ESS 265
Instrumentation, Data Processing and Data Analysis in Space Physics

Lecture 2: Mission Design

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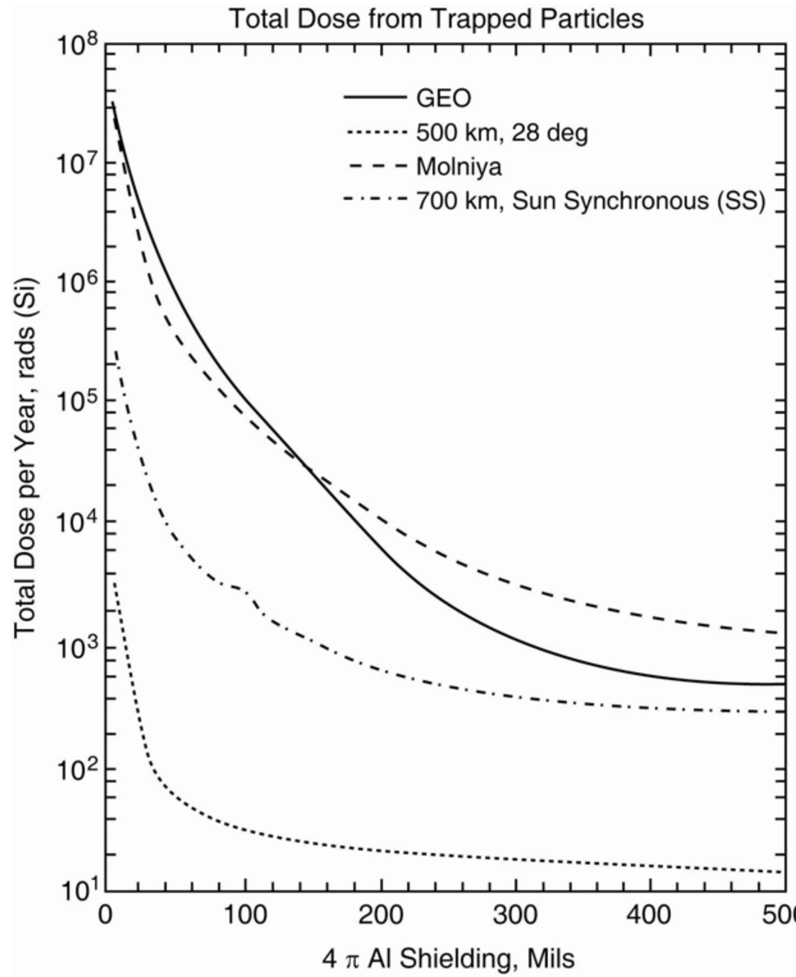
April 2, 2008

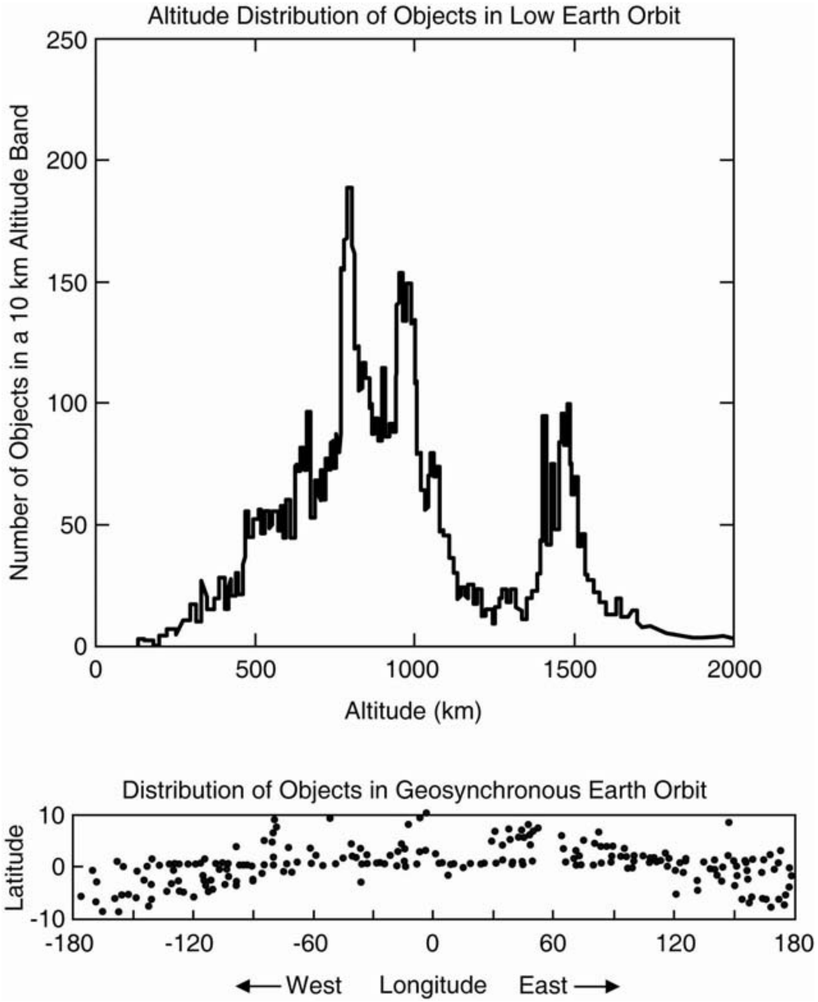
The Space Environment: Radiation Damage

- Choosing the orbit for a space mission is perhaps the first and most important step and many factors come in to play
  – Radiation dose
  – Viewing
  – Temperatures
  – Communication bandwidth
  – Etc.
- Radiation doses are high in the planetary magnetosphere of the Earth and Jupiter.
  – Below 500 km altitude and at low inclination (⪯ 28°) the annual dose is about 3 krads
  – At 700 km and over the poles one needs to shield the electronics to get the level down to 10 krads using about 40 mils Al.
  – At geosynchronous orbit, 100 mils of Al are needed for 100 krads per year
- The higher the dose the fewer parts are available and the more the parts cost.



The Space Environment: Space Debris

- Space debris is a current hot topic.
  - Orbital velocities are high so even a very small particle can be dangerous to equipment or astronauts.
- Top panel shows an old diagram of number of particles greater than 10 cm in diameter per 10 km altitude band. Exploding launch vehicles, exploding fuel tanks on vehicles and anti-satellite tests have added to this
- At lowest altitudes, atmospheric drag removes orbiting particles fairly rapidly. At high altitudes, there is not much drag.
- The density of the upper atmosphere depends on solar activity. A major geomagnetic storm can suddenly alter the orbit of many spacecraft at once causing a lot of work for military watch dogs.

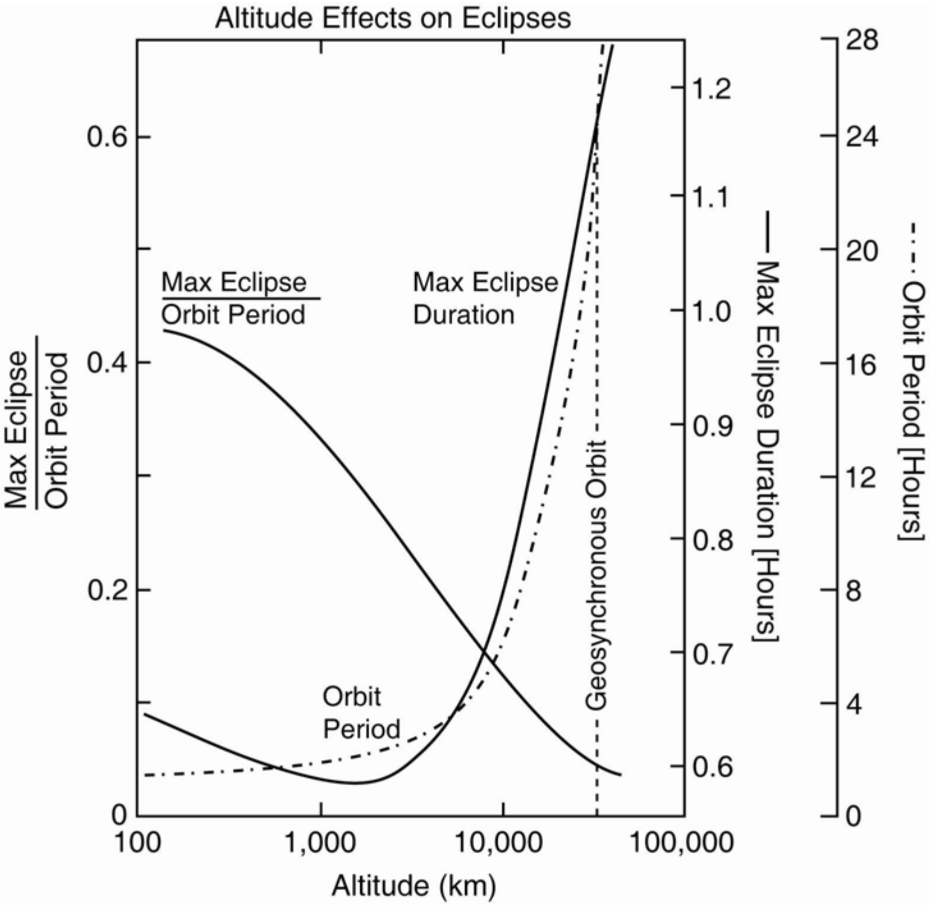


The Space Environment: Solar Occultations

- Low altitude is popular for monitoring the Earth, and one of these orbits, the sun-synchronous orbit is very popular because lightning for cameras remains constant. In this orbit, gravity torques keep the spacecraft orbit precessing at the speed needed to compensate for the motion of the Earth around the Sun.

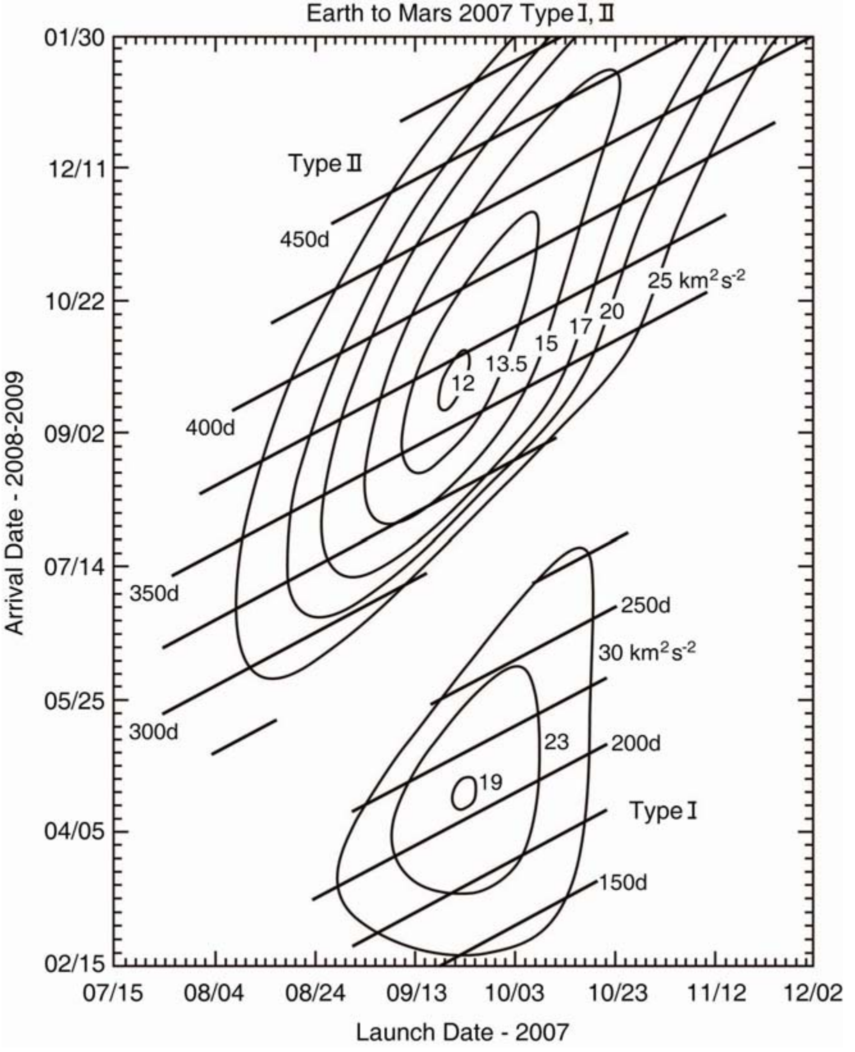
- When spacecraft are in eclipse, they cool off rapidly and very long eclipses can damage spacecraft. Batteries can be used to keep some parts of a spacecraft warm, but this can only be done so long with a standard spacecraft battery.

- While the fractional time in solar eclipse decreases with altitude, the maximum eclipse duration increases.



Launch Considerations

- Launch vehicle costs are a major fraction of the cost of a space mission, so it is desirable to use the least possible energy that allows one to reach their target in a reasonable amount of time.
- If one is launching in a low inclination Earth orbit or on an interplanetary trajectory, one can get some benefit from launching at low latitudes, even on the equator, and get energy from the Earth rotation. Launches in a north-south orbit are generally from Vandenberg A.F.S. in California to avoid flying over populated areas.
- Planetary encounters are complicated. If one wishes to orbit or land, one needs to approach the planet slowly. Oftentimes, two or more trajectories are possible with different arrival speeds, arrival dates and payload capability.
- C3 is the energy per unit mass that the payload receives from the rocket relative to the energy needed to escape the Earth.

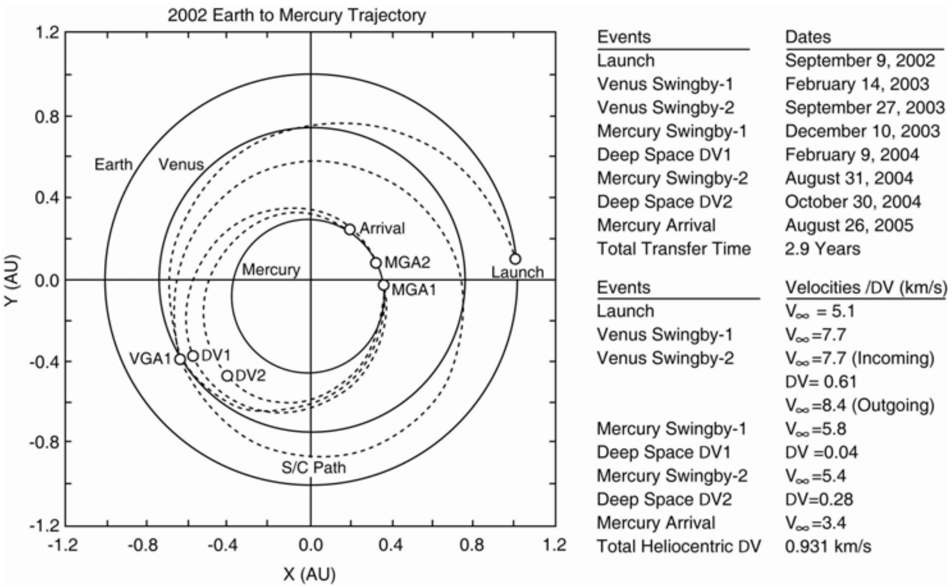


Launch Considerations: Gravity Assists

- It is possible to gain energy or to lose energy in a planetary flyby. Thus it is possible to save energy by multiple planetary encounters.

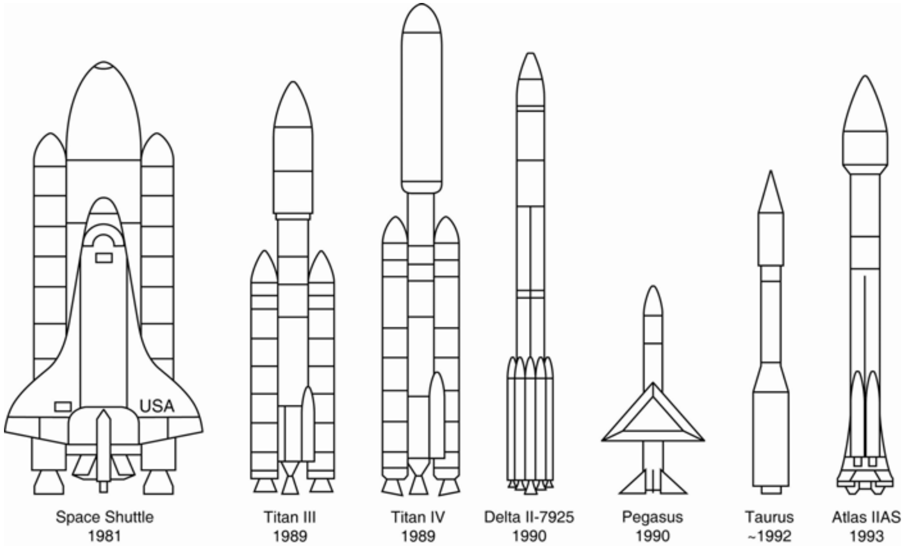
- This has been used by Voyager and Pioneer to explore the outer solar system, by Galileo and Cassini that used Venus and Earth to get to Jupiter and Saturn, respectively. Dawn is using Mars to get a boost on the way to Vesta. Messenger recently used Venus on its way to Mercury.

- Several spacecraft have even used the Earth's moon to start an interplanetary voyage. The first of these was ISEE-3 and the most recent STEREO A and B.



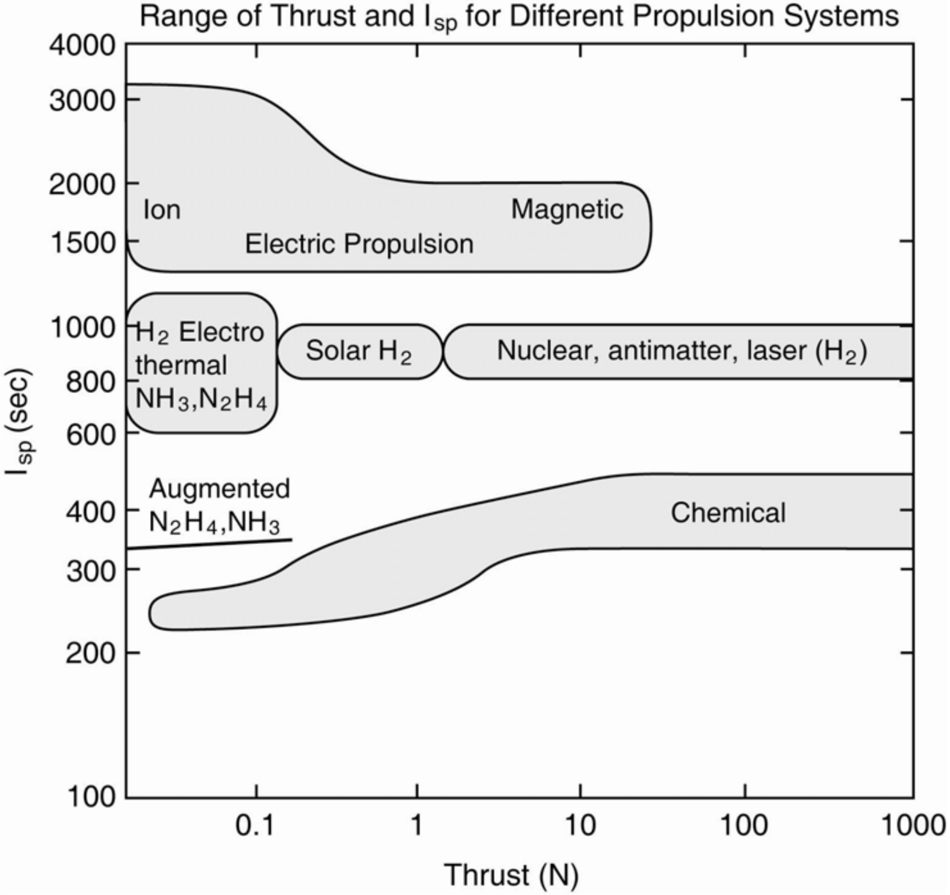
Launch Vehicles

- With the increase in the capability to miniaturize electronics, one might think that the need for large launch vehicles might disappear.
- However, there are some items that cannot be miniaturized, such as humans, telescopes and communication antennas.
- On planetary missions, we need to communicate long distances. When we arrive, we need to use telescopes that need to be sensitive.
- The Pegasus is useful only for low altitude small spacecraft. It was used for FAST, SMEX and in a more powerful form for IBEX later this year.
- The Delta II has been a workhorse for the planetary program but is threatened with extinction.



In-Flight Propulsion

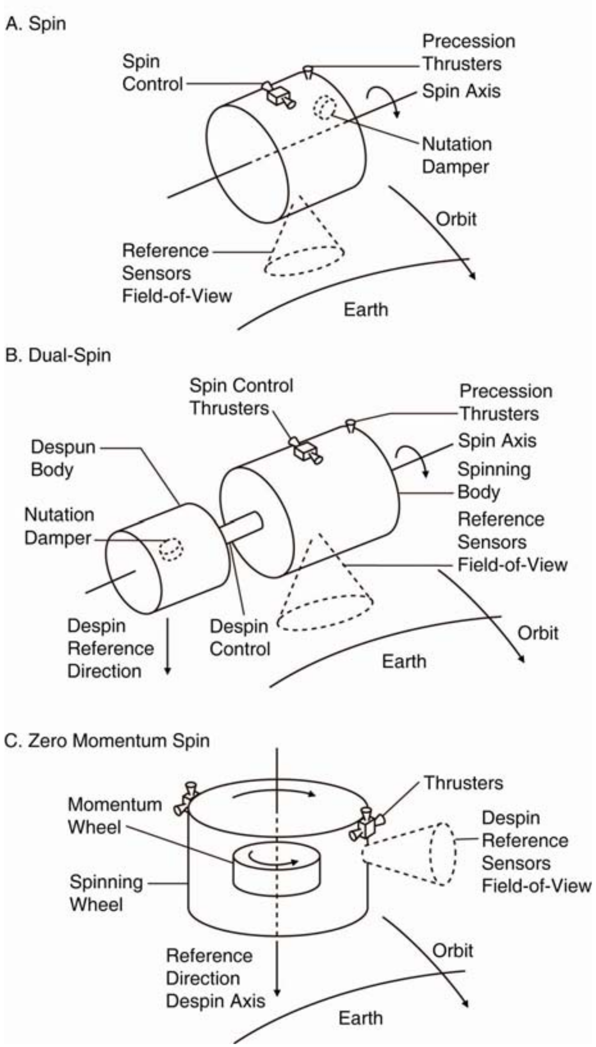
- In-flight propulsion is often needed to maintain an orbit or to change it upon mission end or even to reach the desired orbit once off the rocket.
- The fuel gives the spacecraft a change in momentum. Thus the faster the fuel travels out the thruster, the less fuel needs to be carried.
- Sometimes a spacecraft needs to change momentum in a hurry. If so, its engine needs to provide a high thrust.
- If a low thrust is acceptable and if there is a long time for thrusting, then electric ion propulsion has many advantages. Dawn uses electric propulsion.



Spacecraft Stabilization: Spinning Spacecraft

- An inexpensive way to stabilize a spacecraft is to spin it. This is especially beneficial to sensors that wish to scan in all directions.
- For magnetometers, this helps obtain the zero level in the spin plane and keep the sensors intercalibrated, but it is more complicated to reduce the data.
- For some of the advantages of both a spinning spacecraft and a stabilized spacecraft, one can despin a platform. This was done on Polar and Galileo.
- A variant of this is to have a momentum wheel inside the spacecraft that spins so that the total angular momentum is zero.

Spacecraft Stabilization Techniques on Spinning Spacecraft



Spacecraft Stabilization: Three Axis Stabilization

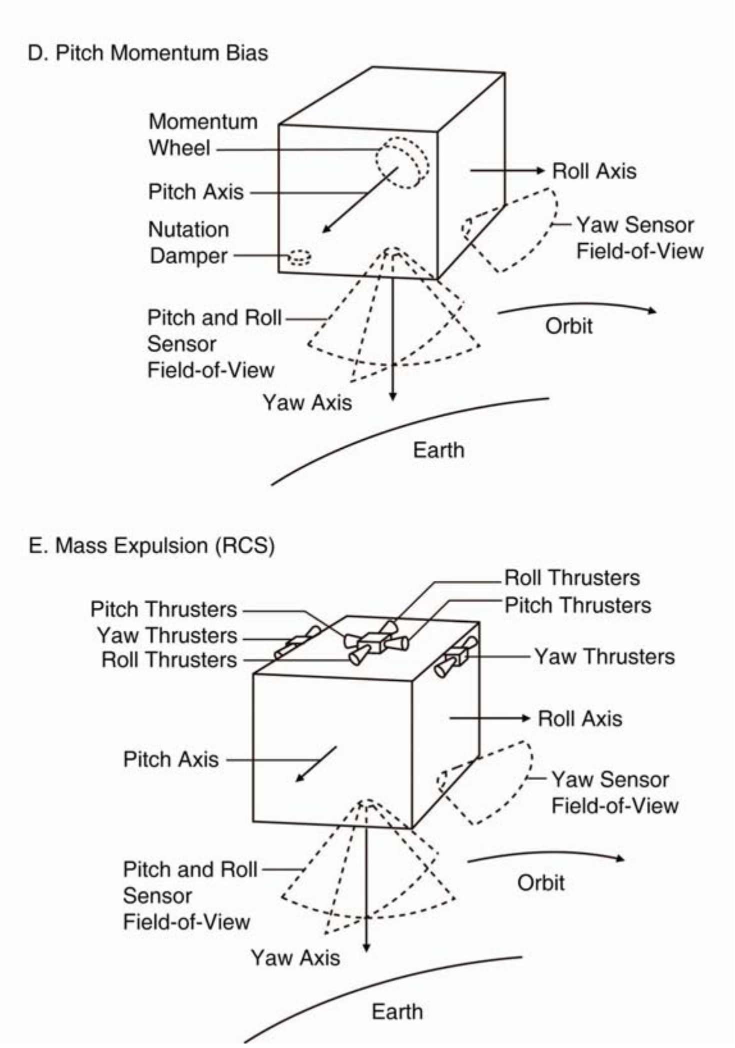
- When imaging is an objective, a three-axis stabilization is usually used. This can be done in two ways: with momentum or reaction wheels, or with thrusters.

- Reaction wheels store angular momentum. Usually there is one for each of three orthogonal directions. If there is one spare, it is oriented at an angle to the rotation axes of the other three.
  - Reaction wheels can only store so much angular momentum. When they reach their maximum capacity, they must be desaturated with thrusters.
  - Reaction wheels can wear out.
  - They are helpful when there are periodic reversing torques

- Thrusters use non-renewal propellant and in general are coarser than reaction wheels.

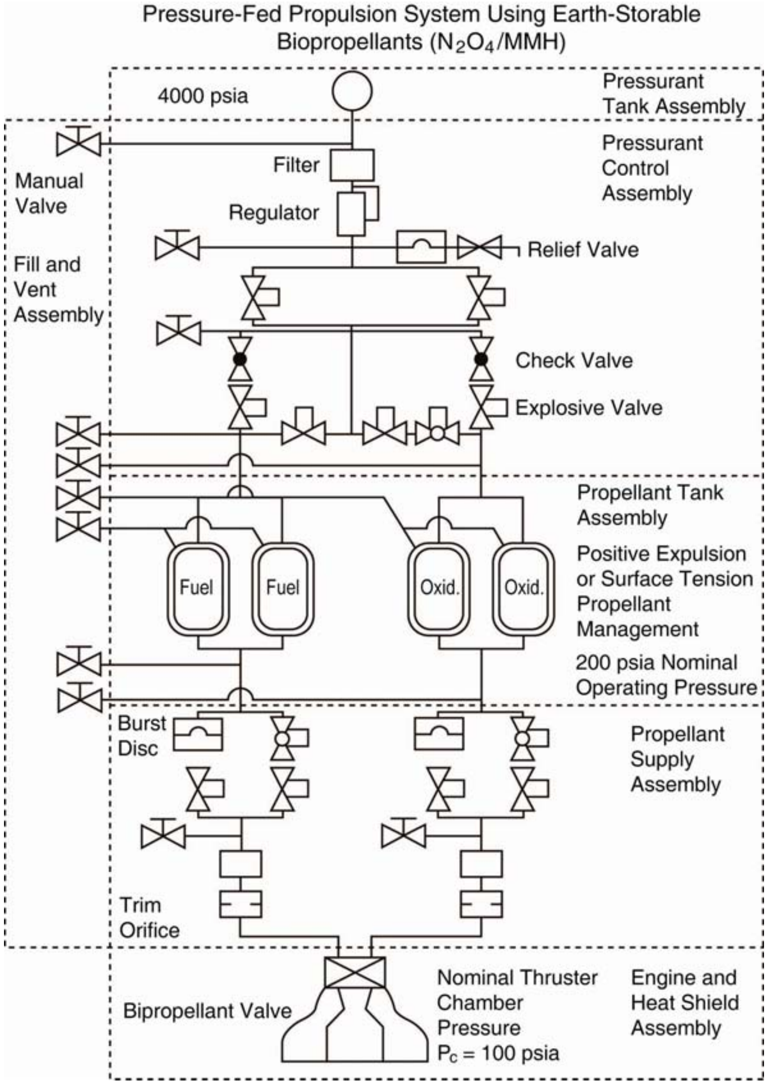
- Dawn uses both reaction wheels and thrusters, relying on reaction wheels most of the time.

Spacecraft Stabilization Techniques on Interially Stabilized Spacecraft



On-Board Propellant: Bi-Propellant

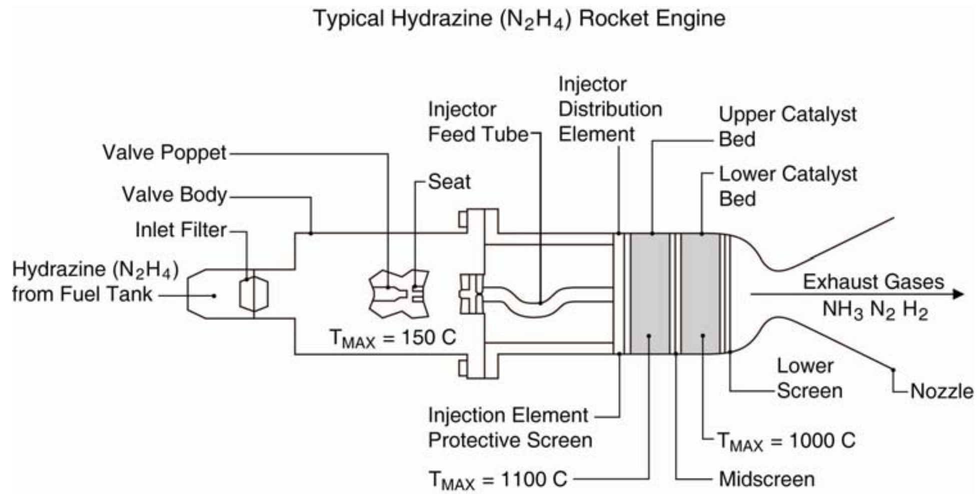
- On-board propellant may consist of oxydizer and fuel, monopropellant that contains both, or cold gas (or some exotic system like ion drive or teflon).
- Bi-propellant systems have a lot of plumbing but give a high thrust and have high exit velocities for the gas from the nozzle.
- Complexity does increase mass and cost.

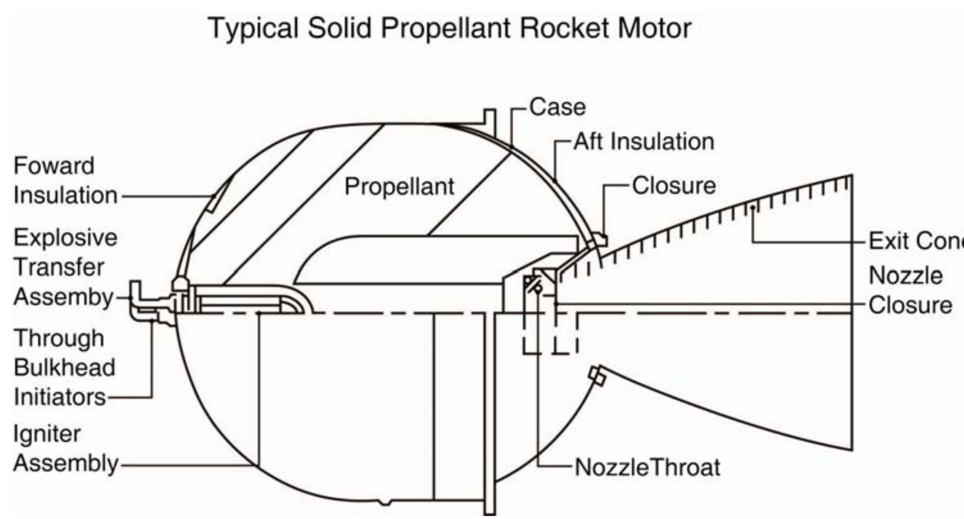


On-Board Propellant: Monopropellant

- Hydrazine (N_2H_2) can be made to burn with a catalyst. It is quite acceptable but difficult to handle.

- A solid propellant is often acceptable but since it burns to completion once lit





On-Board Propellant: Electric Ion Propulsion

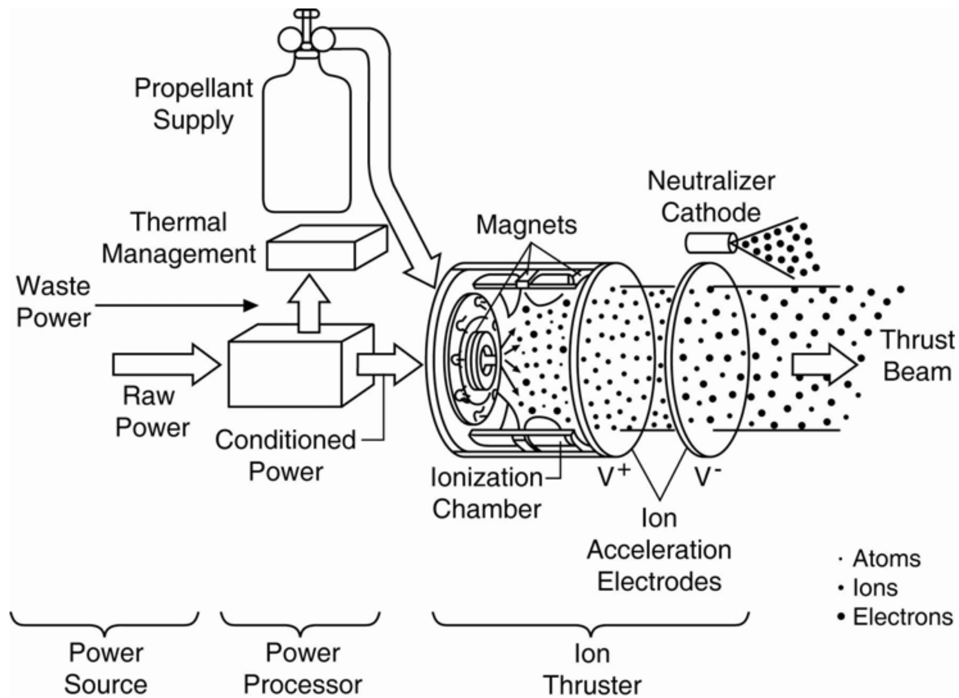
- Electric ion propulsion system uses a power source (up to now, solar) to ionize and accelerate ions to very high velocity. Dawn uses xenon accelerated to 35 km/s. This is 10x the speed of chemical rocket exhaust.

- The ion beam is neutralized by injecting it with electrons so that the spacecraft does not charge up, decelerating the beam.

- The grid on the thruster that accelerates the ions is ablated by the fast ions and has a finite lifetime.

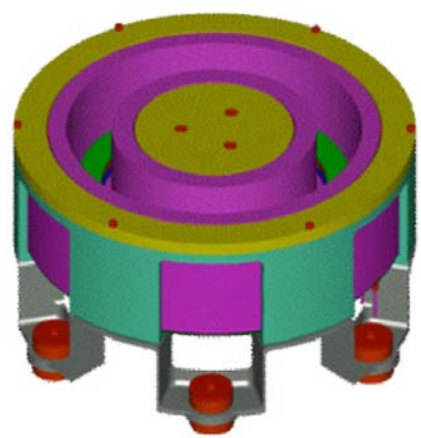
- Dawn carries 425 kg of Xenon and can change its velocity by 11 km/s. This is as much as the launch vehicle gave to the spacecraft.

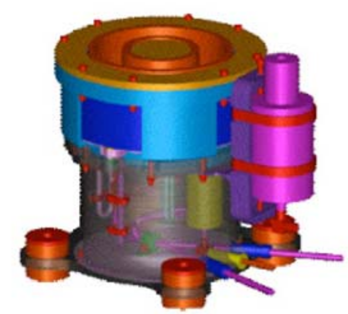
- The thruster is only 91 m Newtons or the weight of a piece of paper in the Earth's gravity.



On-Board Propulsion: Hall Effect Ion Propulsion

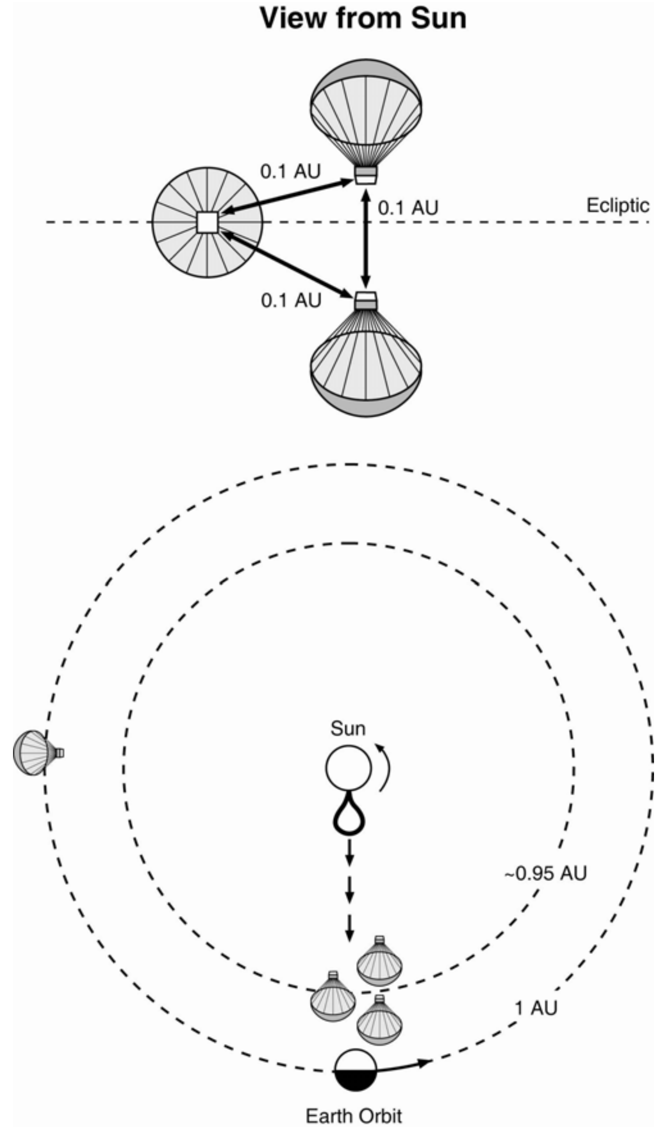
- While an electric ion engine uses an electrostatic field to accelerate ions, a Hall effect thruster uses the J x B force.
- These engines give greater thrust but lower efficiency.
- A Hall thruster was used on ESA's SMART-1 to the Moon.
- This mission had very little margin but did meet its objectives.





On-Board Propulsion: Solar Sails

- Solar sails involve no consummables, which is very attractive for a long-term mission.
- A useful solar sail would have to have 100’s of meters square solar sail area.
- It would be practical to have a solar sail sit at 0.95 AU orbiting the Sun and staging on the Earth-Sun line.
- Deployment is of much concern as the material has to be light and thin and minimal support structure can be used.
- This parachute design is but one possible configuration for a solar sail mission.



Telemetry

- NASA’s principal ground stations are part of the Deep Space Network. Their main receiving sites are near Goldstone, CA; Madrid, Spain; and Canberra, AU. The main receiving antennas have diameters of 70m, 34m, and 26m. Occasionally, 11m dishes are used. UCB has an 11m dish that it uses for RHESSI and THEMIS.
- The telemetry band used is a compromise between several constraints. The background noise drops as the frequency increases. However, the precision of the antenna transmitting and receiving antenna must increase with frequency. Omnidirectional antennas can be used in emergencies.
- The transmitted radio beam can be narrow at high frequencies but then the accuracies of the pointing must be high.
- Today very little S-band is used, as most recent missions have relied on X-band. New missions often include K-band.
- K-band can be blocked by rainstorms.

Research Satellite Frequency Bands	
Band	Range [Mhz]
S-Band	2,025 – 2,110 2,200 – 2,290
X-Band	7,250 – 7,750 7,900 – 8,400
K-Band	13,400 – 14,200 14,500 – 15,350

Other Issues

- Missions require operations teams on the ground. Science operations on an orbiting science mission can be quite complicated. Cassini is an example in which science planning is all-consuming.

- Solar power is good only so far out in the solar system. Dawn's solar arrays can generate 10k Watts at 1 AU, but only 1 kW at 3 AU. It needs much of this for thrusting. The US is short on Plutonium for RTGs for power generation in deep space.

- Thermal control is as much an art as a science but is very important. Control can be maintained through the choice of paint, thermal blankets (multilayer insulation), heat pipes, louvers and heaters. It is not always possible to expend solar array power for heating as it is needed for operating the spacecraft.

- Mutual interference of instruments is often a concern.

- Magnetic and electric cleanliness is also important on many missions.

The NEAR Mission

- Near-Earth Asteroid Rendezvous mission was one of the first two Discovery missions selected for flight. It had a total mission cost in the neighborhood of $125M.
- It was launched in February 1996 and reached Eros (after some mishaps) in February 2000.
- It weighed 788 kg with 319 kg of this being fuel.
- It carried 56 kg of scientific instruments and required 314 W to operate.
- The mission was designed to orbit and map Eros.
- The mission eventually “landed” on Eros and continued to operate for several days.

NEAR Equipment List

Table 2.2 - NEAR mass and power summary

Component	Mass(kg)	Power(W)
Instruments		
Multi-spectral imager (MSI)	7.8	13.9
Near imaging spectrograph(NIS)	14.2	20.0
X-ray/gamma-ray spectrograph(XGRS)	27.3	31.3
Magnetometer	1.6	1.5
Laser rangefinder	5.1	26.8
Propulsion		
Propulsion structure	33.1	
Propulsion system	85.1	
Propellant and pressurant	319.7	
Power		
Solar panels	46.1	
Battery	12.2	4.3*
Power system electronics	6.1	2.5*
Telecommunication		
High gain antenna	6.5	
Medium/low gain antennas	0.7	
Solid state amplifiers (2)	4.1	38.7*
Transponders(2)	8.2	18.1*
Command detector units(2)	0.7	
Telemetry conditioner units(2)	1.7	3.8*
RF switches coaxial cables	3.0	
Guidance and control		
Reaction Wheels (4)	12.9	20.0*
Star tracker	2.7	9.9*
Inertial measurement unit	5.3	21.4*
Digital sun sensors(5)	1.9	0.3*
Attitude interface unit	6.4	10.8*
Flight computers	4.7	8.0*
Command and data handling		
Command and telemetry processors(2)	9.8	18.2*
Solid state recorders(2)	3.0	6.4*
Power switching unit	5.9	0.7*
Mechanical		
Spacecraft primary structure	78.0	
Spacecraft secondary structure	18.1	
Despin mass and balance mass	6.1	
Thermal		
Thermal blankets, heaters, thermostats	11.0	
Propulsion survival heaters		75.8*
Spacecraft and instrument survival heaters		71.0*
Instrument operations heaters		40.2*
Harness		
Harness and terminal boards	38.8	4.5*
Totals	787.8	314.4*

*indicates configuration at minimum power point

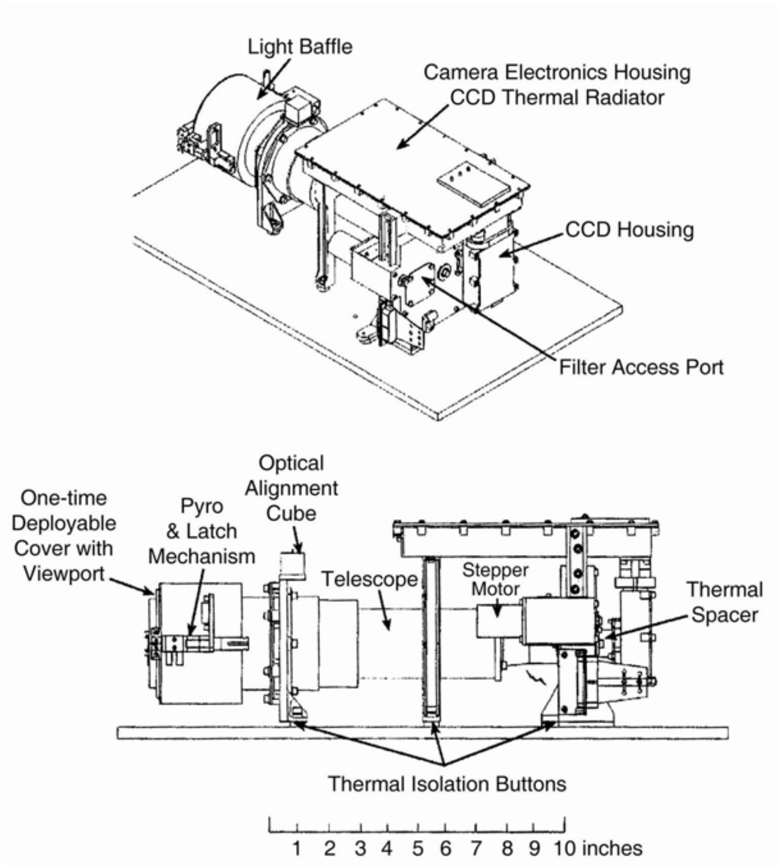
The Near-Earth Asteroid Rendezvous mission major equipment list

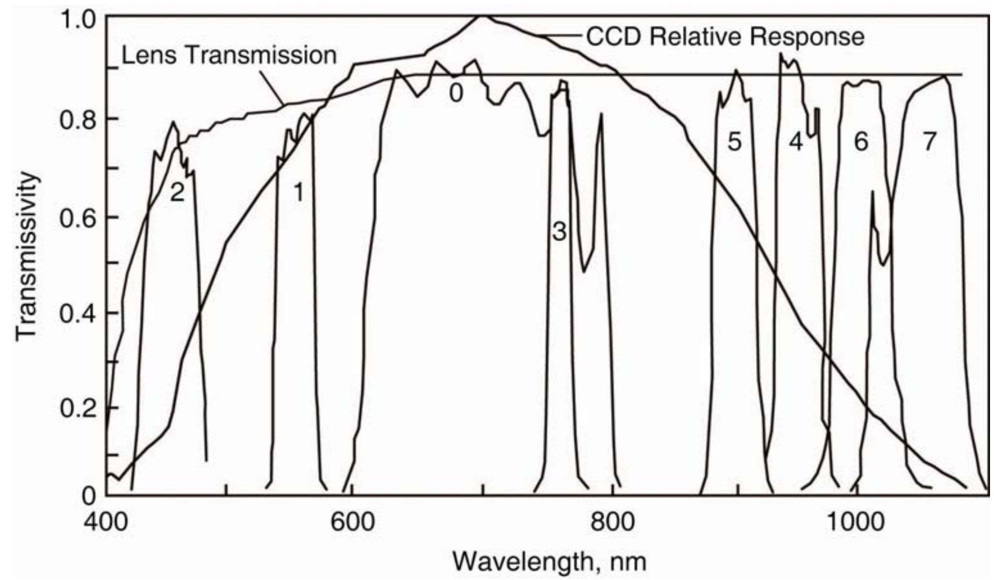
NEAR Mission: Guidance and Control

Guidance and control system components

Item	Supplier	Characteristics
Inertial measurement unit	Delco	Gyros (4):30 mm hemispherical resonator gyros Rate bias $<$ 0.01 deg hr^{-1}over 16 hr ARW $<$0.001 deg hr$^{-1/2}$ Accelorometers (4): Sunstrant QA-2000 $<$100 μg RMS noise
Star tracker	Ball	FOV: 20 X 20° Sensitvity: +0.1 to +4.5M No. of stars tracked: 5 Output rate: 5 Hz
Reaction wheels	Ithaco	Brushless DC motor Momentum: 4 Nms (@ 5100 RPM) Torque: 0.025 Nm
Sun sensors	Adcole	Quantization: 0.5° Accuracy: 0.25°
Attitude interface unit	JHU/APL	Clock: 6 MHz Memory (16 bit words): RAM: 64K EEPROM: 64K PROM: 2k Processor: RTX 2010
Flight computer	Honeywell	Clock: 9 MHz; Memory (16 bit words): RAM: 512K EEPROM: 256K PROM: 16k Processor: MIL-STD-1750A

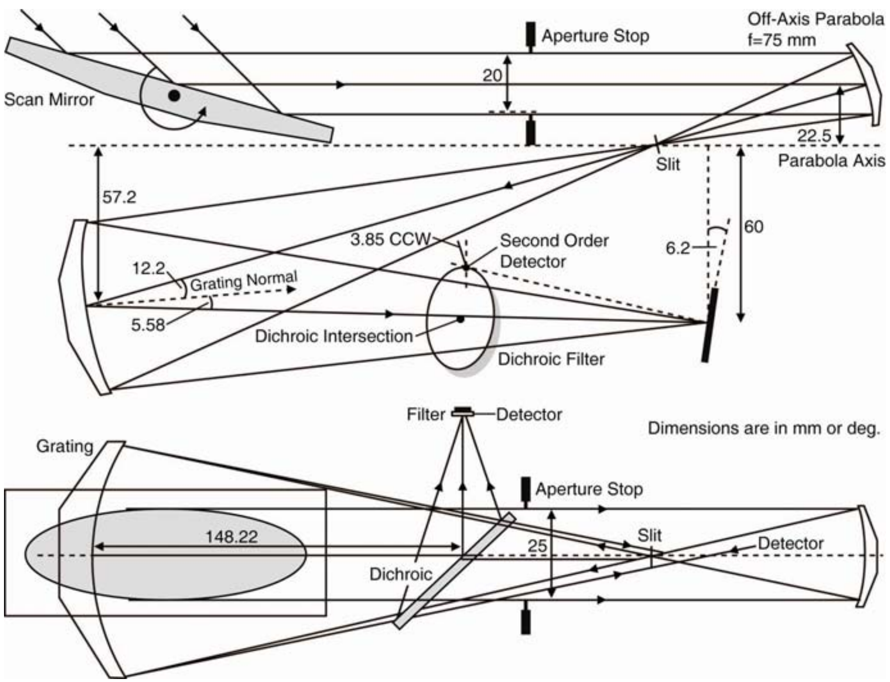
NEAR Payload: Multispectral Imager

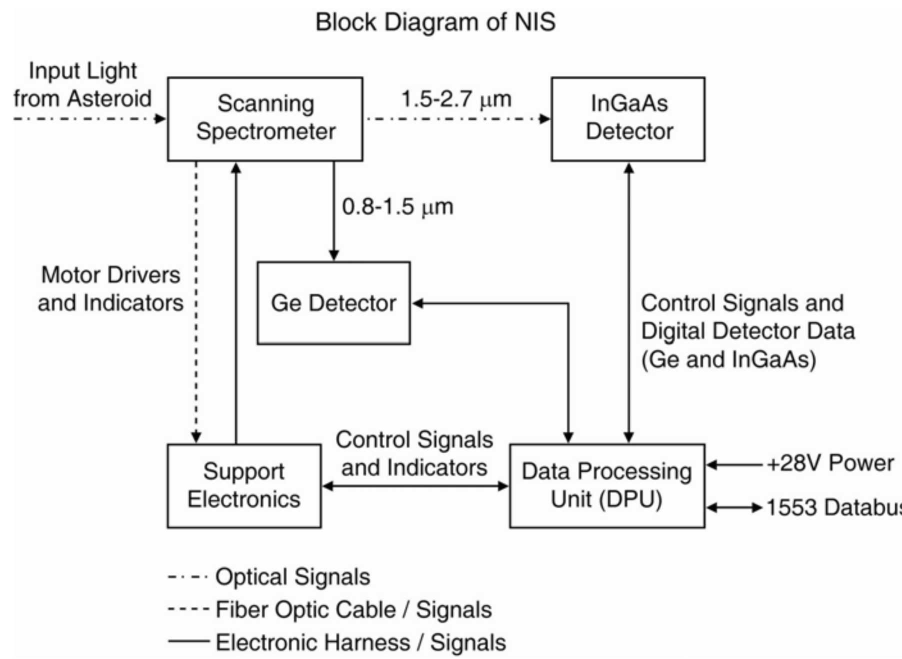




- The multispectral imager was designed to take pictures and determine the color of the surface.
- These data give the geology and tectonics of the body.

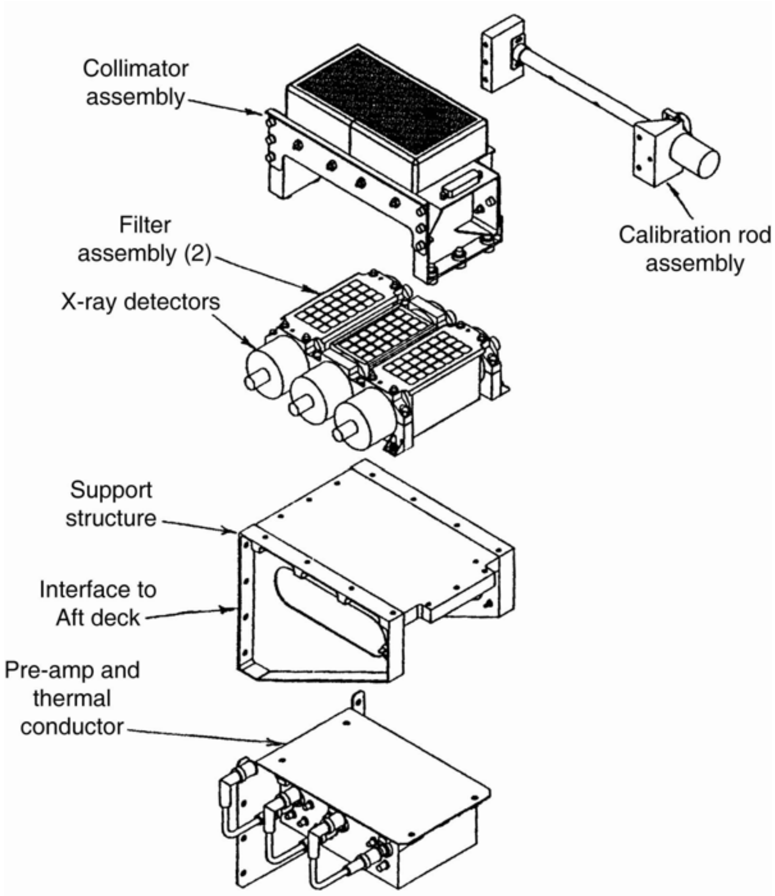
NEAR Payload: Near-IR Spectrometer

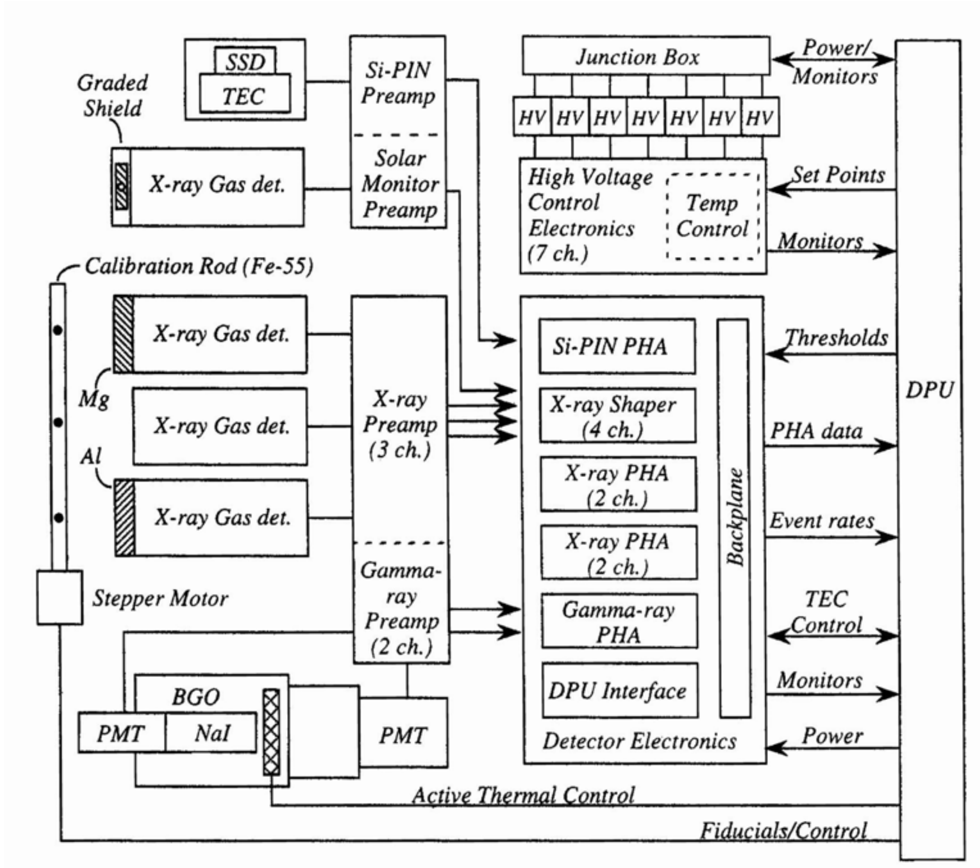




- The IR spectrometer identified absorption features in the reflected sunlight that were characteristic of specific minerals.

NEAR Payload: X-Ray Spectrometer

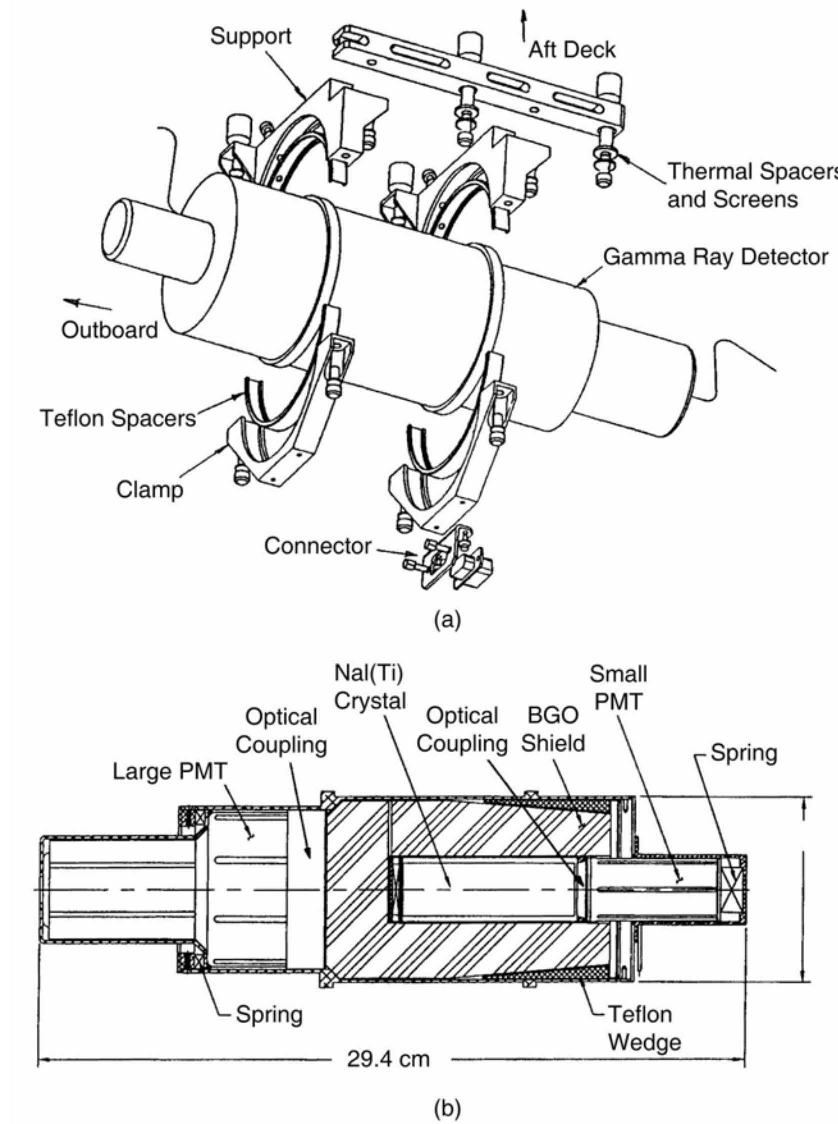




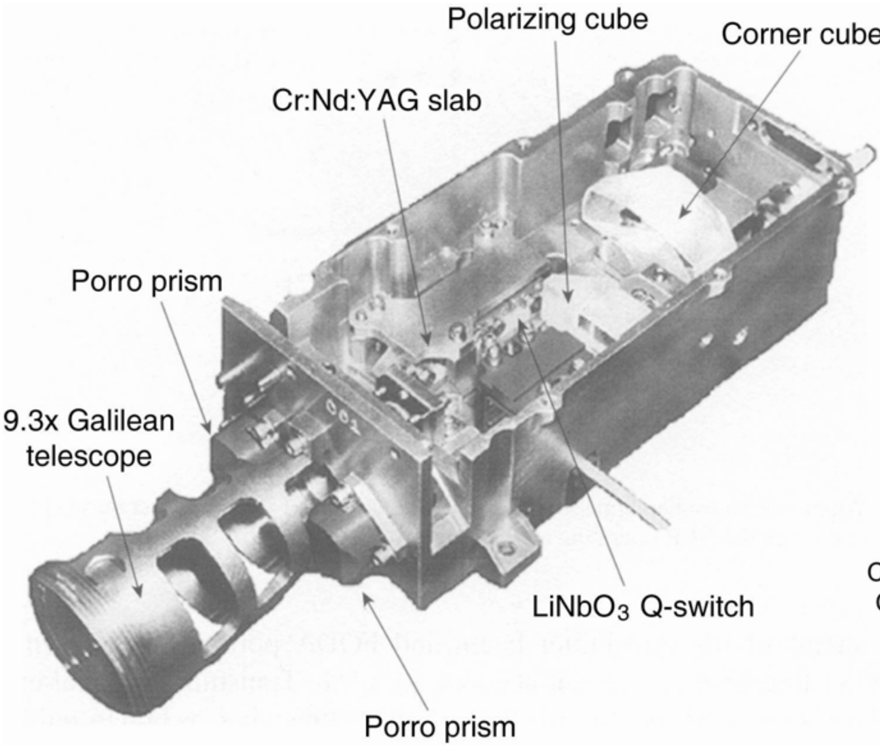
- The X-ray spectrometer provided identification of elements.
- It depended on solar X-rays as input.

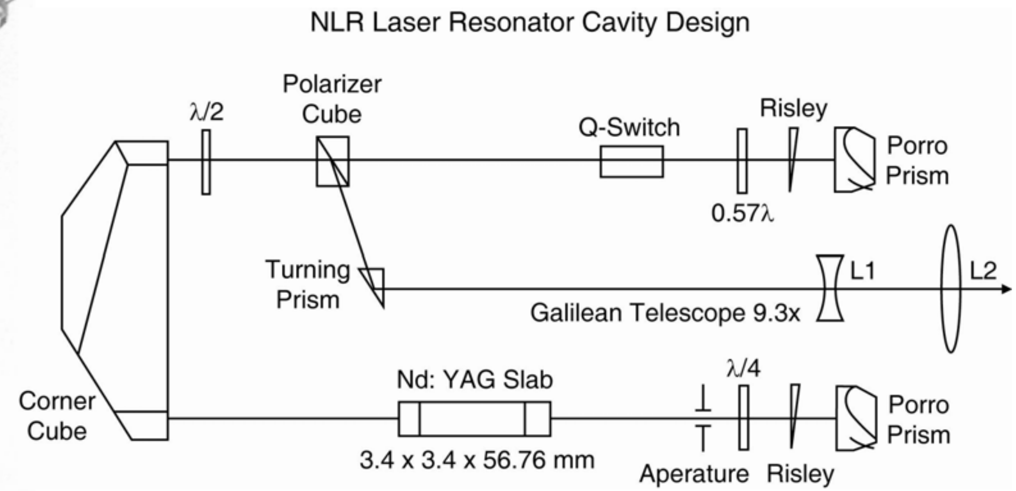
NEAR Payload: Gamma-Ray Spectrometer

- The gamma-ray spectrometer provided elemental abundances.
- It depended on natural radioactivity and cosmic ray excitation.
- It was undersized for the task at hand and did not work successfully until the landing when it was very close to the surface.



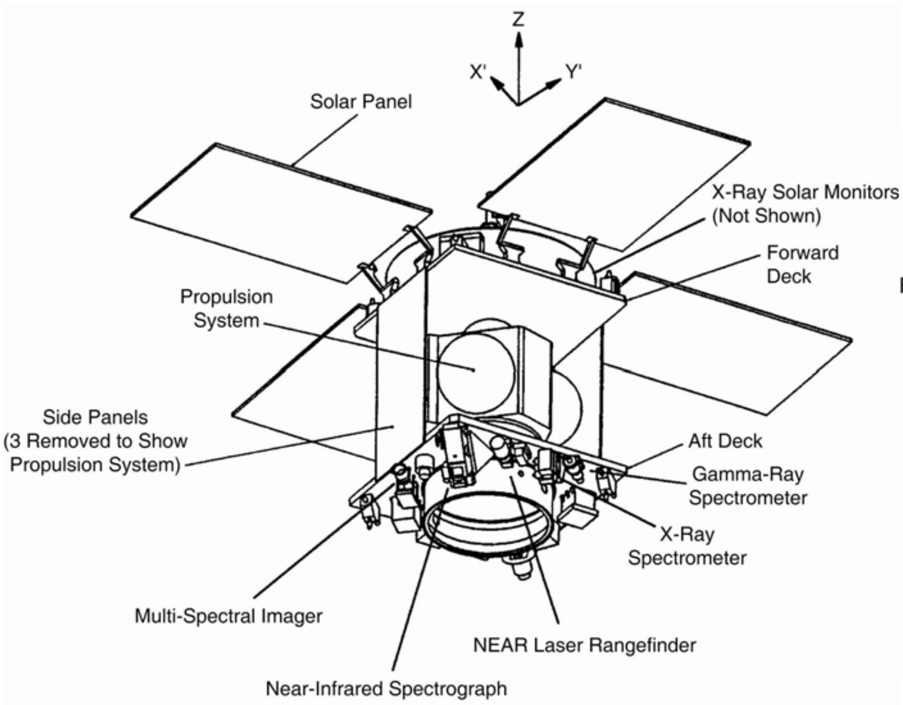
NEAR Payload: Laser Altimeter

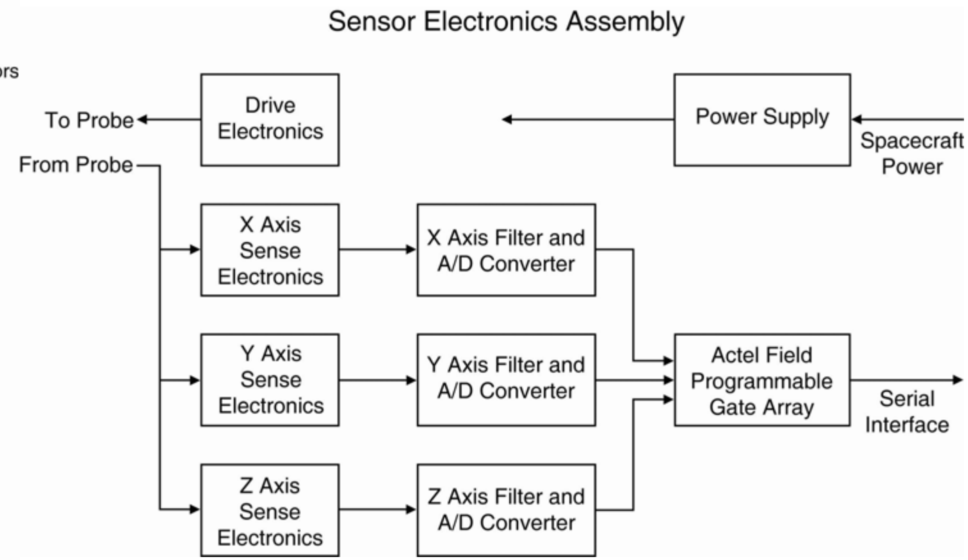




- The laser altimeter measured the size and shape of Eros.
- It is not as needed on a small body such as Eros (average radius ~8 km).
- It is very useful for Mars-sized objects.

NEAR Payload: Magnetometer





- Magnetometer was mounted on the communication antenna. This was too close to magnetic sources.
- The heater was poorly designed and gave a magnetic signature that was hard to remove.
- Eros was non-magnetic, but the magnetometer was great for ICMEs.

Summary

- Designing a space mission is complex. It requires many skills possessed only by a team of top-flight engineers and scientists.
- Need to work with an Institute or Laboratory with the required expertise.
- Attending the JPL summer school on space mission development is a good idea.
- Experience is essential, so get involved in a hardware mission as soon as you can.