Professional Development Short Course On:

Space Systems Fundamentals

Instructor:

Dr. Mike Gruntman

ATI Course Schedule: http://www.ATIcourses.com/schedule.htm

ATI's Space Systems Fundamentals: http://www.aticourses.com/space_systems_fundamentals.htm

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Space Systems Fundamentals

February 5-8, 2018
Albuquerque, New Mexico
$2190 **(9:00am - 4:30pm)**

"Register 3 or More & Receive $100[00] each Off The Course Tuition."

Summary

This four-day course provides an overview of the fundamentals of concepts and technologies of modern spacecraft systems design. Satellite system and mission design is an essentially interdisciplinary sport that combines engineering, science, and external phenomena. We will concentrate on scientific and engineering foundations of spacecraft systems and interactions among various subsystems. Examples show how to quantitatively estimate various mission elements (such as velocity increments) and conditions (equilibrium temperature) and how to size major spacecraft subsystems (propellant, antennas, transmitters, solar arrays, batteries). Real examples are used to permit an understanding of the systems selection and trade-off issues in the design process. The fundamentals of subsystem technologies provide an indispensable basis for system engineering. The basic nomenclature, vocabulary, and concepts will make it possible to converse with understanding with subsystem specialists.

The course is designed for engineers and managers who are involved in planning, designing, building, launching, and operating space systems and spacecraft subsystems and components. The extensive set of course notes provide a concise reference for understanding, designing, and operating modern spacecraft. The course will appeal to engineers and managers of diverse background and varying levels of experience.

Instructor

Dr. Mike Gruntman is Professor of Astronautics at the University of Southern California. He is a specialist in astronautics, space physics, space technology, rocketry, sensors and instrumentation. Gruntman participates in theoretical and experimental programs in space science and space technology, including space missions. He authored and co-authored nearly 300 publications.

What You Will Learn

- Common space mission and spacecraft bus configurations, requirements, and constraints.
- Common orbits.
- Fundamentals of spacecraft subsystems and their interactions.
- How to calculate velocity increments for typical orbital maneuvers.
- How to calculate required amount of propellant.
- How to design communications link.
- How to size solar arrays and batteries.
- How to determine spacecraft temperature.

Course Outline

1. Space Missions And Applications. Science, exploration, commercial, national security. Customers.

2. Space Environment And Spacecraft Interaction. Universe, galaxy, solar system. Coordinate systems. Time. Solar cycle. Plasma. Geomagnetic field. Atmosphere, ionosphere, magnetosphere. Atmospheric drag. Atomic oxygen. Radiation belts and shielding.

3. Orbital Mechanics And Mission Design. Motion in gravitational field. Elliptic orbit. Classical orbit elements. Two-line element format. Hohmann transfer. Delta-V requirements. Launch sites. Launch to geostationary orbit. Orbit perturbations. Key orbits: geostationary, sun-synchronous, Molniya.

4. Space Mission Geometry. Satellite horizon, ground track, swath. Repeating orbits.

5. Spacecraft And Mission Design Overview. Mission design basics. Life cycle of the mission. Reviews. Requirements. Technology readiness levels. Systems engineering.

6. Mission Support. Ground stations. Deep Space Network (DSN). STDN. SGLS. Space Laser Ranging (SLR). TDRSS.

7. Attitude Determination And Control. Spacecraft attitude. Angular momentum. Environmental disturbance torques. Attitude sensors. Attitude control techniques (configurations). Spin axis precession. Reaction wheel analysis.

8. Spacecraft Propulsion. Propulsion requirements. Fundamentals of propulsion: thrust, specific impulse, total impulse. Rocket dynamics: rocket equation. Staging. Nozzles. Liquid propulsion systems. Solid propulsion systems. Thrust vector control. Electric propulsion.

9. Launch Systems. Launch issues. Atlas and Delta launch families. Acoustic environment. Launch system example: Delta II.

10. Space Communications. Communications basics. Electromagnetic waves. Decibel language. Antennas. Antenna gain. TWTA and SSA. Noise. Bit rate. Communication link design. Modulation techniques. Bit error rate.

11. Spacecraft Power Systems. Spacecraft power system elements. Orbital effects. Photovoltaic systems (solar cells and arrays). Radioisotope thermal generators (RTG). Batteries. Sizing power systems.

12. Thermal Control. Environmental loads. Blackbody concept. Planck and Stefan-Boltzmann laws. Passive thermal control. Coatings. Active thermal control. Heat pipes.

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Space Systems Fundamentals

Space Systems Fundamentals

Mike Gruntman

2017

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Space Systems Fundamentals

Four-day course

- Section 01 – 50–70 min
  - break 10–15 min
- Section 02 – 50–70 min
  - break 10–15 min
- Section 03 – 50–70 min

Lunch break

- Section 04 – 50–70 min
  - break 10–15 min
- Section 05 – 50–70 min
  - break 10–15 min
- Section 06 – 50–70 min

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Space Systems Fundamentals

Day 1

- **Part 01**
  Organization and Scope of the Course. Space Missions and Applications.
- **Part 02**
  Universe, Galaxy, Solar System
- **Part 03**
  Space Environment I

- **Part 04**
  Space Environment II
- **Part 05**
  Orbital Mechanics I
- **Part 06**
  Orbital Mechanics II

Day 2

- **Part 07**
  Orbital Mechanics III
- **Part 08**
  Space Mission Geometry
- **Part 09**
  Operations. Reliability.

- **Part 10**
  Space Mission Overview. System Engineering.
- **Part 11**
  ADC I
- **Part 12**
  ADC II

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Day 3

- Part 13
  ADC III
- Part 14
  Propulsion I
- Part 15
  Propulsion II
- Part 16
  Propulsion III
- Part 17
  Launch Systems I
- Part 18
  Launch Systems II

Day 4

- Part 19
  Communications I
- Part 20
  Communications II
- Part 21
  Electric Power I
- Part 22
  Electric Power II
- Part 23
  Thermal Control I
- Part 24
  Thermal Control II

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Global Space

American economy, infrastructure, and national security depend on satellites more than those of any other nation.

Global space

2005	**$189 B**
2006	**$219 B**
2007	**$236 B**
2008	**$248 B**
2009	**$259 B**
2010	**$275 B**
2011	**$290 B**
2012	**$302 B**
2013	**$314 B**
2014	**$329 B**
2015	**$323 B**

The Space Report 2014, 2016, Space Foundation

Europe 2015 – $8.2 B

ESA (Eur. Sp. Ag.)	**$ 4.9 B**
European Union	**$ 0.1 B**
France	**$ 1.4 B**
EUMETSAT	**$ 0.4 B**
Germany	**$ 0.6 B**
Italy	**$ 0.5 B**
Spain	**$ 0.2 B**
United Kingdom	**$ 0.1 B**

Based on *The Space Report 2016*, Space Foundation

Government space $76.5B in 2015

United States	**$44.6 B**
Europe	**$ 8.3 B**
Brazil	**$ 0.1 B**
Canada	**$ 0.4 B**
China (PRC)	**$ 4.2 B**
India	**$ 0.9 B**
Israel	**$ 0.05 B**
Japan	**$ 2.7 B**
Russia	**$ 3.0 B**
South Korea	**$ 0.6 B**
a few countries	**$ 0.1 B** each
many countries	≤ **$0.01B** ea.
non-U.S. military	**$ 10.6 B**

Based on *The Space Report 2014, 2016*, Space Foundation

Commitment (or lack thereof) to space

Only France (and the old Soviet Union in the past) approaches the U.S. space expenditures in terms of the fraction of the gross domestic product (GDP). Most other industrialized countries (Europe and Japan) spend in space, as fraction of GDP, four to six times less than the United States. — M. Gruntman, *Blazing the Trail*, 2004

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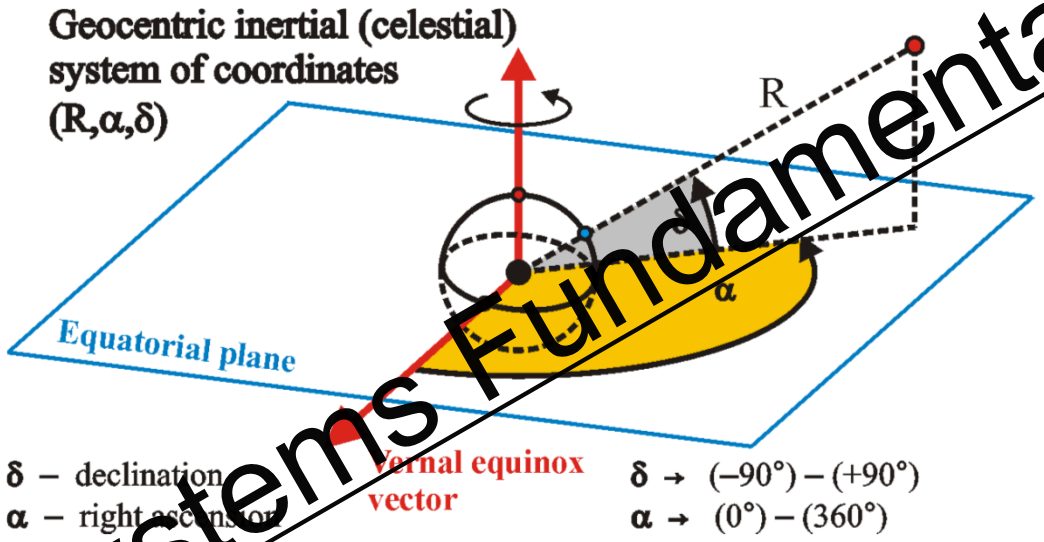
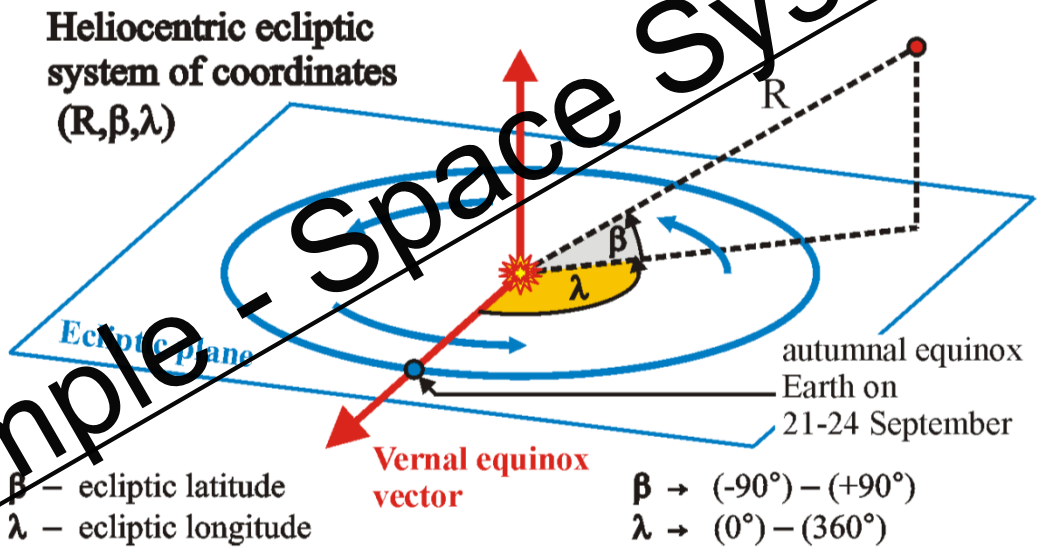
Inertial Systems of Coordinates





$\mathbf{n}_{EQ} \perp \mathbf{n}_{X}$

$\mathbf{n}_{ECL} \perp \mathbf{n}_{X}$

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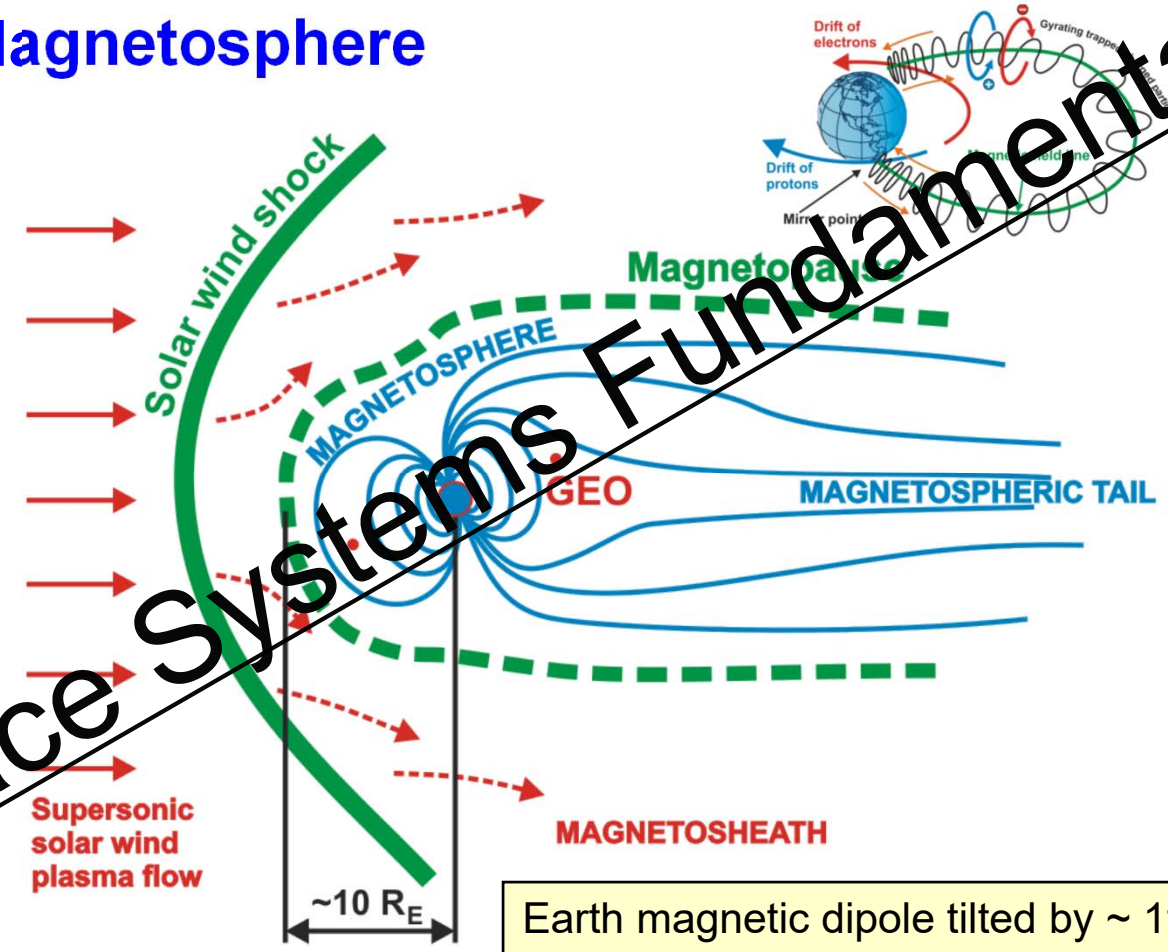
Magnetosphere

- The region beyond the ionosphere is called the magnetosphere.
- In this region, the Earth's magnetic field dominates physical processes and largely determines its structure.
- The highly supersonic solar wind flow impinges on the magnetosphere and forms a bow shock.
- Inside the magnetopause, energetic charged particles are "trapped" by the magnetic field (ions gyrate around magnetic lines).



Earth magnetic dipole tilted by ~ 11° with respect to the earth spin axis.

The magnetosphere is bounded from interplanetary space by a current layer, called the magnetopause (at ~10 R_E in the sunward direction).

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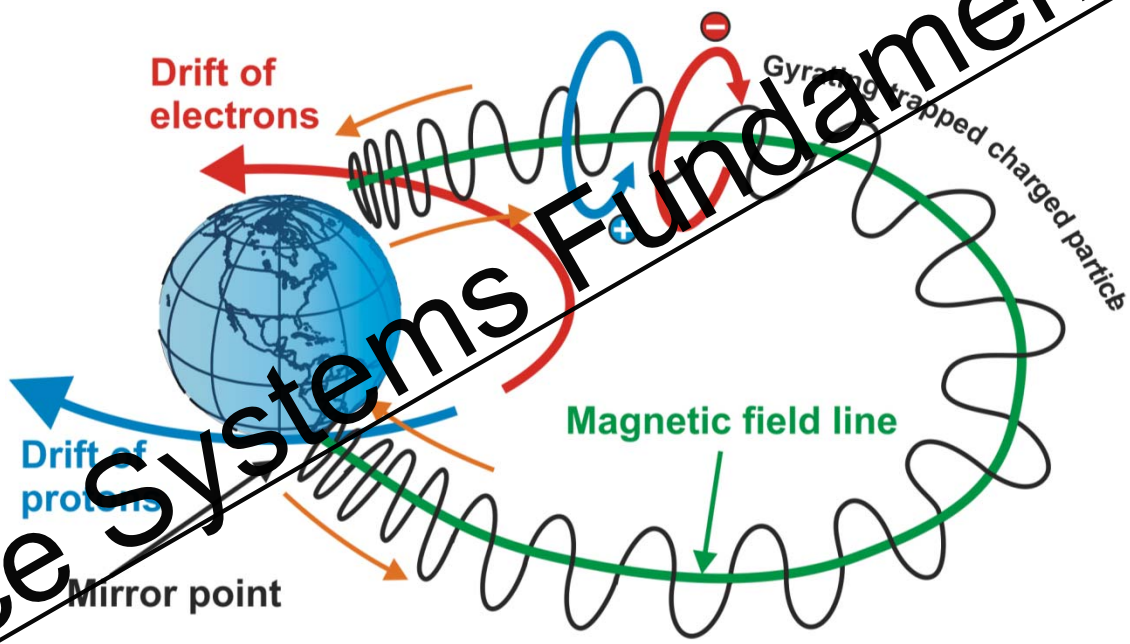
Radiation belts

- During magnetospheric disturbances, strong precipitation of these ions to lower altitudes may occur in polar regions which produces spectacular aurorae.
- Anisotropy of energetic particle velocities is often described through the pitch-angle distribution
- It is usually assumed that spacecraft bombarded by energetic particles from all directions (isotropically)

Trapped Energetic Particles



Trapped ions gyrate around magnetic field lines while moving back and forth from one polar region to another (between the "mirror" points).

Example: **1-MeV electrons at 4 R_E**

gyroradius – **6.3 km** gyroperiod – **0.22 ms**
mirror period – **0.27 sec** drift period – **3.7 min**

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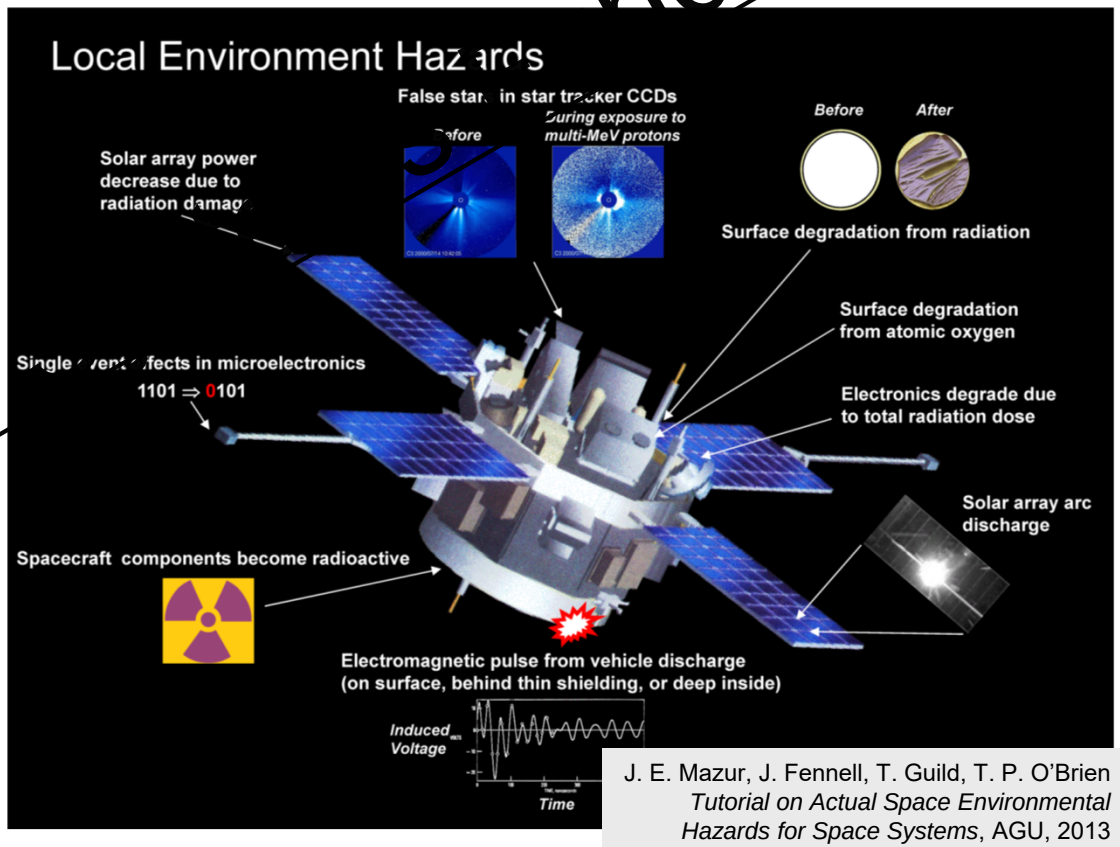
Trapped Energetic Electrons and Ions and Plasma

Protons	**1-10 MeV**	LEO, MEO, GEO **dose, SEE** **nuclear activation**
	> 10 MeV	LEO, MEO **dose (e.g., solar cells), SEE,** **DD (displ damage)**
	> 50 MeV	MEO, GEO **nuclear activation**
Heavy ions	**>10 MeV**	MEO, GEO **SEE**
Electrons	**0.1-1 MeV**	MEO, GEO **internal charging** **dose**
	> 1 MeV	LEO, MEO, GEO **internal charging** **dose**
Plasma	**10eV - 100keV**	LEO, MEO, GEO **surface charging** **dose**



J. E. Mazur, J. Fennell, T. Guild, T. P. O'Brien *Tutorial on Actual Space Environmental Hazards for Space Systems*, AGU, 2013

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Space Debris

	As of January 2013		
Sat	catal-oged	decay-ed	in orbit
FY-1C	3378	302	3076
Cosmos 2251	1603	261	1342
Iridium 33	598	119	479

Orbital Debris Quarterly News , v.17, is.1, p.8, 2013

Monthly Number of Cataloged Objects in Earth Orbit by Object Type

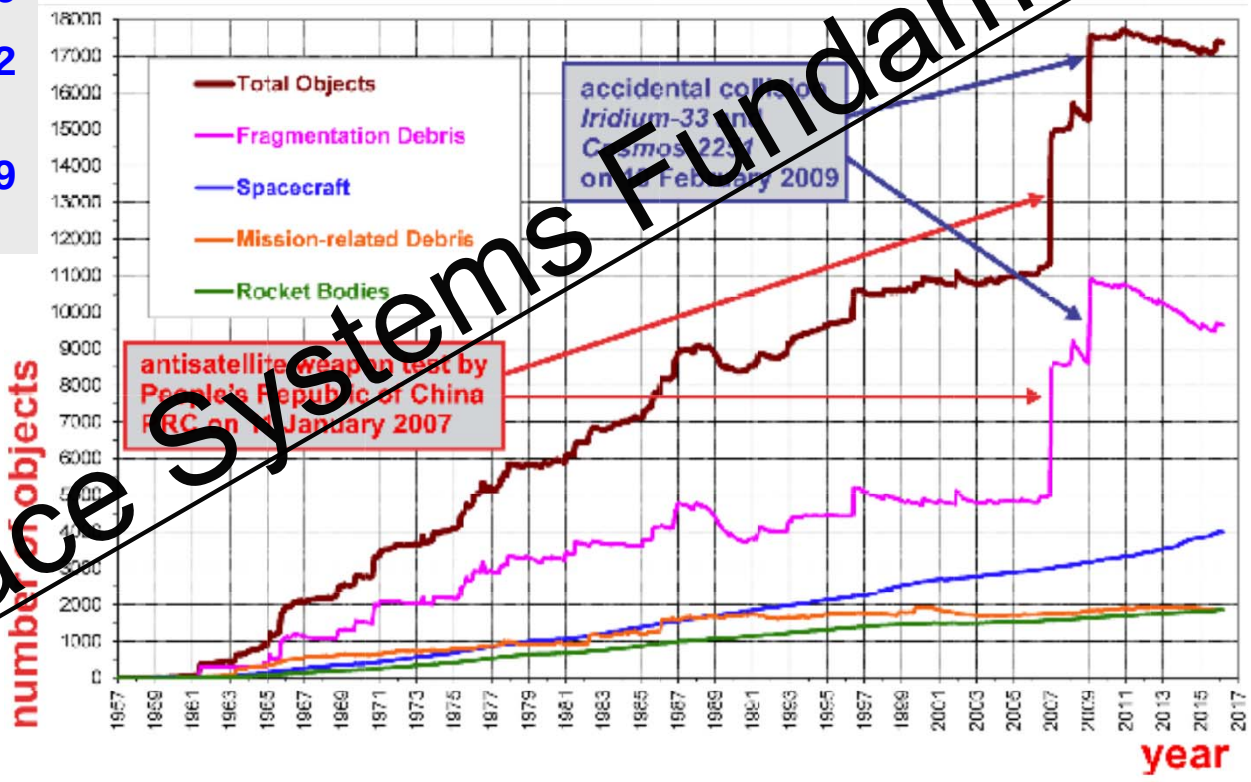

Figure from
***Orbital Debris Quarterly News* (NASA),**
v. 20, issue 1-2, p.14
April 2016.
Figure augmentation by Mike Gruntman

Summary of all objects in Earth orbit officially cataloged by the U.S. Space Surveillance Network. "Fragmentation debris" includes satellite breakup debris and anomalous event debris, while "mission-related debris" includes all objects dispensed, separated, or released as part of the planned mission.

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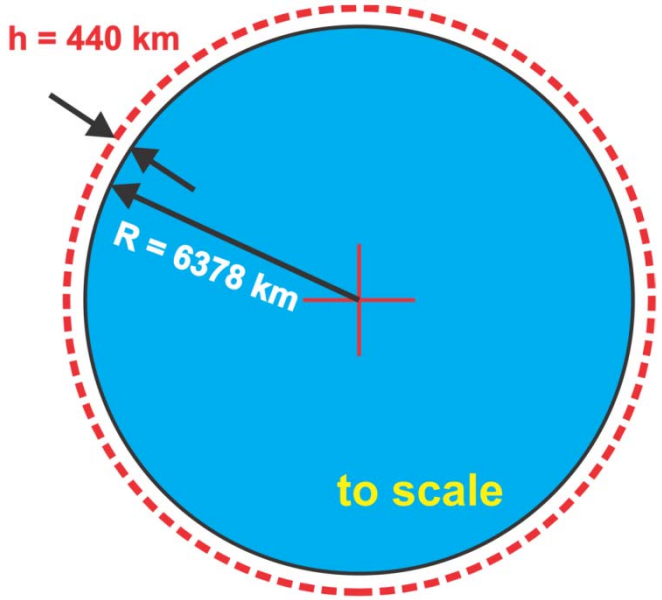
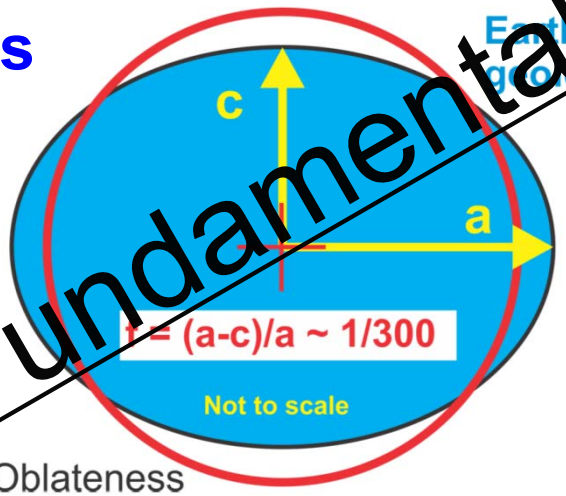


Earth Oblateness

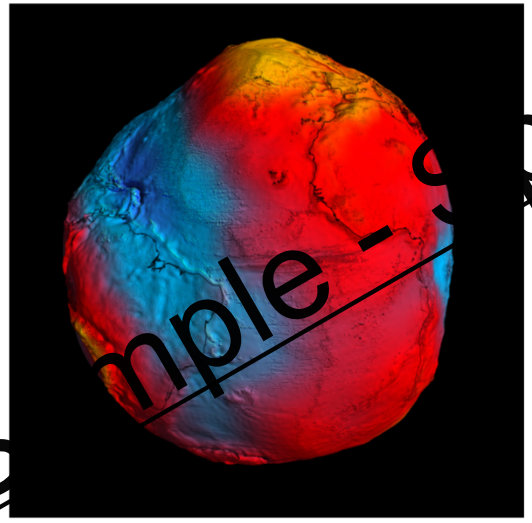
Geoid = equipotential surface of the gravity field most closely approximating mean sea level



Especially important:
J_2 and J_2^2 (or J_{22})

Oblateness

$$V(r,\theta,\lambda) = -\frac{GM}{r}\left[1 - \sum_{n=2}^{\infty}\left(\frac{a}{r}\right)^n J_n P_n(\cos\theta) + \sum_{n=2}^{\infty}\sum_{m=1}^{n}\left(\frac{a}{r}\right)^n J_{nm} P_{nm}(\cos\theta)\cos m(\lambda - \lambda_{nm})\right]$$



Accurate **geoid model** produced by the *Gravity field and steady-state Ocean Circulation Explorer* (**GOCE**) mission. The deviations in height (–100 m to +100 m) from an ellipsoid are exaggerated 10,000 times in the image. The blue colors represent low values and the reds/yellows represent high values.

Credit: ESA/HPF/DLR and NAS

equatorial radius: R_e = **6378.14 km**
polar radius: R_p = **6356.8 km**

volumetric radius: R_v = **6371.0 km**
volumetric mean radius is the radius of a sphere with the same volume

orbit altitude commonly referred to the difference between the **orbit radius** and the **equatorial radius**:

$$h = R - R_e$$

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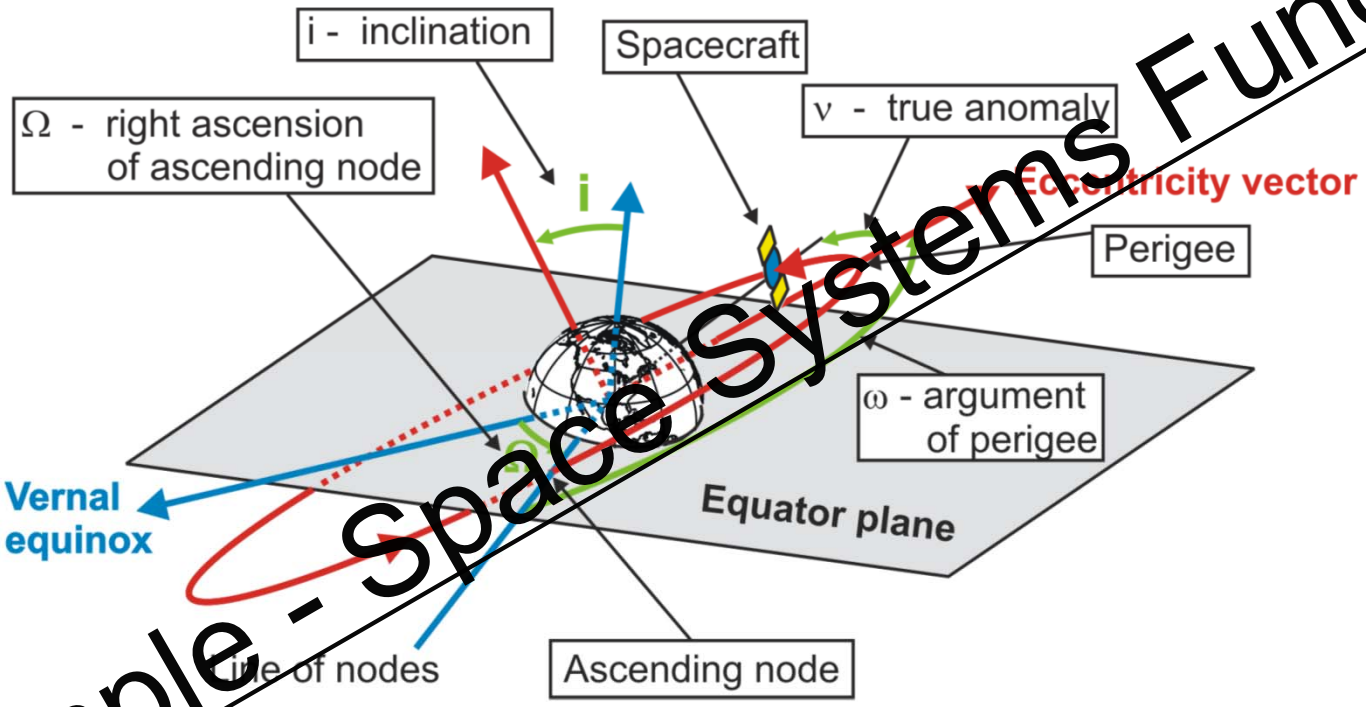
Classical Orbital Elements



- **a** semi-major axis
- **e** eccentricity
- **i** inclination
- **Ω** right ascension of ascending node
- **ω** argument of perigee
- **ν** true anomaly

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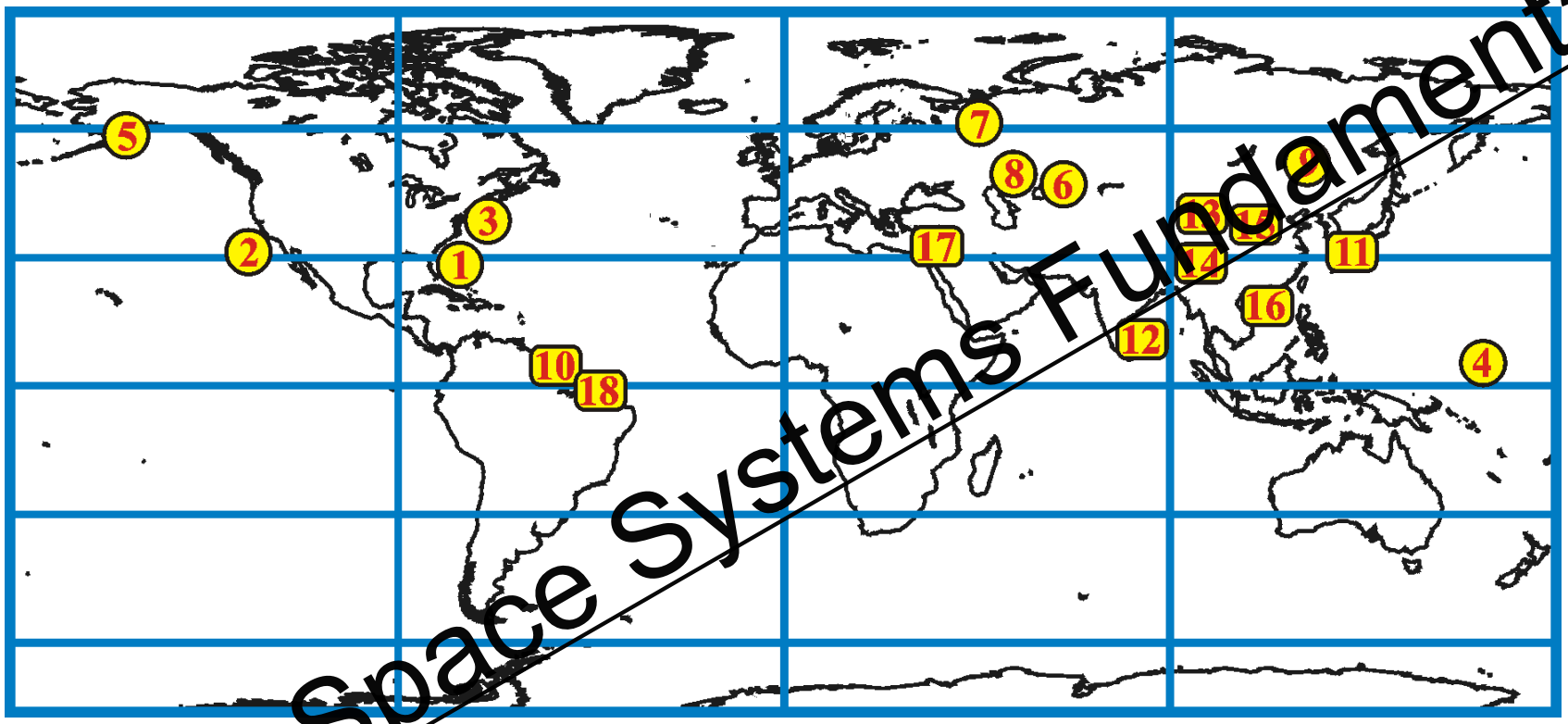
Main Launching Sites



1) Cape Canaveral, Florida
2) Vandenberg Air Force Base, California
3) Wallops Island
4) Kwajalein Atoll
5) Kodiak Island
6) Baikonur, or Tyuratam, Cosmodrome
7) Plesetsk Cosmodrome
8) Kapustin Yar
9) Svobodny
10) Kourou, French Guiana
11) Tanegashima Island
12) Sriharikota Space Center, Tamil Nadu
13) Jiuquan Satellite Launch Center, Gobi Desert (1st)
14) Xichang Satellite Launch Center, Sichuan Province
15) Taiyuan (Wuzhai) Satellite Launch Center, Shanxi Province
16) Wenchang Satellite Launch Center, Hainan Province
17) Yavne, Palmachim Air Force Base
18) Alcantara

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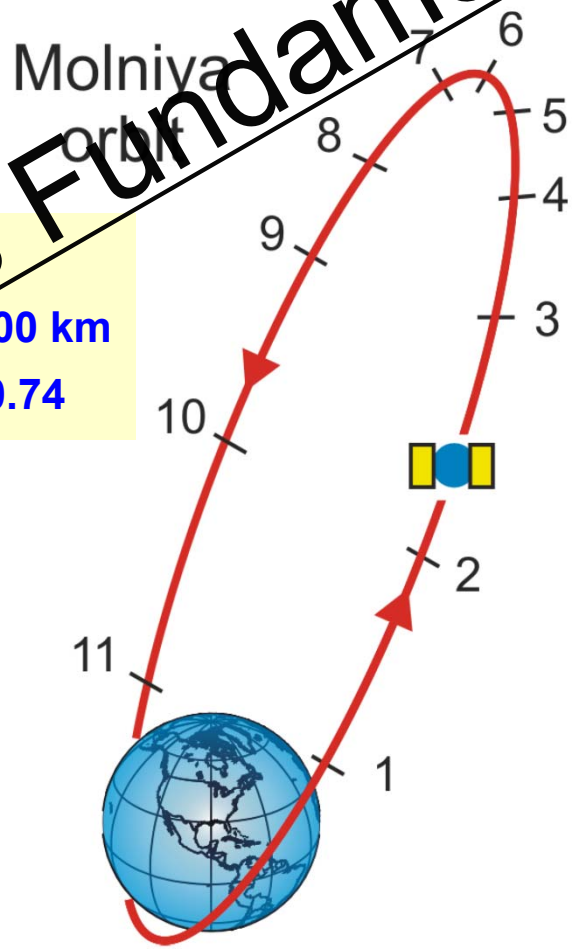
Devised by the USSR to provide

- features of a geosynchronous orbit
- with better coverage of northern latitudes
- USSR was largely a Northern country:
  - latitude of Moscow = mid-Labrador, Hudson Bay
  - latitude of Leningrad = southern tip of Greenland
- global coverage from an orbit without the large orbital plane change during launch
  - Tyuratam (Baikonur) – 45°54' N
  - Plesetsk – 62°48' N

Molniya Orbit



typical
h_p = 500–1200 km
e = 0.71 – 0.74

$$\frac{d\omega}{dt} = \frac{3\,n\,J_2\,R_0^2\left[4 - 5\sin^2(i)\right]}{4\,a^2\,(1-e^2)^2} = 0 \quad \Rightarrow$$

$$\sin(i) = \sqrt{4/5} \;\Rightarrow\; i = 63.4^\circ \text{ or } i = 116.6^\circ$$

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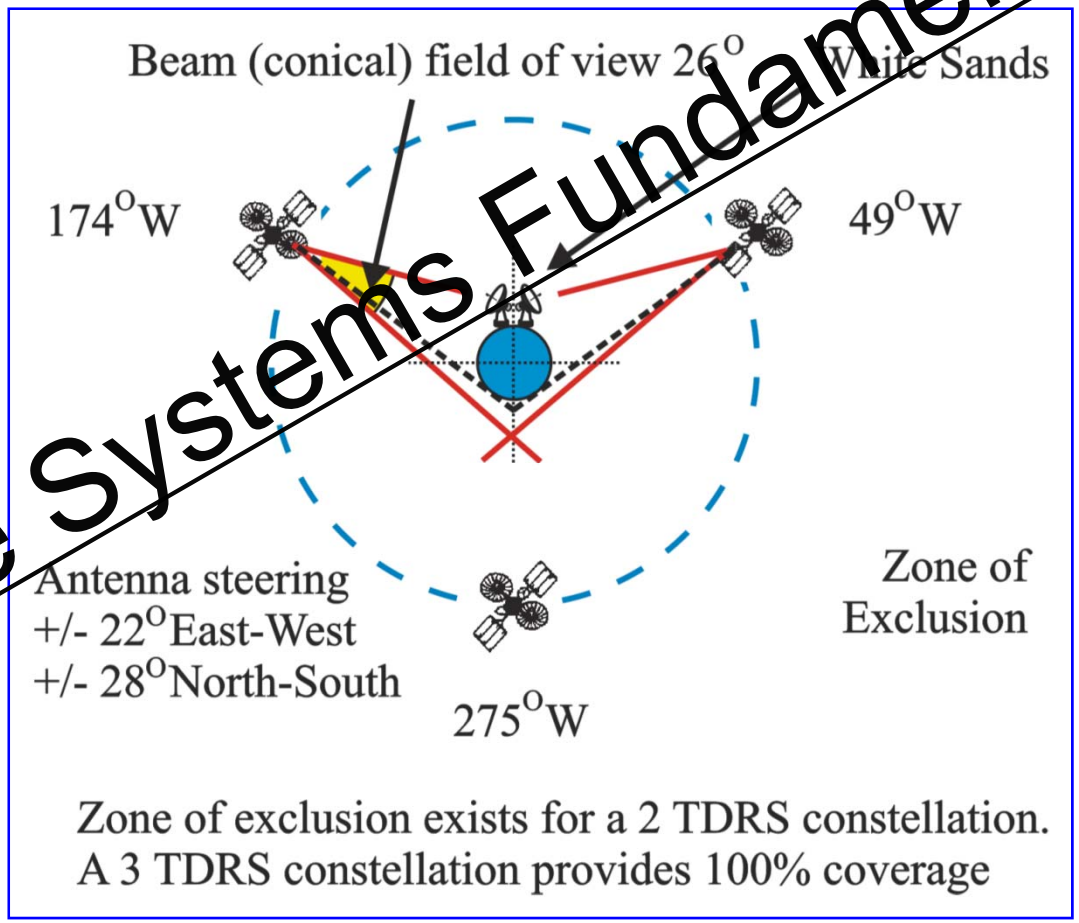
Tracking and Data Relay Satellite System (TDRSS)

- Relay satellites in geosynchronous orbit
- Eliminates the need for worldwide network
- the first TDRS was launched in 1983
- operational satellites are separated by 135° of longitude
- ground terminal at White Sands
- initially provided 85% coverage of satellite orbits
- expanded to 100% with the addition of the third location (satellite) and ground terminal in Guam



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Technology Readiness Levels – TRLs

TRL 9

Actual system "flight proven" through successful mission operations

TRL 8

Actual system completed and "flight qualified" through test and demonstration (ground or flight)

TRL 7

System prototype demonstration in a space environment

TRL 6

System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 5

Component and/or breadboard validation in relevant environment

TRL 4

Component and/or breadboard validation in laboratory environment

TRL 3

Analytical and experiment critical function and characteristic proof-of-concept

TRL 2

Technology concept and/or application formulated

TRL 1

Basic principles observed and reported

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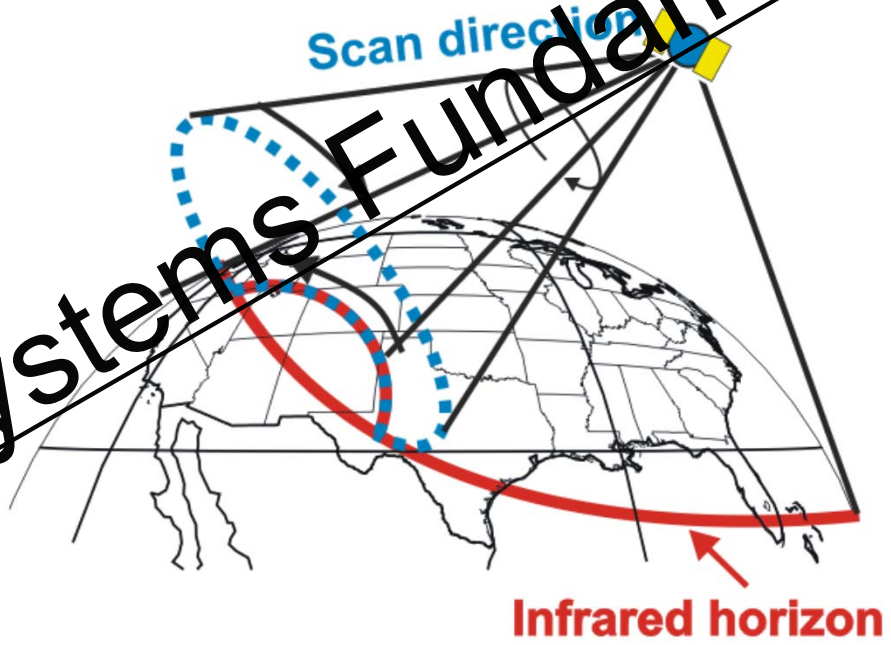
Earth Horizon Sensors – Scanning Sensors

Scanning Sensors

- employ a spinning mirror or prism to focus a narrow pencil of light onto sensing element
- sensing element is usually a bolometer
- electronics in the sensor detect when the infrared (IR) signal from the Earth is first received or finally lost during each sweep of the scan cone
- horizon sensor detects not the first contact with land or ocean, but the point in the atmosphere at which the 16 μ radiation reaches a certain intensity
- from the time between the arrival of signal (AOS) and loss of signal (LOS) the Earth width is determined



Simple narrow field-of-view fixed head sensor types (called pippers or horizon crossing indicators) are used on spinning spacecraft

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Dual Spin

- cylindrical solar array
- spinning sensors (sun, earth, star, RF)
- despun platform
- speed and precession control
- wobble and nutation (dampers)
- despin control

example:

DSCS II, TIROS, HS376, HS396

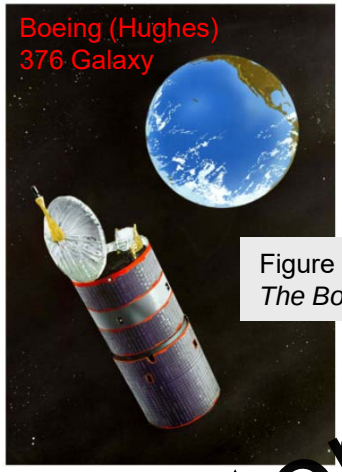
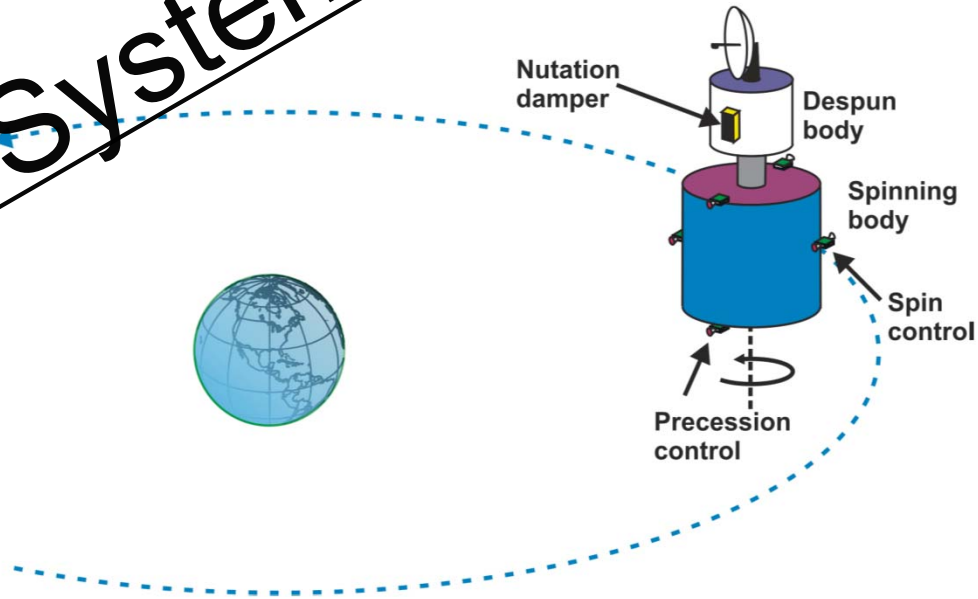


Figure courtesy
The Boeing Company

Boeing (Hughes) 376 stowed (left) and deployed.
Figure courtesy
The Boeing Company



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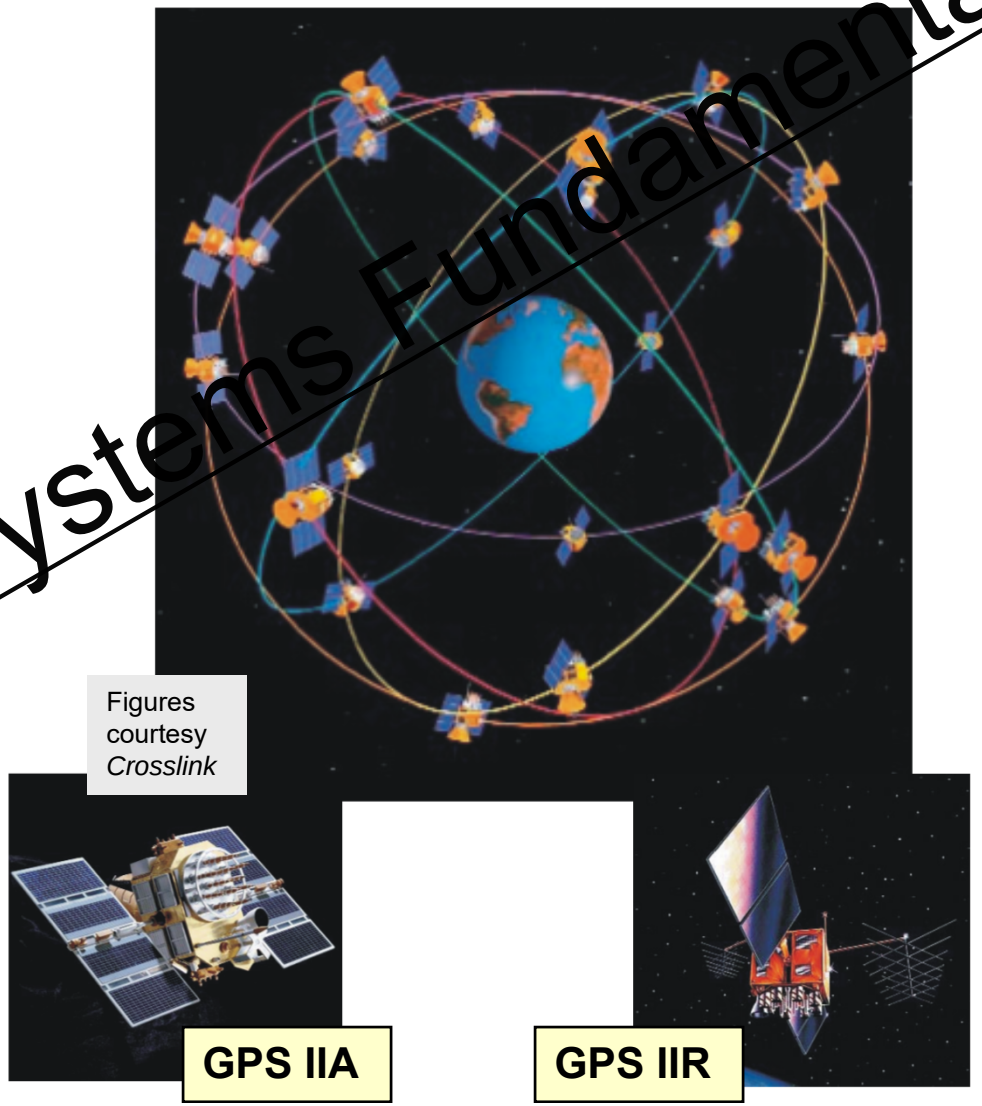
GPS Space Segment

- 24 satellites in six orbit planes
- 4 satellites in each orbit
- 12-hour period 26,561.75 km circular orbits
- inclination: 55°
- longitude crossing at the equator kept fixed to within ±2° by the GPS Control Segment
- perturbations:
  - ➢ atmospheric drag is insignificant
  - ➢ lunar and solar gravitational pull can be significant
  - ➢ solar radiation pressure can be significant
- precisely timed GPS signals are transmitted at two L-band frequencies: 1.57542 GHz and 1.2276 GHz
- frequencies are selected to minimize interference with radio astronomy bands



Figures courtesy *Crosslink*

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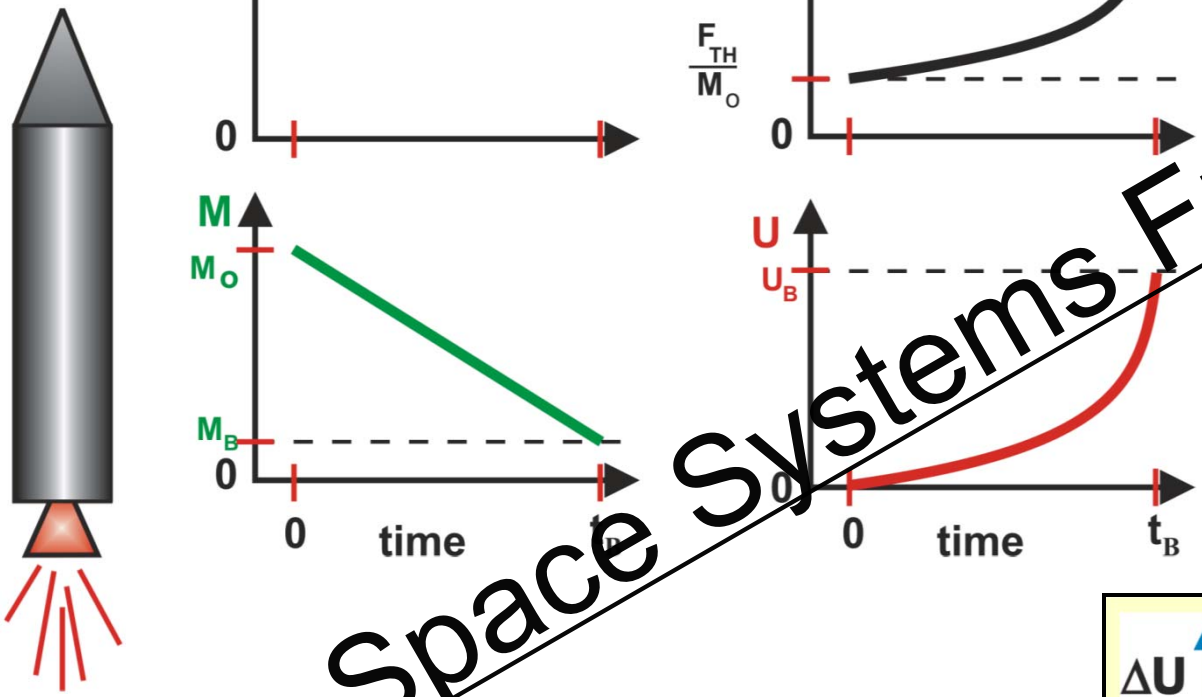


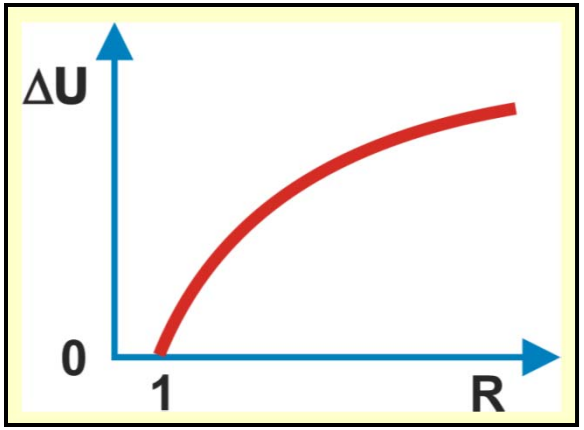
Rocket Equation

Assume:

- no gravity
- no drag
- $\dot{m}$ = constant
- F_{TH} = constant
- t_B is the burnout time
- **U** is the rocket speed

$$\Delta U = u_{eq} \ln R$$

$$u_{eq} = g_e I_{SP}$$



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$$\frac{dA}{A} = \frac{du}{u}\left(M^2 - 1\right)$$

Converging-Diverging (De Laval) Nozzle

Area-velocity relation

M → 0

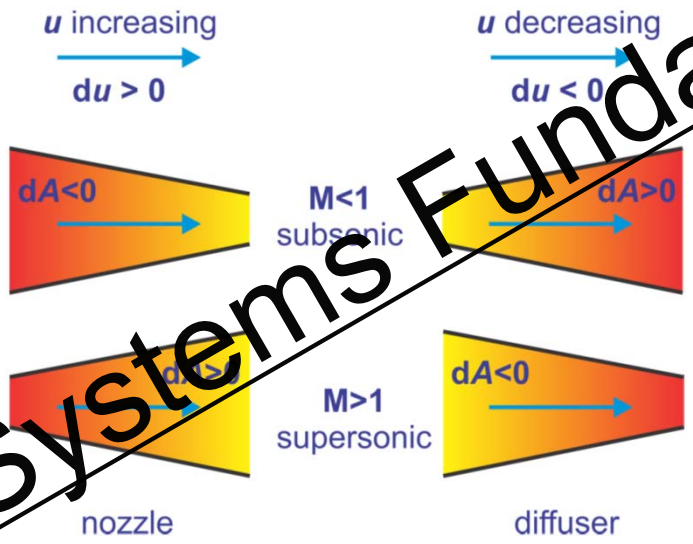
incompressible flow and
Au = constant

0 ≤ M <1 (subsonic flow)

an increase in velocity ($du > 0$)
for a decrease in area ($dA < 0$)

M >1 (supersonic flow)

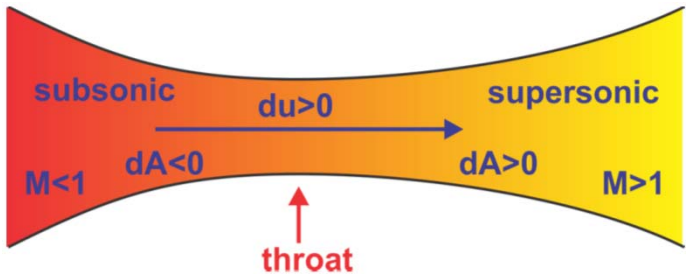
an increase in velocity ($du > 0$)
for an increase in area ($dA > 0$)

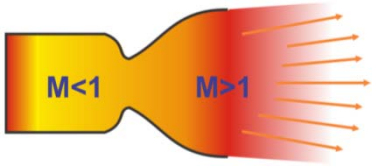


nozzle
velocity
increases

diffuser
velocity
decreases

converging-diverging nozzle (***de Laval*** or ***Laval nozzle***) **needed for transition from a subsonic flow to a supersonic flow**





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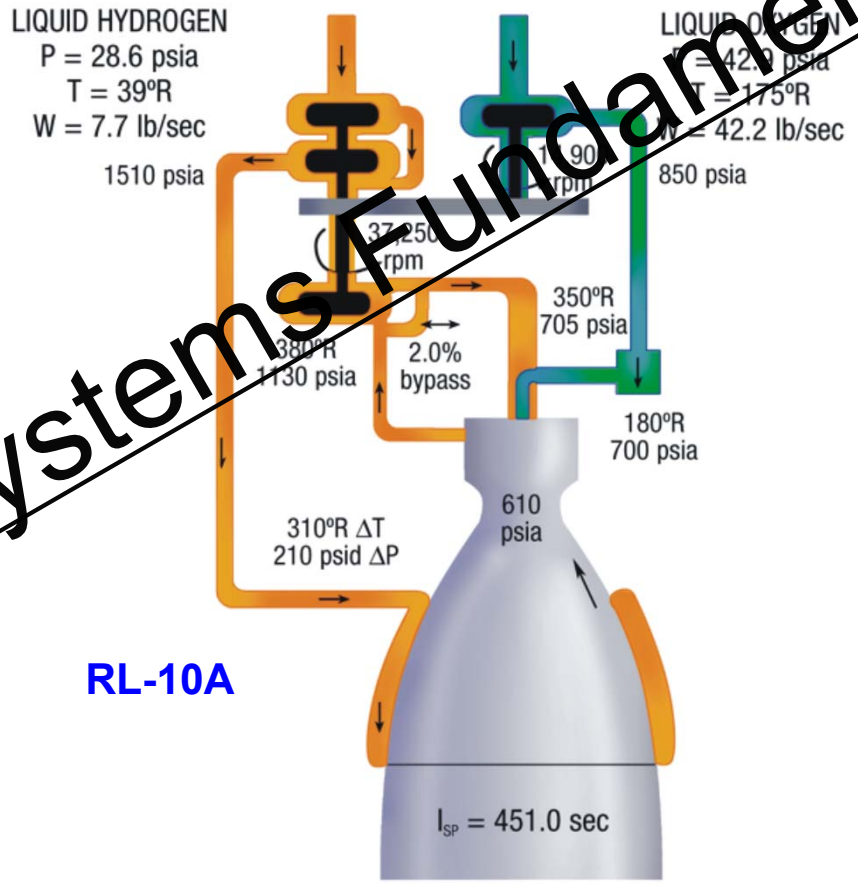
Regenerative Cooling – RL10

- Pratt & Whitney developed RL10 in 1959
- initially liquid H_2 is heated to a temperature sufficiently higher above the critical temperature that it can be used to expand as a gas through the turbine that drives the liquid H_2 and O_2 pumps.
- capable of self-starting in space (using pressure in hydrogen tanks)
- pressure is high
  - no boiling takes place
- gaseous H_2 is an excellent coolant
  - high thermal conductivity



RL-10A

Figure courtesy
Pratt & Whitney, A United Technologies Company

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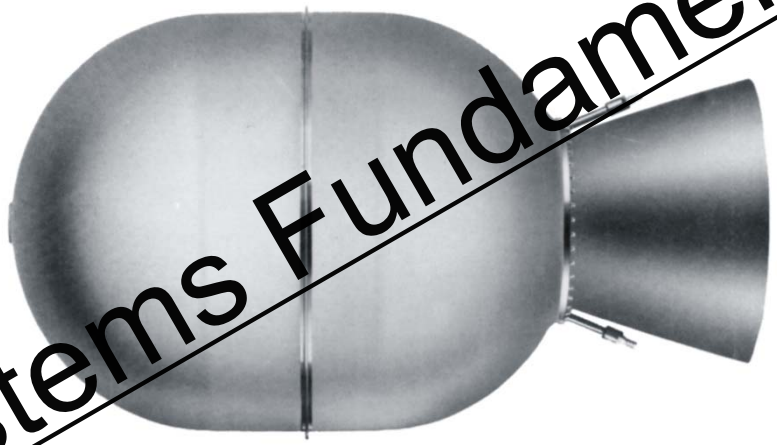
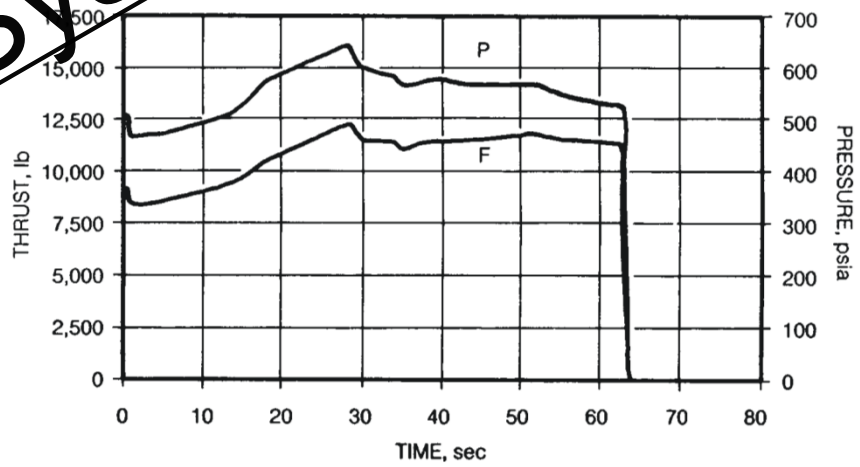
Solid Rocket Motor. Example – Star 37 FM

The STAR 37FM rocket motor was developed and qualified for use as an apogee kick motor on FLTSATCOM and GPS Block IIR satellites and serves as the third stage on Boeing's Delta II launch vehicle. The motor design features a titanium case, a 3D carbon-carbon throat, and a carbon-phenolic exit cone. Maximum propellant weight is 2350 lb. The motor has been qualified for propellant off-loading up to 2257 lb.





25 Star-37FM motors were flown from 1986-2012

Figures courtesy *ATK Alliant Techsystems*

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Magnetoplasmadynamic Thrusters (MPD)

- **steady-state MPD thrusters**
- discovered in 1960s
- capable of producing continuous thrust
- require very high power
- geometry similar to arcjet
  - relatively low pressure
  - high magnetic field
  - higher electric field
- common propellants
  - hydrogen
  - argon
  - xenon
  - lithium
- no neutralizer required

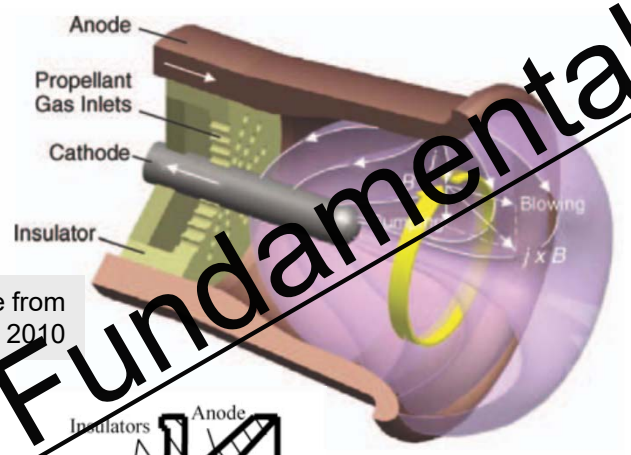
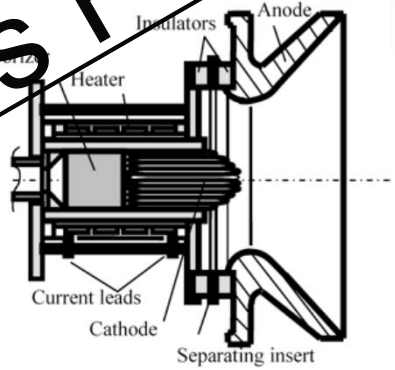
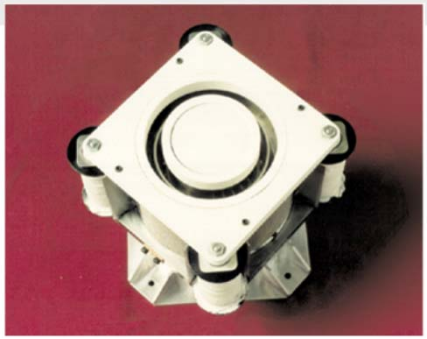


Figure from M. Andrenucci, 2010



Flight model of "Micron" lithium thruster (left) and 500 kW lithium SF-MPD (right). Gorshkov et al., IEPC, 2007

BPT-2000 Hall thruster by General Dynamics. Xenon propellant; I_{SP} = 1765 sec; power 1200– 2700 W. Photo courtesy of General Dynamics.



some MPDs are called Hall thrusters

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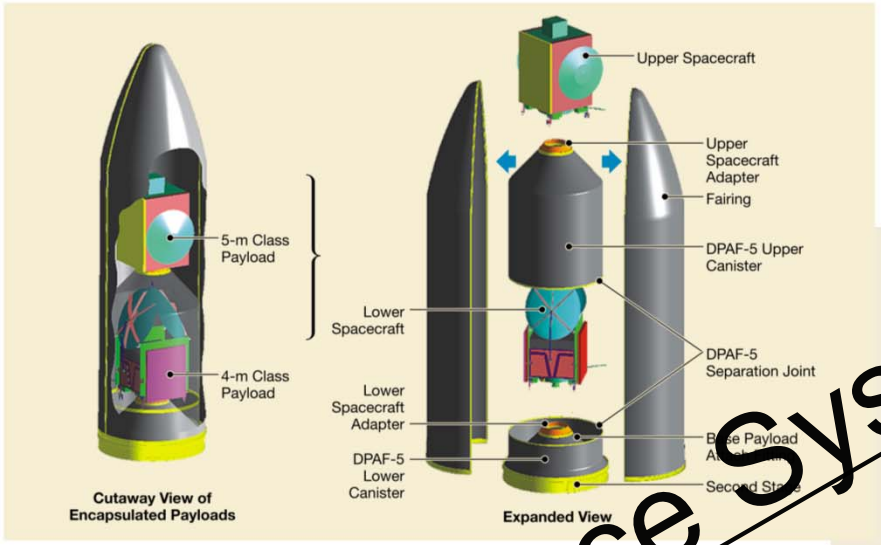
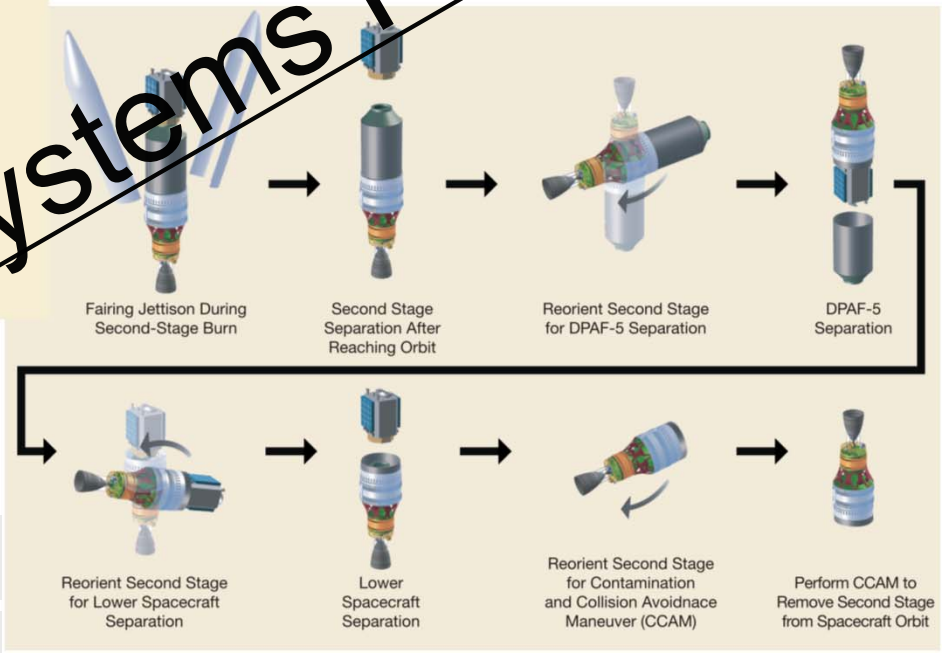
Delta IV – Dual-Payload Launch



Delta IV Heavy Dual-Payload Attach Fitting

Delta IV Heavy Dual-Manifest Spacecraft Deployment Sequence



Figures courtesy of United Launch Alliance, LLC.

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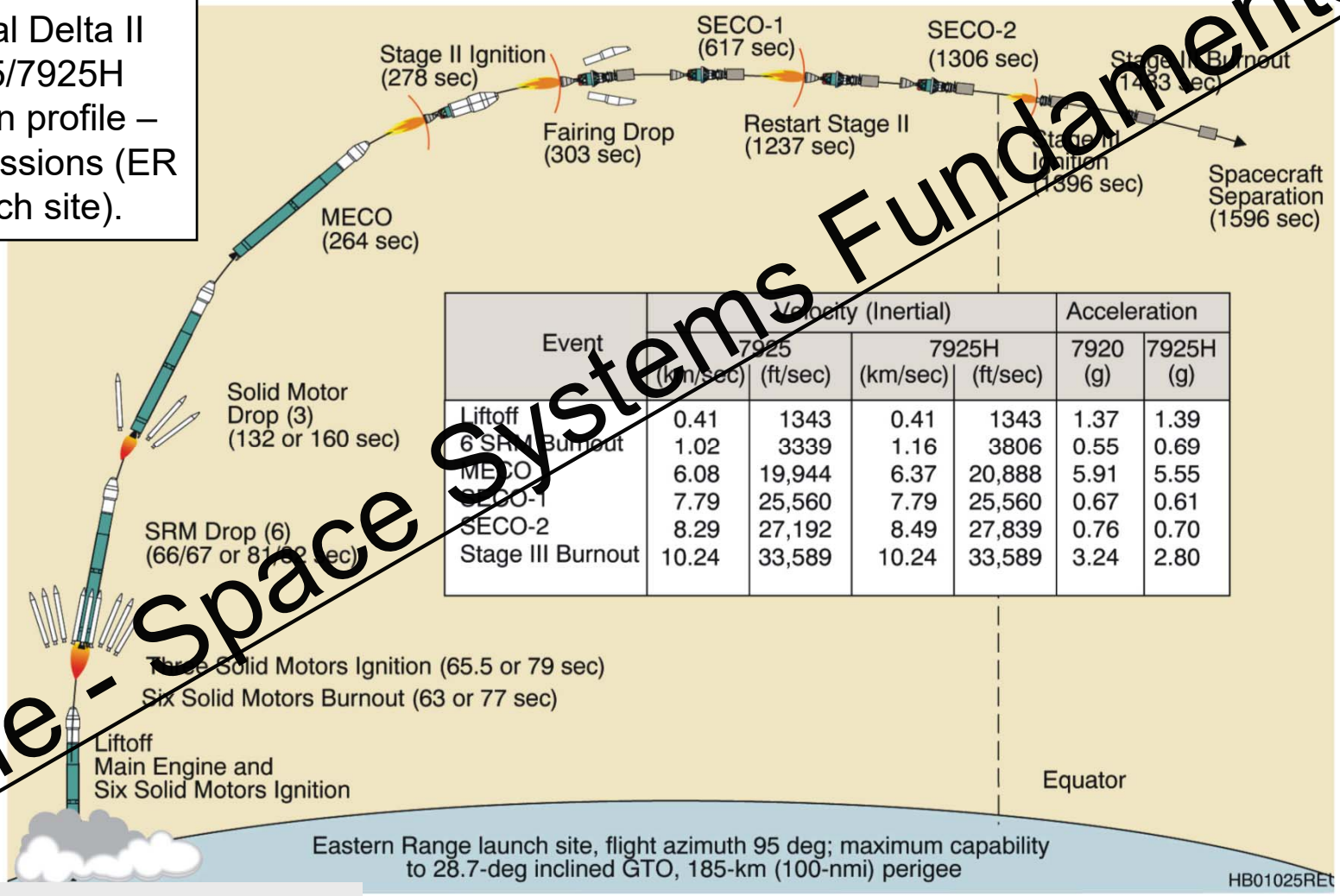
Delta II Launch

Typical Delta II 7925/7925H mission profile – GTO missions (ER launch site).



Event	Velocity (Inertial)				Acceleration	
	7925		7925H		7920	7925H
	(km/sec)	(ft/sec)	(km/sec)	(ft/sec)	(g)	(g)
Liftoff	0.41	1343	0.41	1343	1.37	1.39
6 SRM Burnout	1.02	3339	1.16	3806	0.55	0.69
MECO	6.08	19,944	6.37	20,888	5.91	5.55
SECO-1	7.79	25,560	7.79	25,560	0.67	0.61
SECO-2	8.29	27,192	8.49	27,839	0.76	0.70
Stage III Burnout	10.24	33,589	10.24	33,589	3.24	2.80

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Figure courtesy *The Boeing Company*

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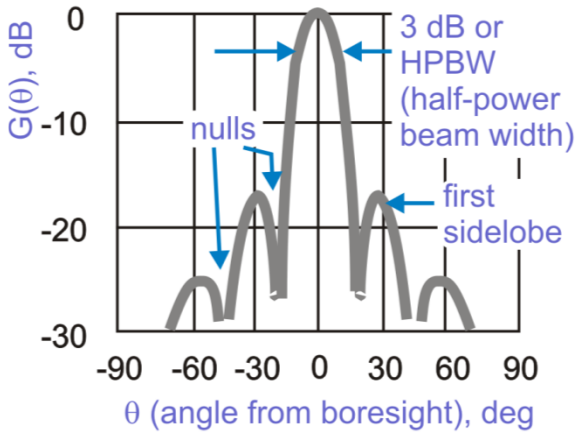
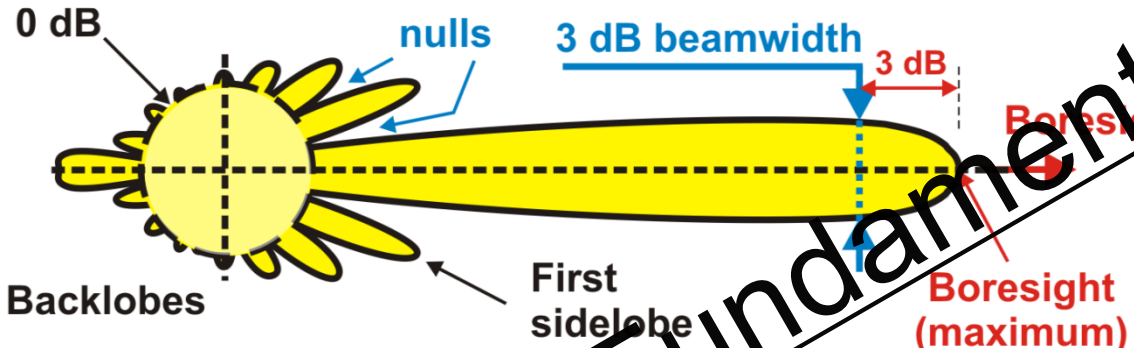
Antenna and Gain





Radiation pattern for a typical high-gain antenna

Antenna directive gain (directivity) G_d

$$G_d = \frac{4\pi}{\Omega} \qquad G_d = \frac{4\pi A}{\lambda^2}$$

$$G_P = \eta G_d$$

Power gain = efficiency × directive gain

For a circular antenna diameter D

$$G_d = \left(\frac{\pi D}{\lambda}\right)^2 \qquad G_P = \eta\left(\frac{\pi D}{\lambda}\right)^2$$

$$\theta_{3-dB} \cong 1.22 \times \frac{\lambda}{D}\,(\text{radians}) \approx 70 \times \frac{\lambda}{D}\ \text{deg}$$

EIRP = Effective Isotropic Radiated Power

$$\text{EIRP} = G_P P_t$$

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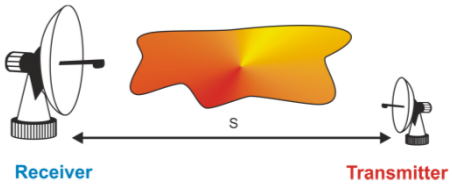
Link Design (cont.)

- signal-to-noise ratio $$\frac{E_b}{N_0} = \frac{W_S}{R} \times \frac{1}{k_B T_S} = \frac{P_t L_{l,t} G_t L_S L_a G_r L_{l,r}}{k_B T_S R}$$

Link Equation or **Link Budget**



$$\frac{E_b}{N_0} = \frac{P_t L_{l,t} G_t L_S L_a G_r L_{l,r}}{k_B T_S R}$$

- often convenient to use the decibel language (addition and subtraction instead of multiplication and division)

$$E_b/N_0 = P_t + L_{l,t} + G_t + L_S + L_a + G_r + L_{l,r} + 228.60 - 10 \log T_S - 10 \log R$$

- losses (L_{lt}, L_S, L_a, L_{lr}) are < 1.0 (in numbers) and negative (in dB language)
- antenna gains (G_t, G_r) are >1.0 (in numbers) and positive (in dB language)

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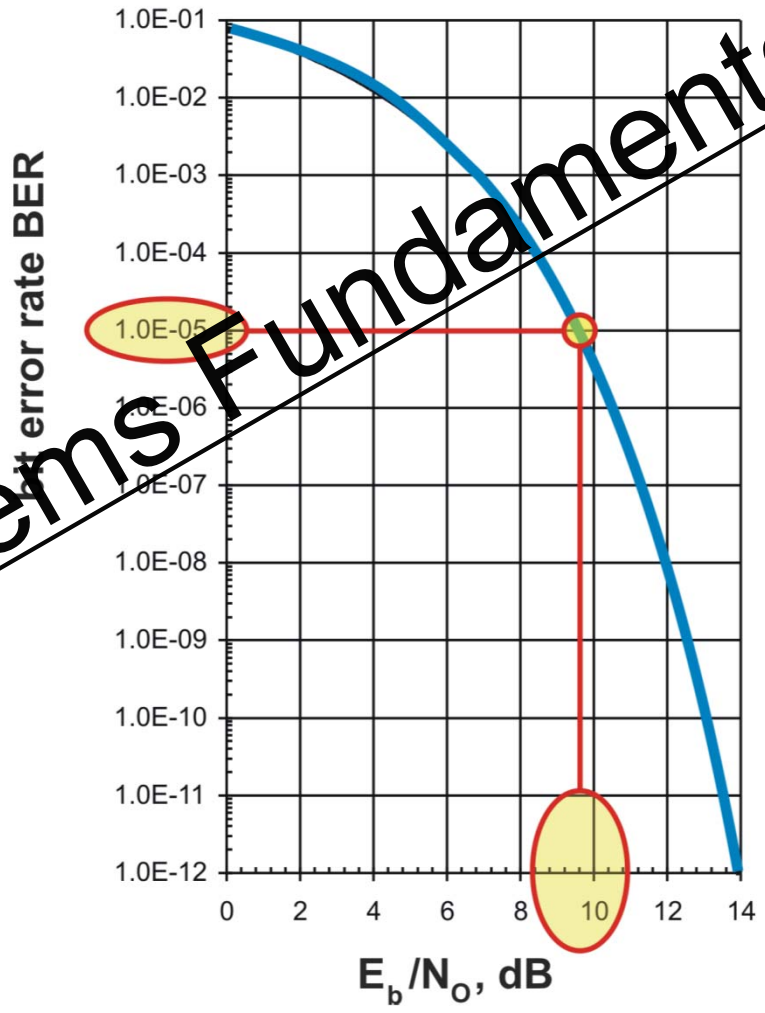
Errors

- bandwidth required to transmit a given bit rate depends on modulation and the details of technique implementation (sideband truncation,…)
- close-to-unity ratio of the data bit rate to the transmission bandwidth (bps/Hz) for QPSK
- noise in the communications link results in errors
- dependence (figure) for an idealized model and optimal RF filtering characteristics
- optimal filtering may not be achieved in practice for a variety of reasons, including manufacturing imperfections
- usually **additional implementation margin, a few decibels,** to allow for possible imperfections in amplifiers and non-linearities in transmission path



The selection of E_b/N_0 would depend on the desired BER

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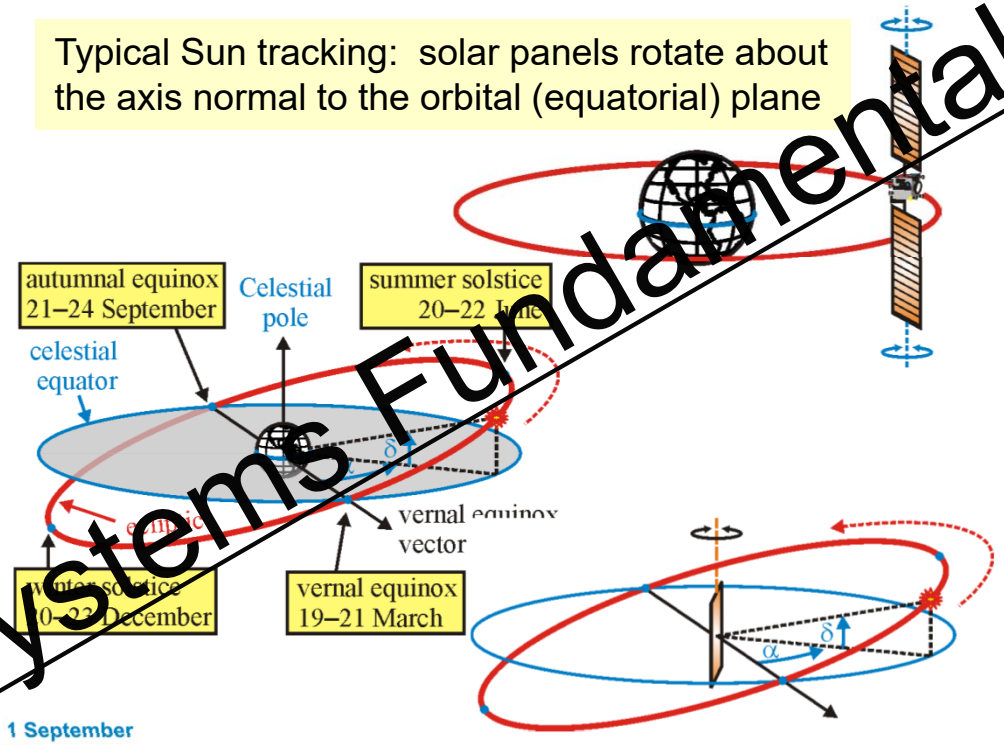
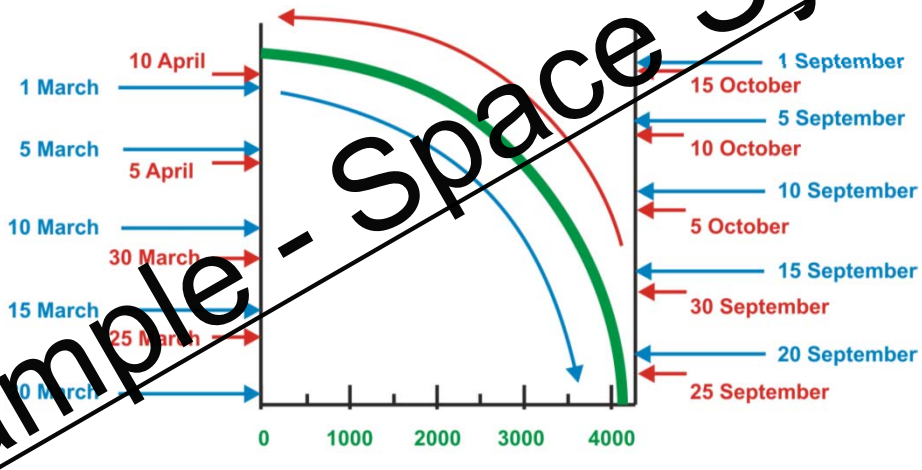
Geostationary Orbit

Typical Sun tracking: solar panels rotate about the axis normal to the orbital (equatorial) plane

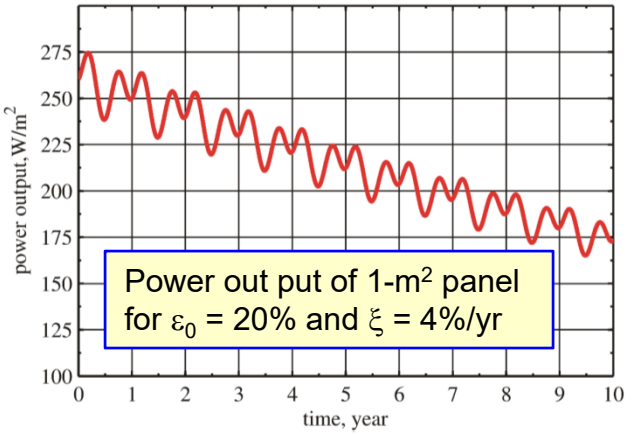
eclipses

- two "seasons" (45 days each) centered around vernal (March 21) and autumnal (September 21) equinoxes
- the longest eclipses, of about 72 minutes, occur at equinoxes





Eclipse duration in geostationary orbit, sec



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Nickel-Hydrogen Batteries

- **qualified for GEO**
- **pressure vessel** (Inconel) at **400–900 psi**
- **negative electrode**
  - hydrogen
  - Teflon-coated platinum (catalyst) plate
- **positive electrode**
  - sintered nickel
- **electrolyte**
  - aqueous solution of potassium hydroxide KOH (typically 31% concentration by weight)
- **separator**
  - fuel cell asbestos (nonwoven mat of chrysotile asbestos fibers) or zirconium

Figure from B. N. Agrawal *Design of Geosynchronous Spacecraft*

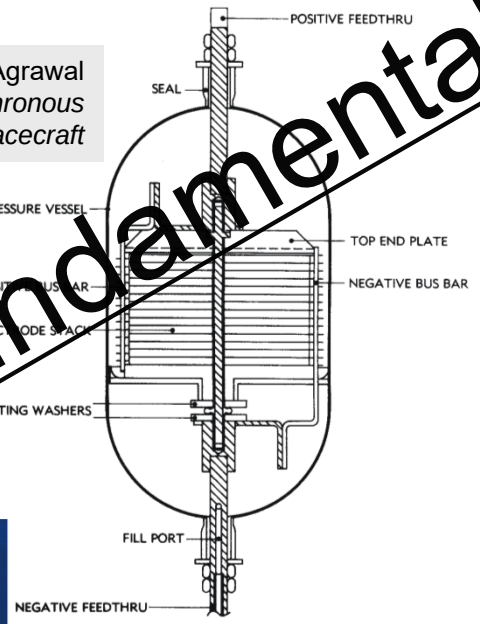
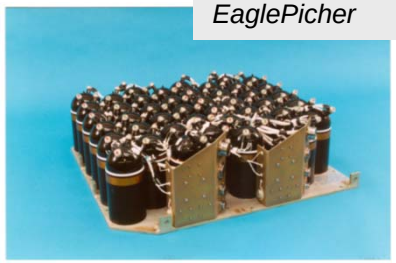


Figure 6.21 Nickel–Hydrogen battery cell (Ref. 7).

Photos courtesy *EaglePicher*



Ni-H2	
specific energy	**30-40 Wh/kg**
energy density	up to **60 Wh/l**
nominal voltage	**1.25 V/cell**

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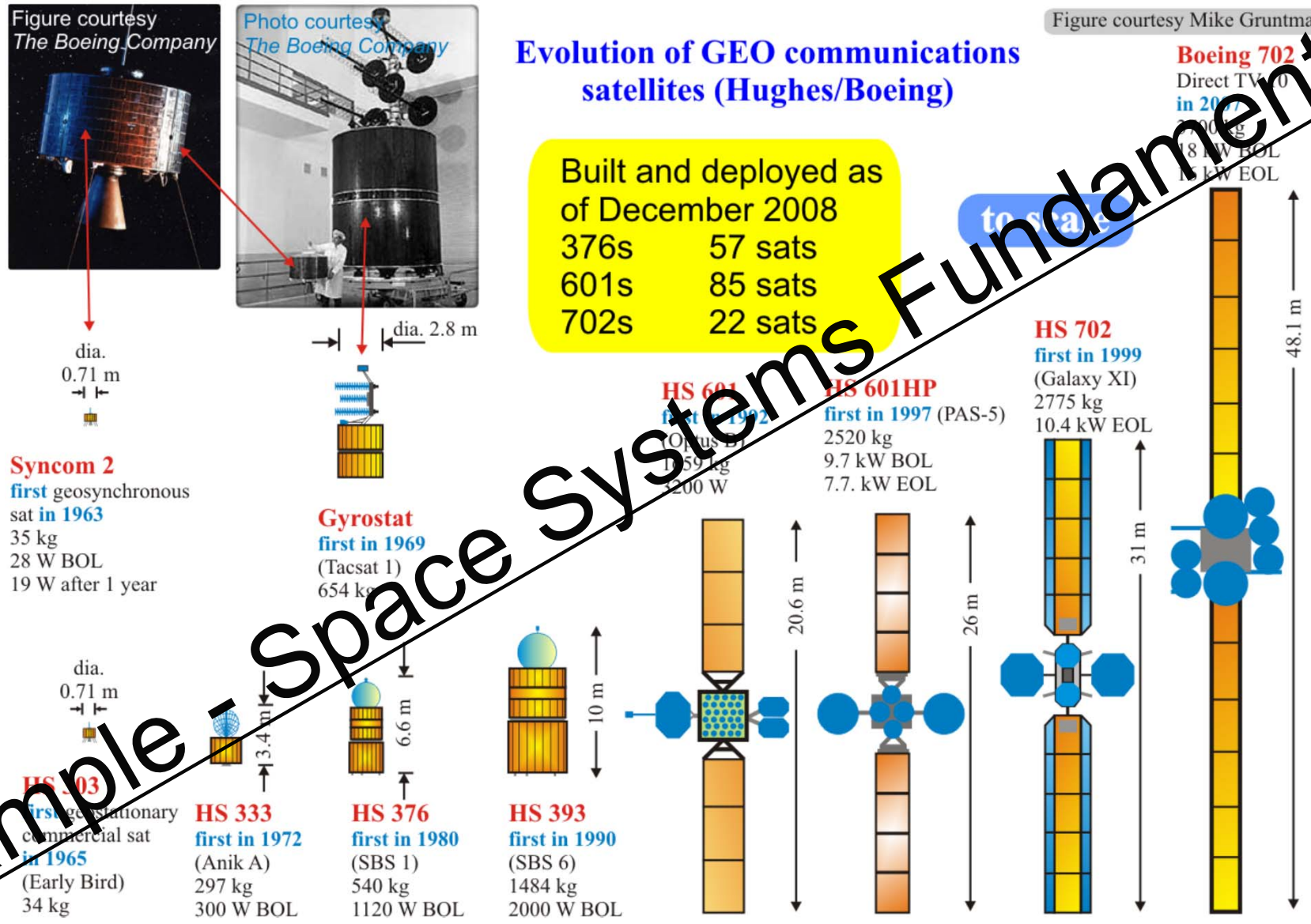

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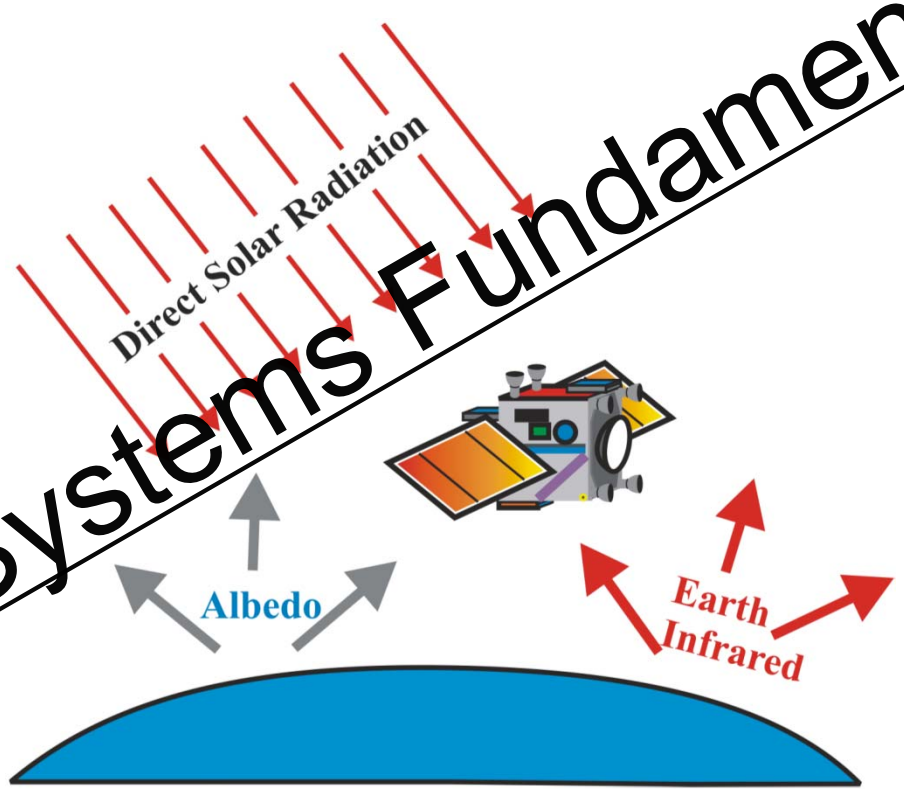
Main Environmental Thermal Loads

- environmental heating on orbit
  - direct sunlight
  - sunlight reflected off the Earth (especially for LEO)
  - infrared (IR) energy emitted from the Earth (especially for LEO)
- free molecular heating during launch or in exceptionally low-altitude orbits



- Overall thermal control of a satellite is usually achieved by balancing
  - energy emitted by the spacecraft (as infrared radiation)
  - energy dissipated by internal electrical components
  - energy absorbed from the environment

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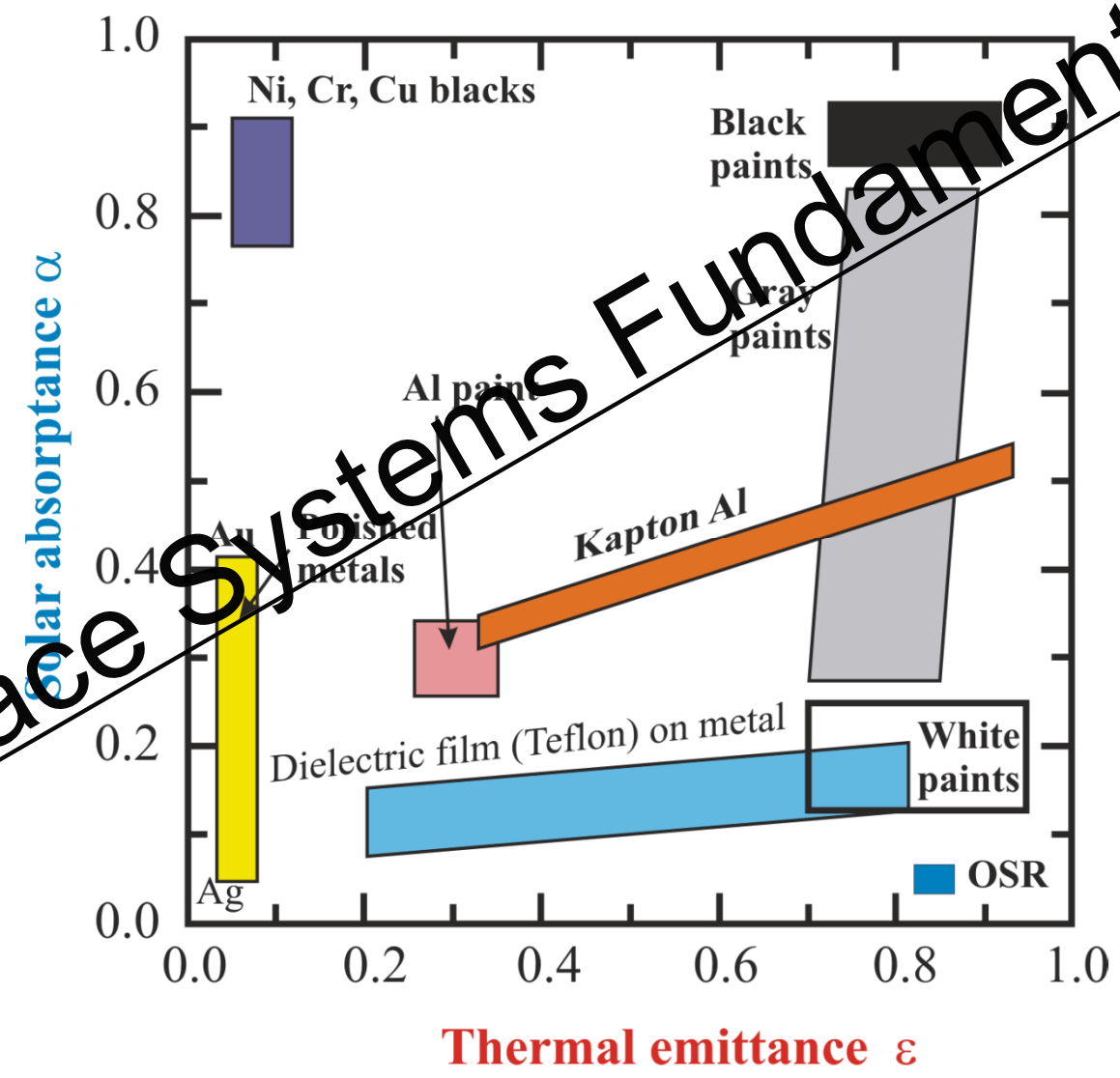
Coatings



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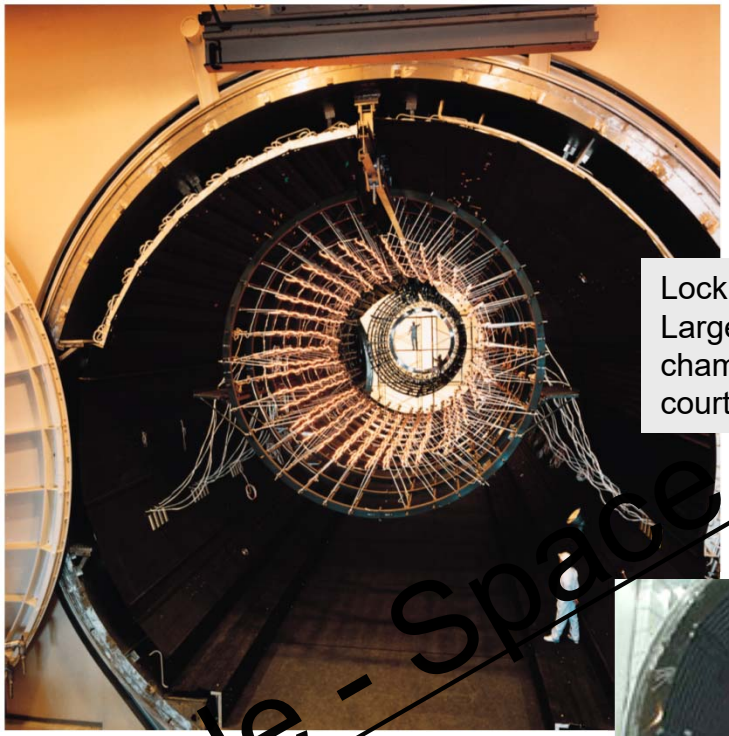
Test Facilities

AEDC Mark 1 chamber
42-ft diameter 82-ft-tall chamber housed in a ten-story building; has 77 K capability

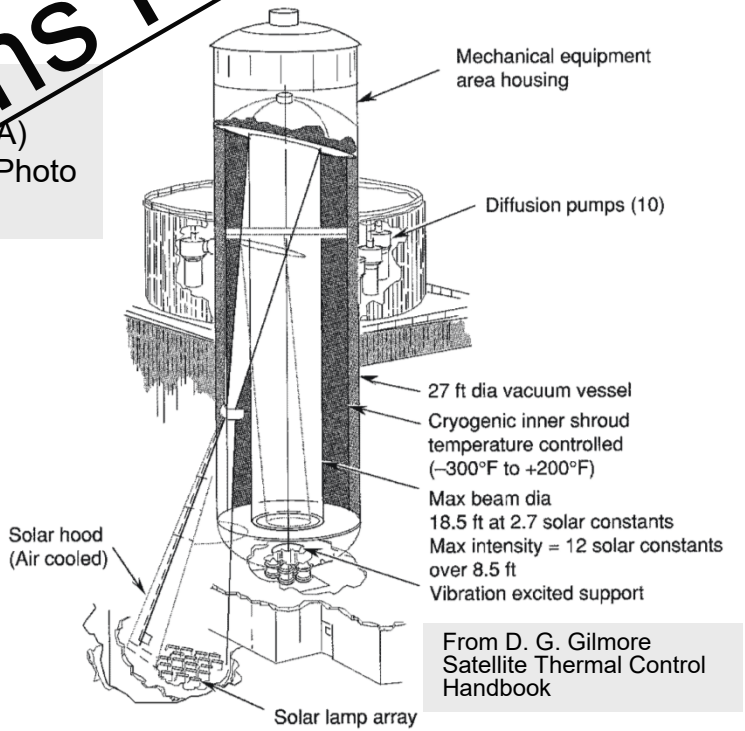
Lockheed-Martin Delta
horizontal 80-ft-long cylinder chamber; 36-ft in diameter; has 90 K capability

JPL facility
pressure 10^{-5}–10^{-6} tor; solar simulation by an array of modules, each containing a 1-kW quartz-iodine lamp; color temperature 5800 K blackbody



Lockheed Martin's Dual Entry Large Thermal Altitude (DELTA) chamber in Sunnyvale, Calif. Photo courtesy Lockheed Martin

Boeing's thermal vacuum test chamber, El Segundo, Calif. Photo courtesy The Boeing Company



From D. G. Gilmore Satellite Thermal Control Handbook

Figure 3. JPL thermal vacuum chamber

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