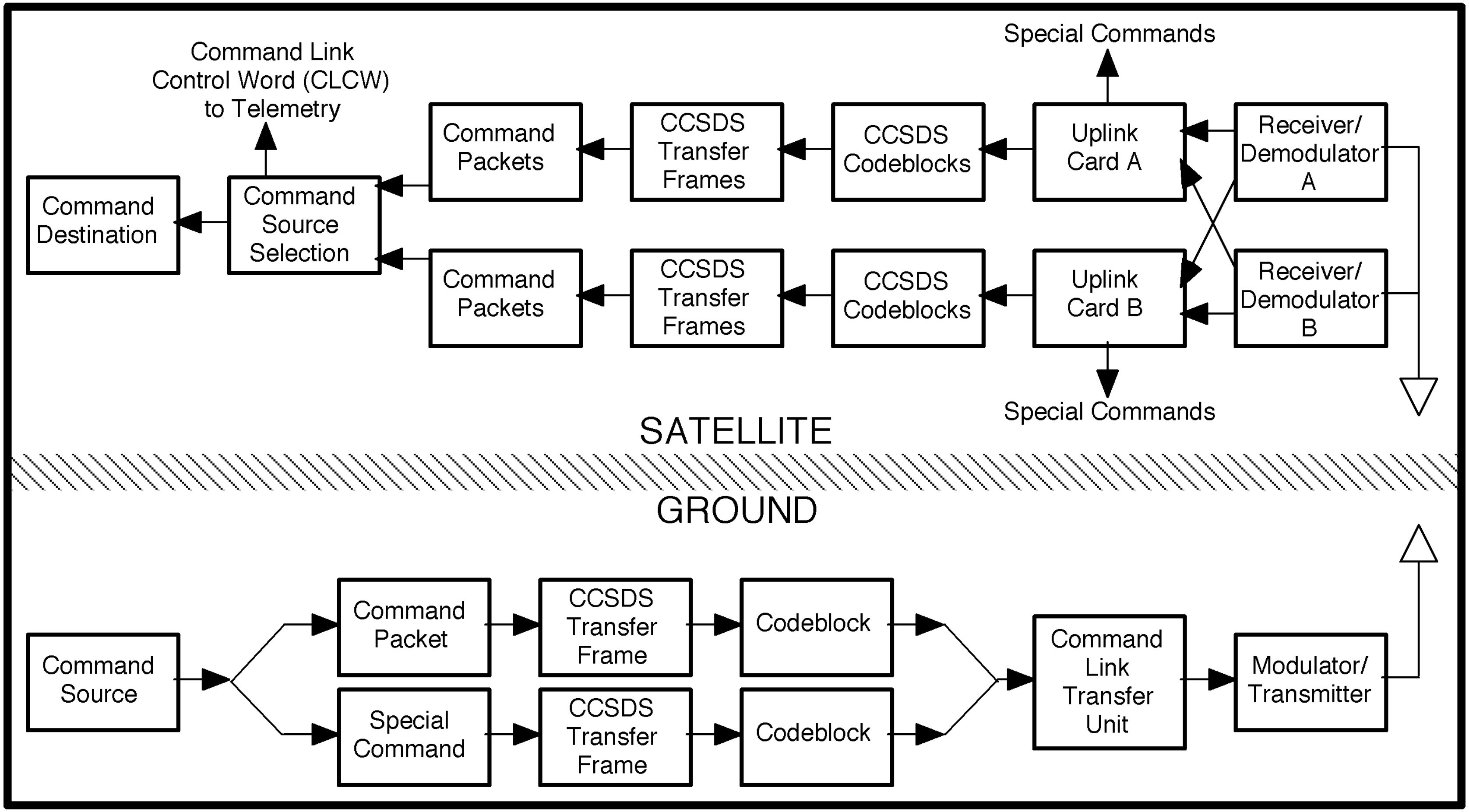
Spacecraft Command System



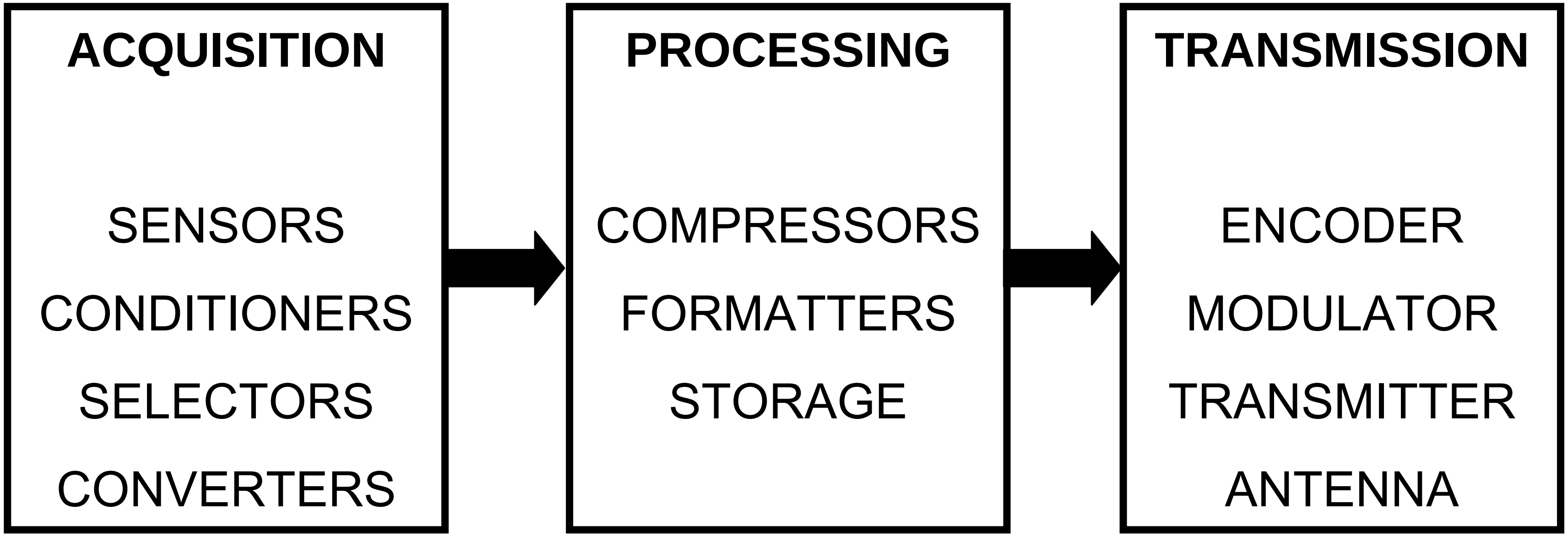
Encryption / Decryption Model



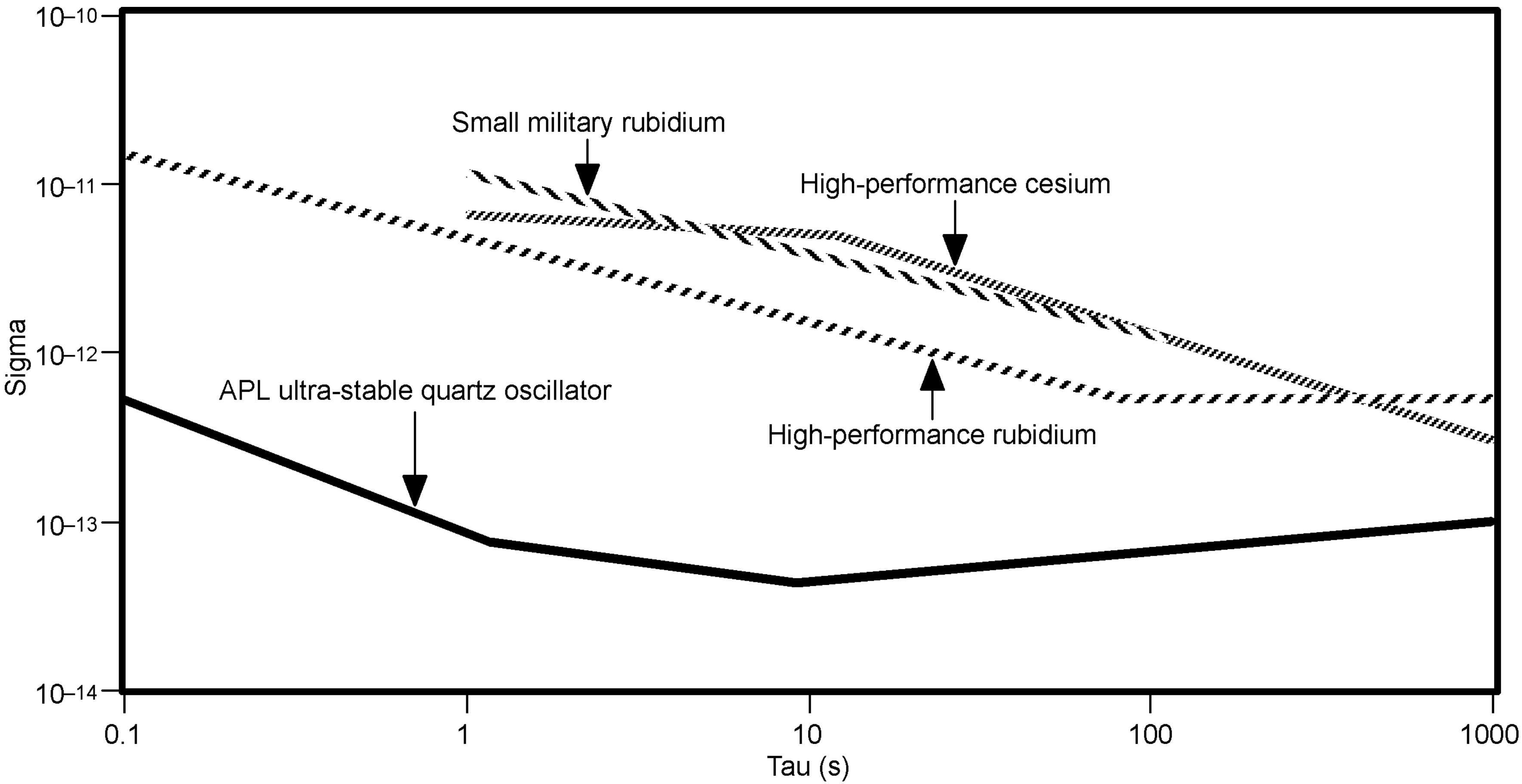
End-to-End Command Flow



Spacecraft Telemetry System



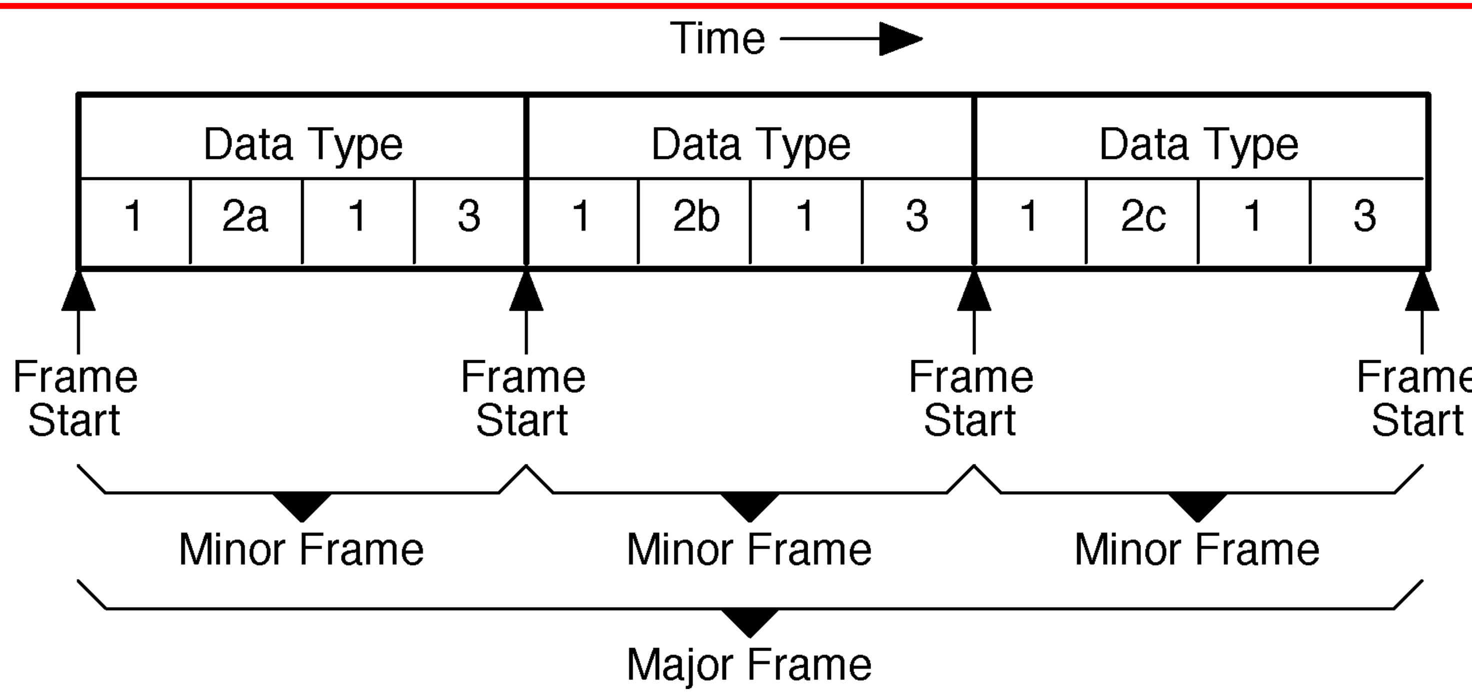
Allan Deviation of Precision Frequency Standards



Telemetry Multiple Access

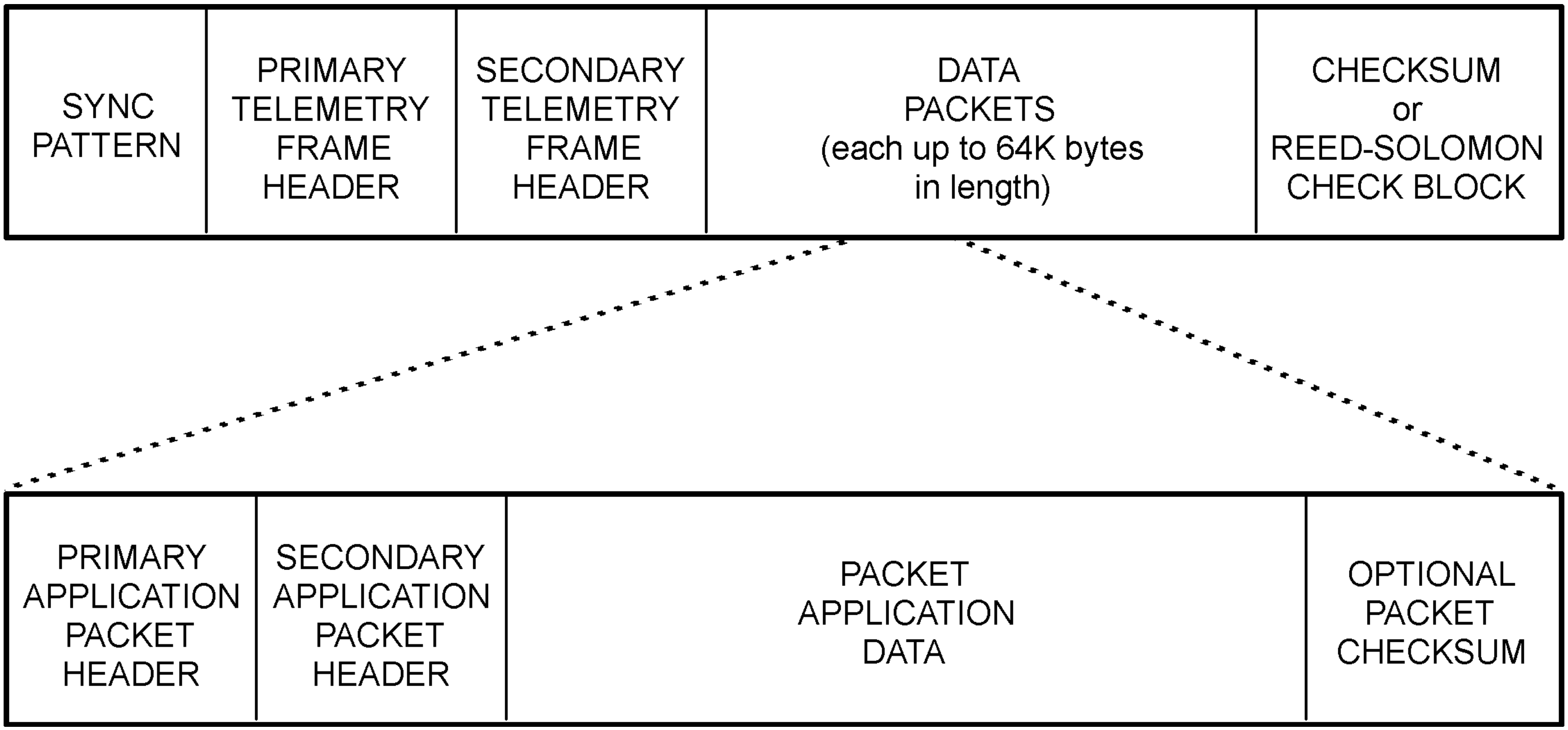
- **Frequency division multiple access** (FDMA): different data on different sub-carrier frequencies
- **Time division multiple access** (TDMA): a cyclic data frame is defined in which different bit fields in the frame are assigned to different users
- **Code division multiple access** (CDMA): coding techniques are used to avoid interference between different users. Each different coding algorithm is decoded using a separate decoder (e.g., ±90º, ±180º phase shift; orthogonal binary pseudo-random modulations; frequency-hopping)
- **Polarization division multiple access** (PDMA): two signal sources use orthogonal polarizations of single carrier
- **Space division multiple access** (SDMA): spot-beam antennas provide spatial separation of RF links

Sub-Commutation and Super-Commutation



Data type 1 is super-commutated. It is sampled more than once in each minor frame. Data types 2a, 2b, and 2c are sampled less often. They are sub-commutated in three successive minor frames.

Structure of a Typical Packetized Telemetry Frame

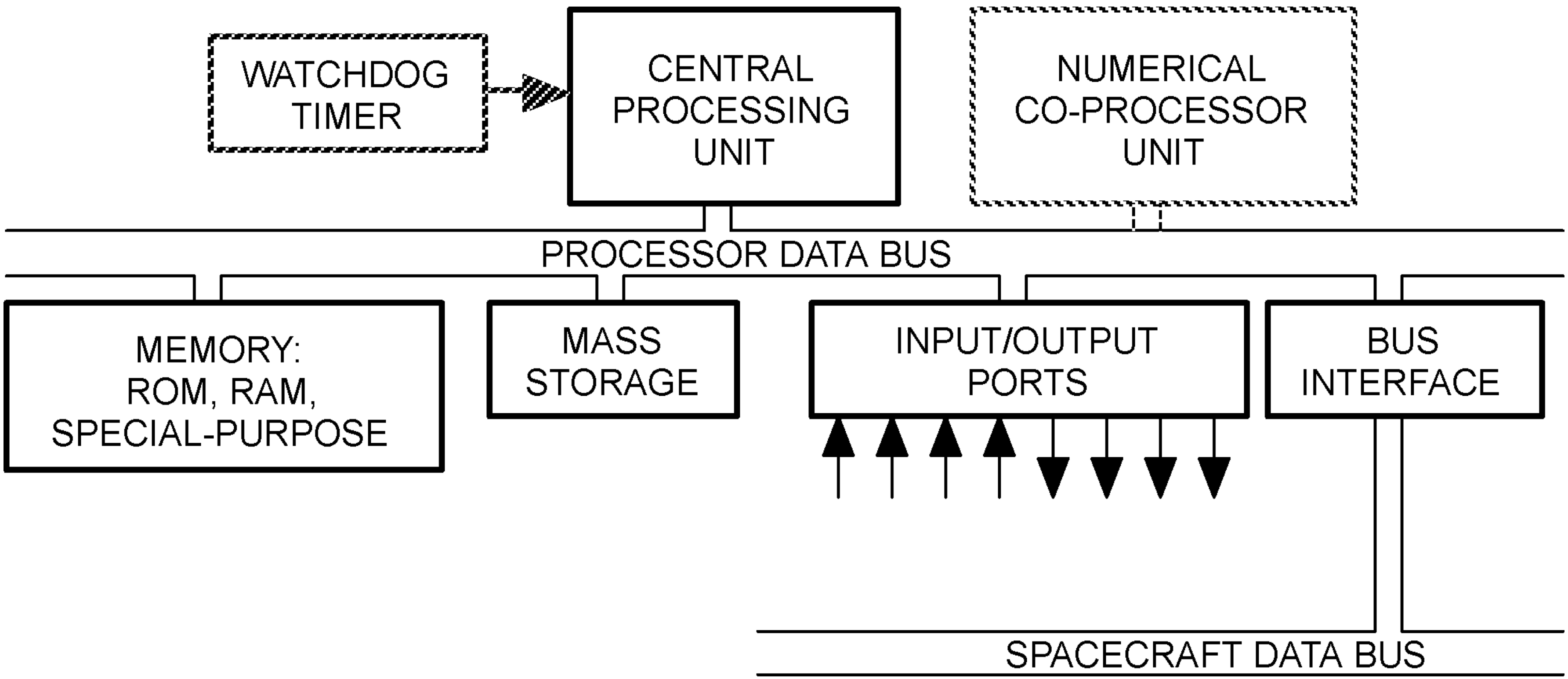


Structure of a Typical Real-Time Communications Bus Schedule

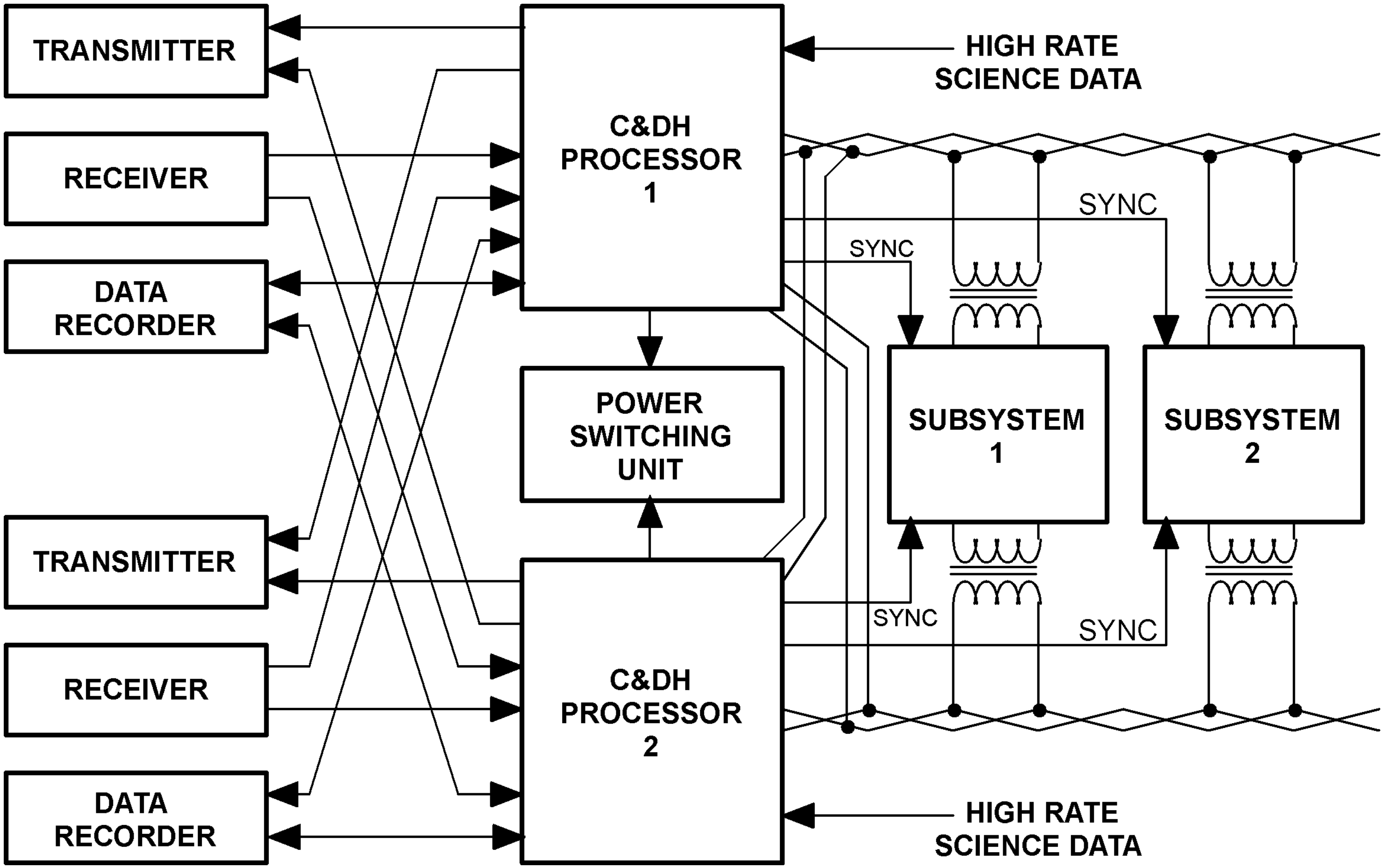
0	Synchronization	25	Instrument short data poll	50	Instrument short data poll	75	Instrument short data poll	100	Instrument short data poll
1	Instrument long data poll	26	Instrument long data poll	51	Instrument long data poll	76	Instrument long data poll	101	Instrument long data poll
2		27	Instrument short data read	52	Instrument short data read	77	Instrument short data read	102	Instrument short data read
3	Instrument long data read	28	Instrument long data read	53	Instrument long data read	78	Instrument long data read	103	Instrument long data read
4	Instrument long data read	29	Instrument long data read	54	Instrument long data read	79	Instrument long data read	104	Instrument long data read
5	Instrument long data read	30	Instrument long data read	55	Instrument long data read	80	Instrument long data read	105	Instrument long data read
6	Instrument long data read	31	Instrument long data read	56	Instrument long data read	81	Instrument long data read	106	Instrument long data read
7	Instrument command	32	Instrument command	57	Instrument command	82	Instrument command	107	Instrument command
8	Instrument short data poll	33	Instrument short data poll	58	Reset IDS Remote Terminal	83	Instrument short data poll	108	Instrument short data poll
9	Instrument long data poll	34	Instrument long data poll	59	Instrument long data poll	84	Instrument long data poll	109	Instrument long data poll
10	Instrument short data read	35	Instrument short data read	60	Time Code Transfer	85	Instrument short data read	110	Instrument short data read
11	Instrument long data read	36	Instrument long data read	61	Instrument long data read	86	Instrument long data read	111	Instrument long data read
12	Instrument long data read	37	Instrument long data read	62	Instrument long data read	87	Instrument long data read	112	Instrument long data read
13	Instrument long data read	38	Instrument long data read	63	Instrument long data read	88	Instrument long data read	113	Instrument long data read
14	Instrument long data read	39	Instrument long data read	64	Instrument long data read	89	Instrument long data read	114	Instrument long data read
15	Instrument short data poll	40	Instrument short data poll	65	Instrument short data poll	90	Instrument short data poll	115	Instrument short data poll
16	Instrument command	41	Instrument command	66	Instrument command	91	Instrument command	116	Instrument command
17	Instrument short data read	42	Instrument short data read	67	Instrument short data read	92	Instrument short data read	117	Instrument short data read
18	Instrument long data poll	43	Instrument long data poll	68	Instrument long data poll	93	Instrument long data poll	118	Instrument long data poll
19		44		69		94		119	
20	Instrument long data read	45	Instrument long data read	70	Instrument long data read	95	Instrument long data read	120	Instrument long data read
21	Instrument long data read	46	Instrument long data read	71	Instrument long data read	96	Instrument long data read	121	Instrument long data read
22	Instrument long data read	47	Instrument long data read	72	Instrument long data read	97	Instrument long data read	122	Instrument long data read
23	Instrument long data read	48	Instrument long data read	73	Instrument long data read	98	Instrument long data read	123	Instrument long data read
24	Instrument command	49	Instrument command	74	Instrument command	99	Instrument command	124	Instrument command

125 real-time slots, each 8 ms in duration
Instrument short data: 256-byte packets, 13 Hz maximum
Instrument long data: 1024-byte packets, 15 Hz maximum
Instrument command: 250-byte packets, 15 Hz maximum
RT reset (slot 58) occurs at 1/8 Hz (i.e., every 8 seconds)

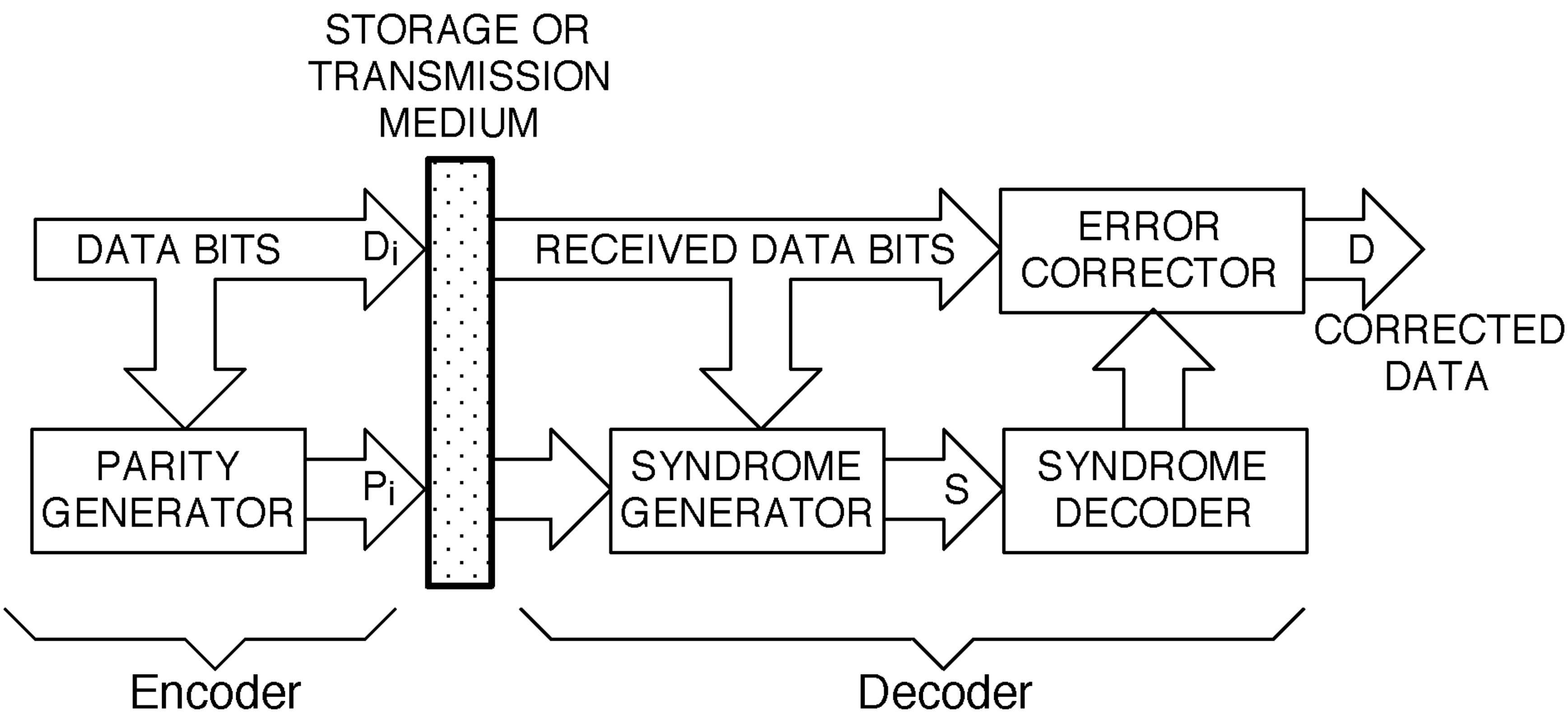
Spacecraft Data Processing System



Spacecraft Block Diagram



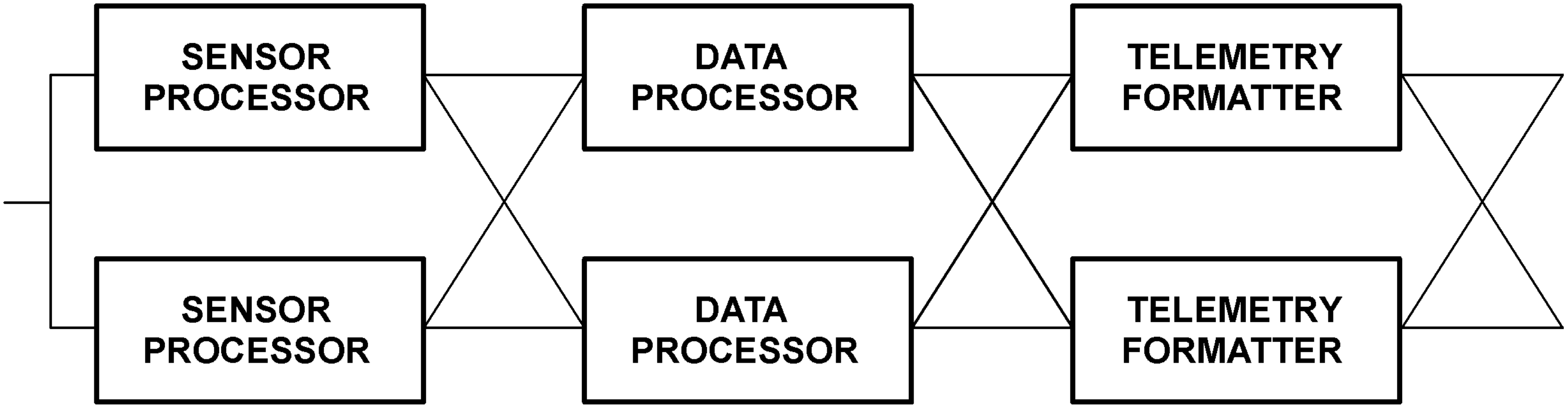
Block Diagram of Error-Correcting Logic



Earth-Orbit Radiation Environment

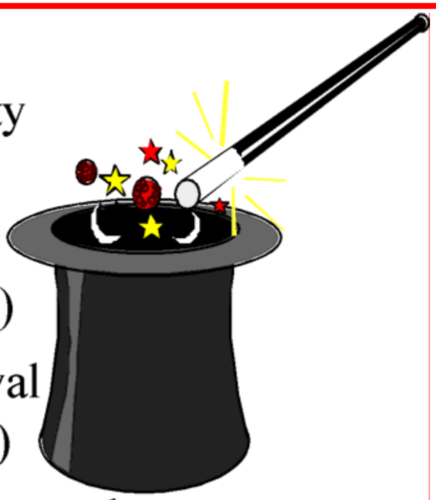
- Low altitude (200 – 500 km), low inclination (i ≤ 28°)
  - 100 – 1k rad(Si)/year. Design to 10k rad(Si)/year. Incident charged particles, Van Allen Belts, make SEUs an important concern at low inclination.
- Low altitude (200 – 1000 km), high inclination (i > 28°)
  - 1k – 10k rad(Si)/year. Design to 100k rad(Si)/year. More protons from Van Allen Belts, so use Adams ten percent worst case environment for SEU calculations.
- Medium altitude (1000 – 4000 km)
  - 100k – 1M rad(Si)/year. Design to 1M rad(Si)/year. Almost no geomagnetic shielding. Must use the most radiation-tolerant parts available.
- High altitude (> 5000 km); e.g., geosynchronous (36,000 km)
  - 1k – 5k rad(Si)/year. Design to 50k rad(Si)/year. Spacecraft charging occurs as Earth's magnetic field interacts with Solar wind, so SEU effects are dominated by the Adams ten-percent worst-case environment.

Cross-Strapping Redundant Systems (Box-level)



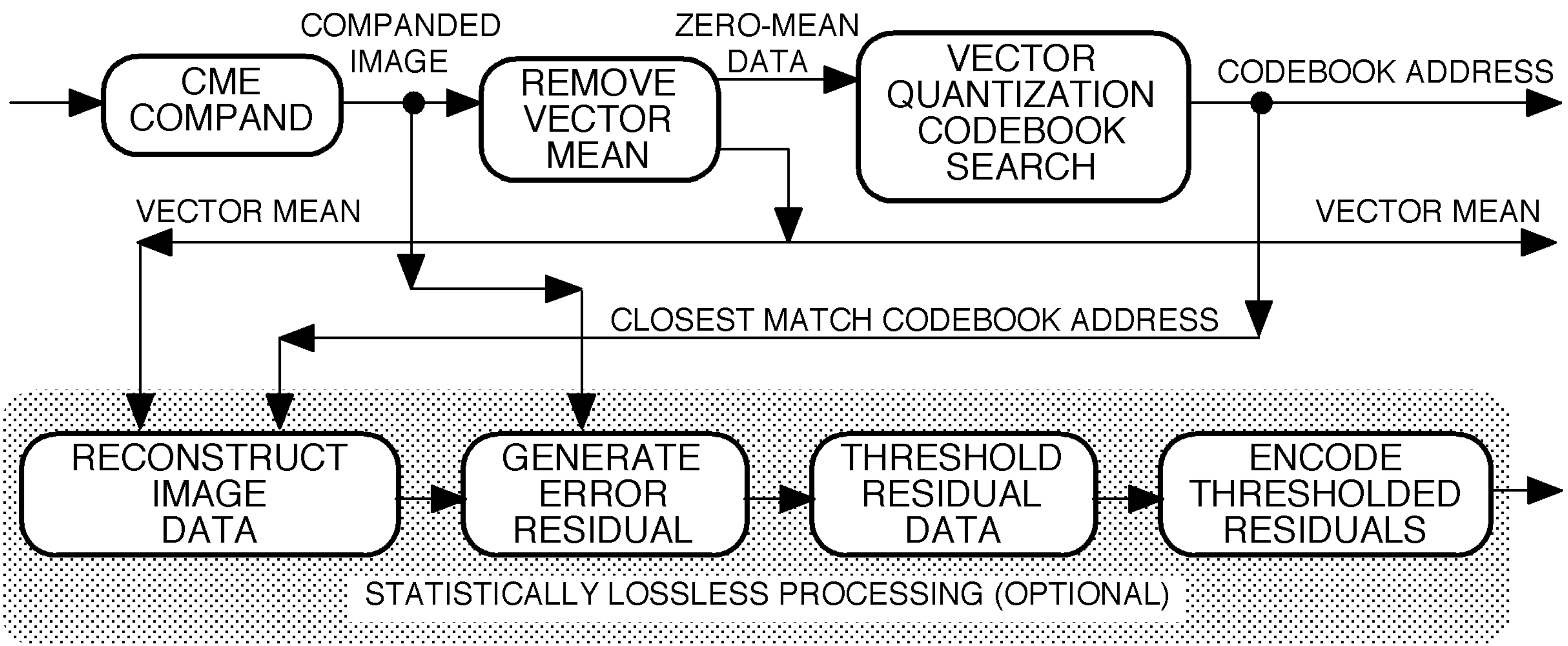
No single-point failure should be able to drag down both sides!

Hot Tips for Flight Software



1. Keep it simple. (10% increase in problem complexity can double the software complexity.)
2. Use the right people. (Good programmers can be up to 30 times more productive than mediocre ones.)
3. Estimate testing realistically. (Error detection/removal accounts for ~ 40% of software development costs.)
4. Address efficiency early in the software development cycle. (Efficiency results from good design more than good coding.)
5. Be alert to the two primary causes of "runaway" software projects:
   - Optimistic estimates, made before the problem is fully understood
   - Unstable requirements that "creep" during the development effort
6. Have serious design reviews and code walkthroughs. (Rigorous reviews can remove up to 90% of errors prior to testing.)

Hybrid Image Compression Algorithm



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