Mission Design and Systems Engineering for Spacecraft

Chris Cully

2008 April 3

chris.cully@irfu.se

Jargon

There is a tremendous amount of jargon and acronyms in space mission design.

I'll do my best to keep the jargon under control.

<u>Please</u> stop me and ask if I use a term that you haven't heard before!

Today's Lecture

- Top Level:
  - Objectives / Applications
  - Sweden in Space
  - Systems Engineering
- Mission Elements (not including the actual spacecraft or payload)
  - Orbit
  - Launcher
  - Ground Support
  - Process and testing
- Case Study: the Themis mission

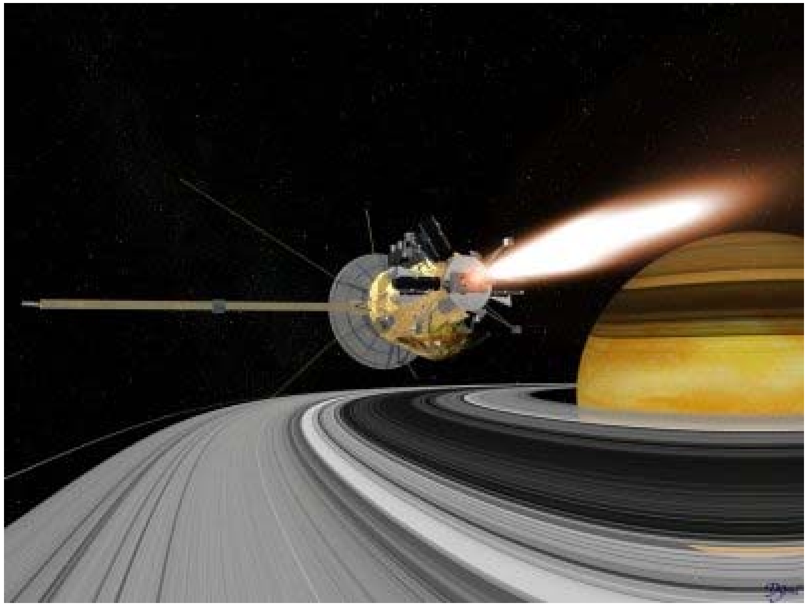
IRF

Exploration

- Explore the solar system and the universe
  - Robotic missions
  - Planets, moons, comets, asteroids, the sun, ...
- Manned missions
  - Not really covered here

ESA Vision of exploration

Cassini at Saturn



UPPSALA UNIVERSITET

Earth Observation

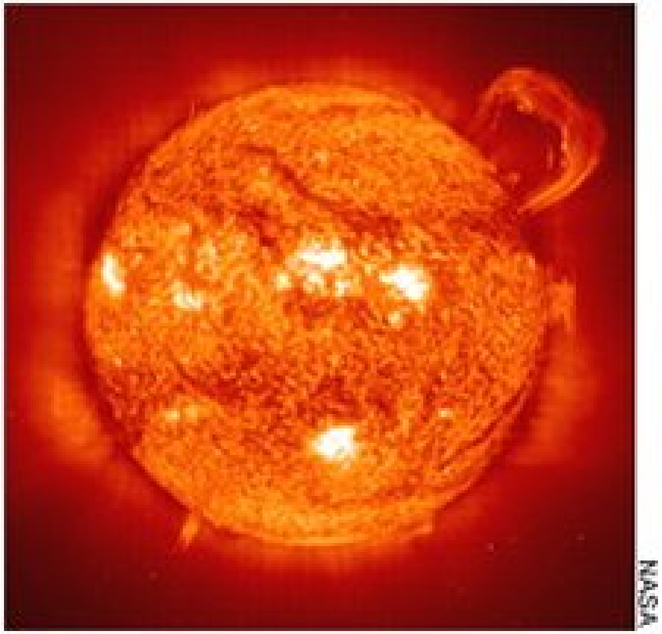
- Environmental monitoring
  - Climate and atmosphere
  - Geophysics
  - Polar environments and ice
  - Marine
- Resource monitoring
  - Water
  - Vegetation and forests
- Land survey
  - Urban planning
- Weather forecasts
- Disaster monitoring

Soil Moisture and Ocean Salinity (SMOS)

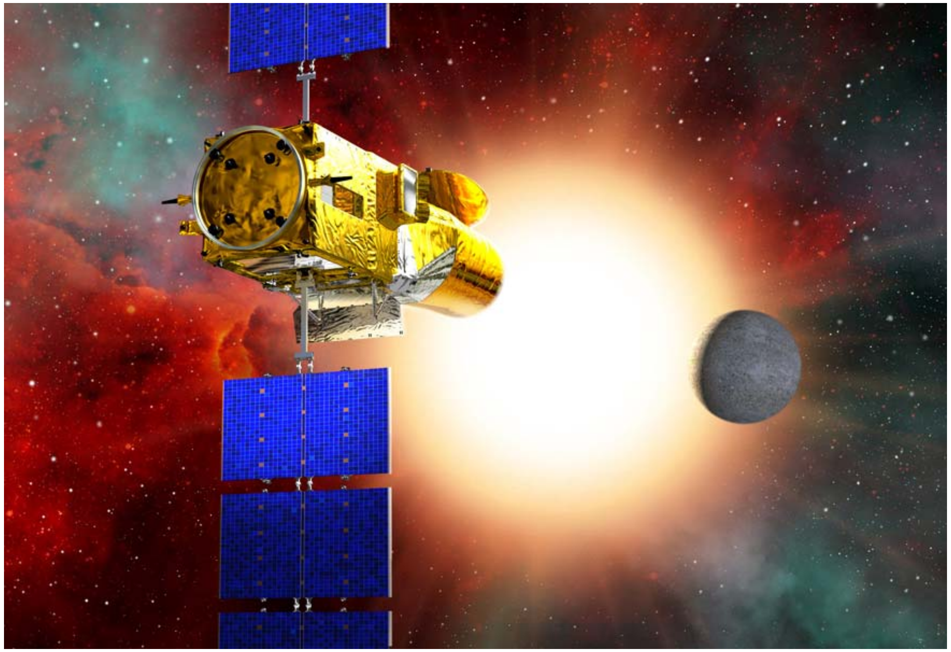
Mission Design

Space Research

- Astronomy
- Solar System
- Plasma science
  - Northern lights
  - Ionosphere and Upper Atmosphere
- Basic physics
  - e.g. general relativity tests



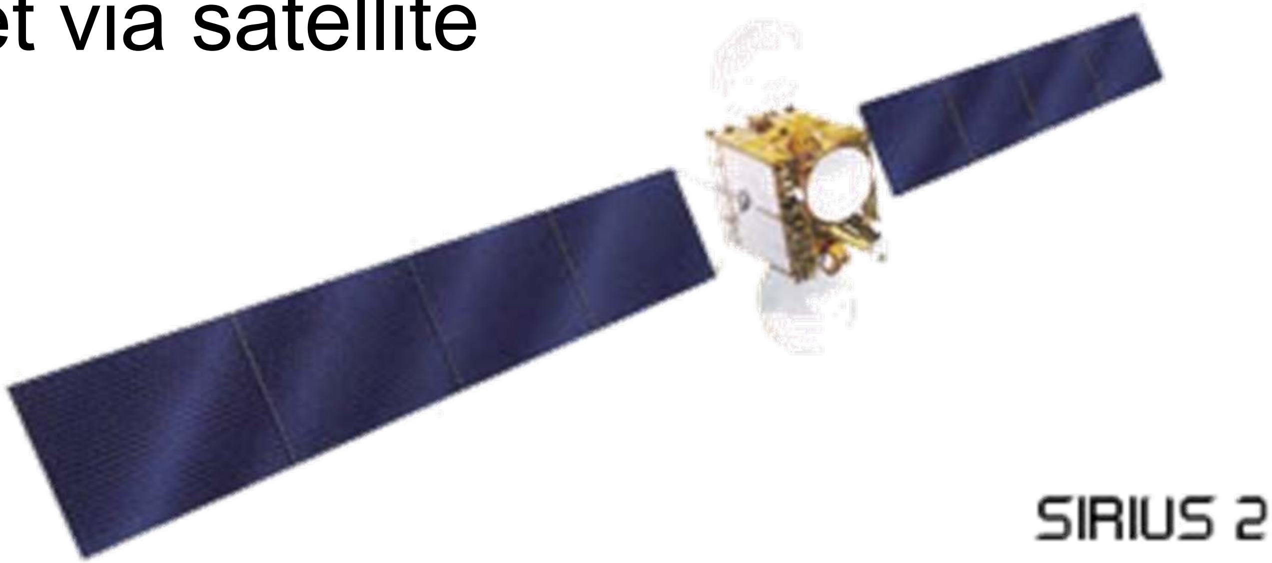
COROT exoplanet finder



UPPSALA UNIVERSITET

Commercial

- Television broadcasting
- Digital multicasting/Video On Demand
- VSAT (Very Small Aperture Terminal)
- Digital Radio
- Internet via satellite



Military

- Purely military
  - Surveillance
  - Anti-missile systems
  - Ground targeting
  - ???
- Civilian applications
  - Reconnaissance
  - Reliable communications
  - Navigation
  - Space environment monitoring
- Treaty monitoring (eg. Comprehensive Test Ban Treaty Organization)

American DMSP satellite

Mission Design

UPPSALA UNIVERSITET

Navigation

- Global coverage
- GPS
  - American military system
  - Meter resolution
  - Accurate time
- Galileo
  - European civil version
  - Independence
  - Similar specifications as GPS

ESA's Galileo

Sweden in Space

1986		
	Viking	Scientific
1989		
	Tele X	Commercial Telecom
1992		
	Freja	Scientific
1994		
	Sirius 1 (Bought in orbit)	Commercial Telecom
1995		
	Astrid 1	Scientific
1997		
	Sirius 2	Commercial Telecom
1998		
	Sirius 3	Commercial Telecom
	Astrid 2	Scientific
2000		
	Munin	Scientific / Technical test
2001		
	Odin	Scientific
2003		
	SMART-1	ESA Technology test

Kronogård 1962

Mission Design

Swedish Spacecraft, Research

- Viking (1986)
- Freja (1992)
- Astrid-1 (1995)
- Astrid-2 (1998)
- Munin (2000)
- Odin (2001)
- SMART-1 (2003, ESA, moon)
- *Prisma (2008, technical test)*
- *MicroLink (2009, technical test)*

- Instruments on

  ESRO-1A (1967), ESRO-1B (1967), ESRO-4 (1972), GEOS-1 (1977), GEOS-2 (1978), Prognoz-7 (1978), Prognoz-8 (1980), Phobos-1 (1988, Mars), Phobos-2 (1988, Mars), Ulysses (1990, heliosphere), Interball-tail (1995), Interball-aurora (1995), Polar (1996), Mars-96 (1996, Mars), Equator-S (1997), Cassini (1997, Saturnus/Titan), Nozomi (1998, Mars), 4xCluster (2000), Mars Express (2003, Mars), DoubleStar (2003), Rosetta (2004, komet), Venus Express (2005, Venus)

  Chandrayaan (2007, månen), 3xSwarm (2009), 2xBepiColombo (2012, Merkurius), 4xMMS (2013)

UPPSALA UNIVERSITET

Mission Design

Systems Engineering

- Key Issues:
  - System is extremely complex
  - Subsystems are tightly interconnected
  - Once it's launched, you can't physically reach it

Ariane-5 failure

- Subsystems need to all work <u>together</u>
  - This is a key concept for this course and for mission design in general.
- Risks: assessed and managed (reduced)

UPPSALA UNIVERSITET

Systems Engineering

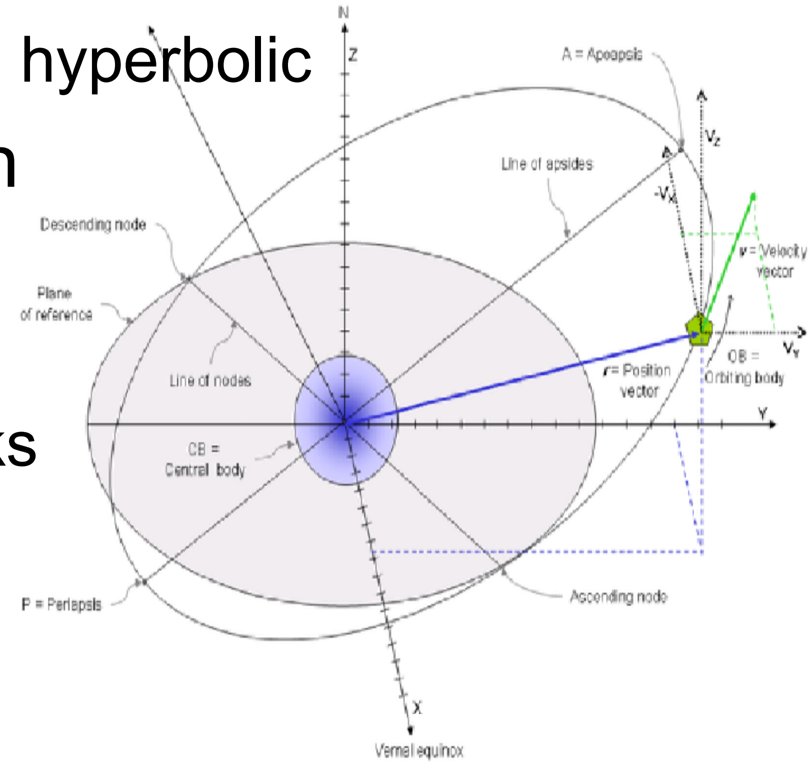
- Need to examine the system and processes **as a whole**
- General idea:
  - Identify and quantify system goals
    - →Requirements flow-down
  - Alternative design concepts
    - → Trade studies
  - Selection and implementation
  - Assessment and closure
- Process is iterative, not linear
- Identify and assess risks, work to minimize them
  - Single points of failure
  - Redundancy
  - Contingency plans

Mission elements

- Today:
  - Orbit
  - Launcher
  - Ground Support
  - Process and testing
- Tomorrow:
  - Satellite bus
  - Payload

Orbit fundamentals

- Idealized case: 2-body point masses
- Conic section orbits (closed = elliptical) in inertial space
- Some special cases:
  - Polar, equatorial, circular, hyperbolic
- Earth rotates underneath
  - Best to launch East (prograde)
  - Complicated ground tracks
- Variable speed
  - Fast at periapsis

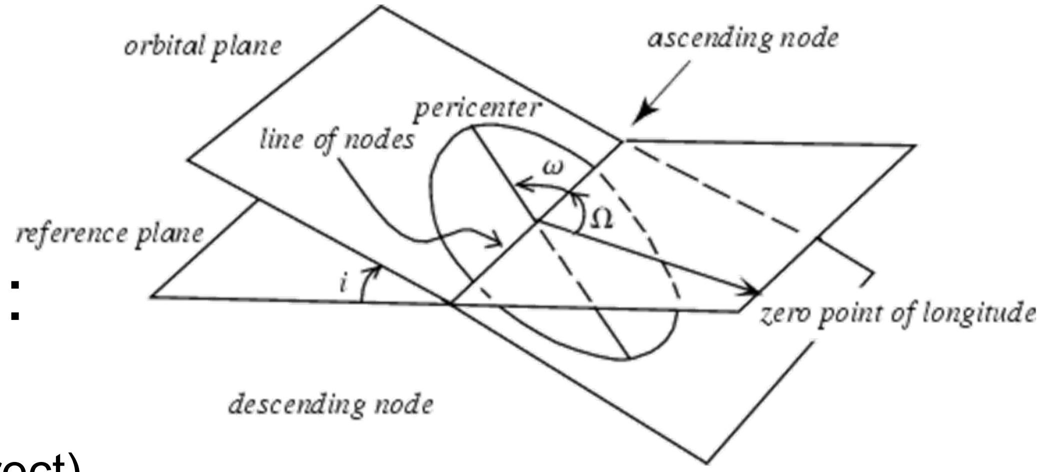


UPPSALA UNIVERSITET

Classical orbital elements

Mission Design

- Ellipse size/shape:
  - a:Semimajor axis
  - e:Eccentricity
    - Circle: e=0
- Plane Orientation:
  - i:Inclination
    - i < 90 prograde (direct)
    - i > 90 retrograde
  - Ω:Right ascension of the ascending node
- Where in the plane
  - ω:Argument of perigee
  - v:True anomaly



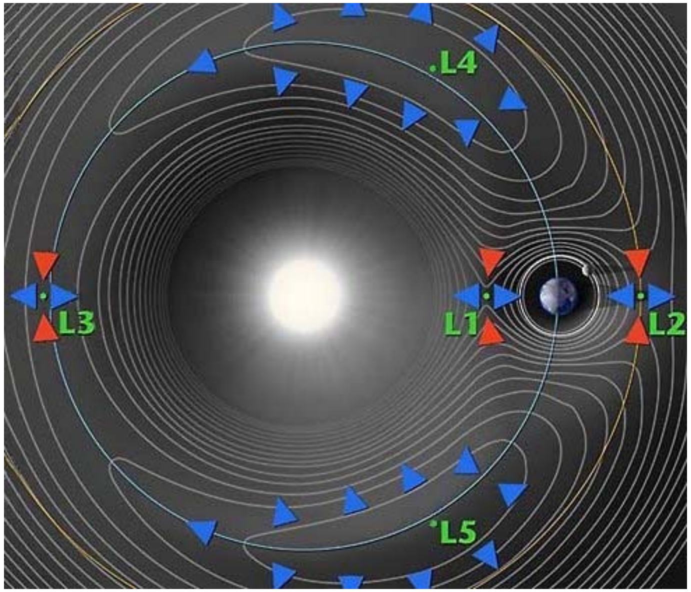
UPPSALA UNIVERSITET

Perturbations

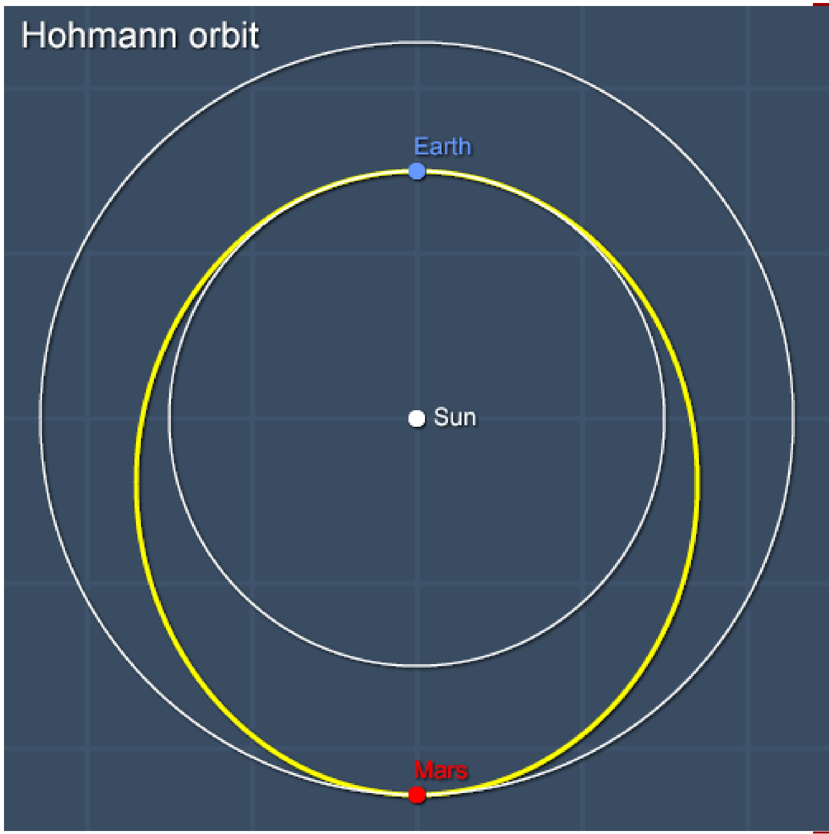
- Non-spherical Earth
  - Regression of line of nodes (Ω)
    - Prograde orbit → westerly rotation
  - Precession of line of apsides (ω)
    - Zeroed for $i=63.4^o$ (Molniya orbit)
- Atmospheric drag
- Radiation Pressure
- 3-body perturbations (sun, moon, Jupiter)

A few specialized Orbits

- Requirements flowdown from the mission objectives
- Earth orbits
  - Geostationary
    - GTO (Geosynchronous Transfer Orbit)
  - LEO (Low-Earth Orbit)
    - Sun-Synchronous
  - HEO High Elliptical Orbit
    - Molniya
- Lissajous orbit
  - Lagrange points



Transfer Orbits



- Hohmann transfer: connect 2 circular orbits with an elliptic section
  - Usually the most efficient (least ΔV)
  - Need large thrusts

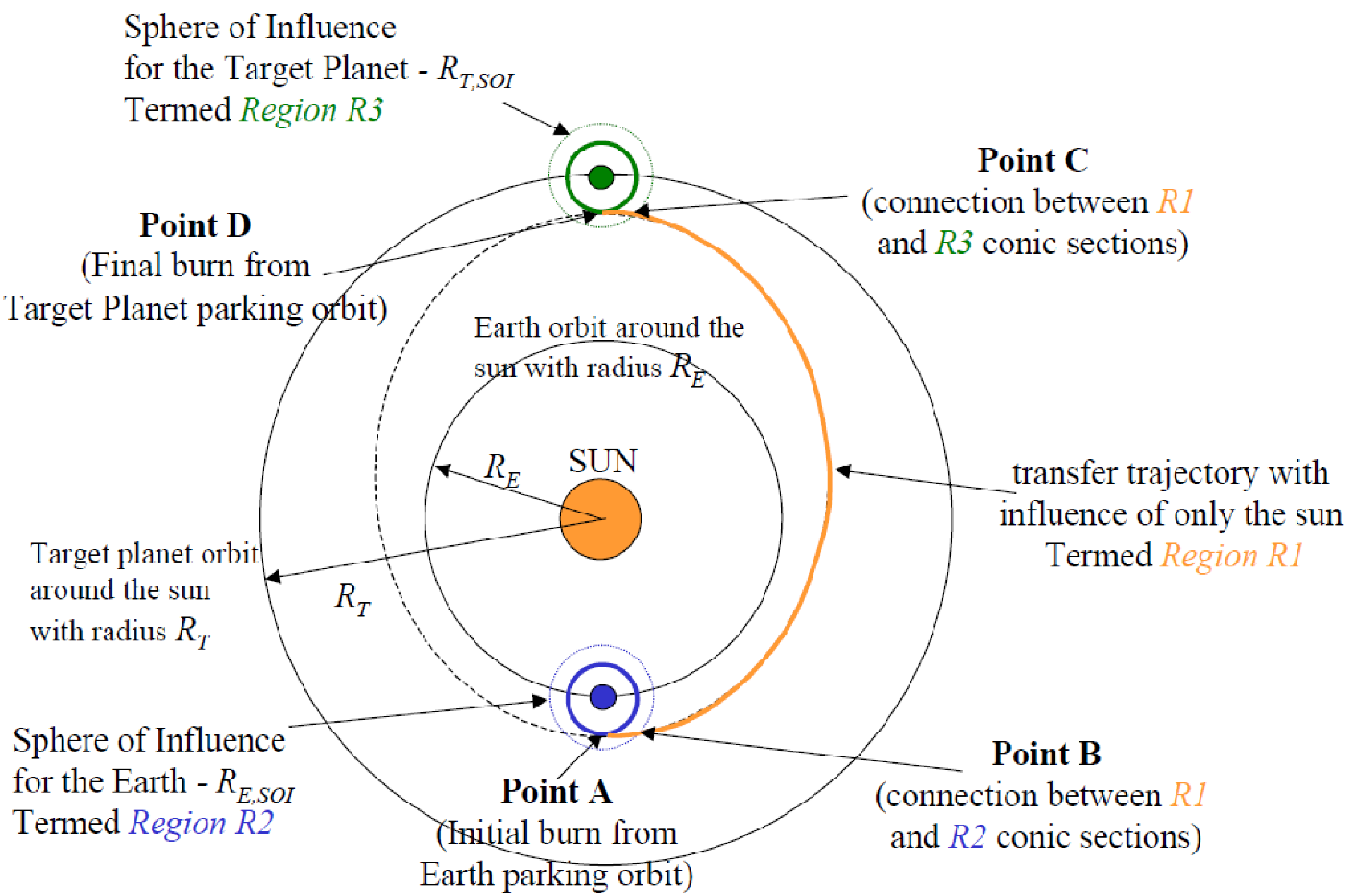
- Other transfers possible
  - e.g. spiral orbits with low thrust from plasma thrusters

Mission Design

UPPSALA UNIVERSITET

Interplanetary orbits

Approximation: patched conics between Hill spheres (spheres of influence)



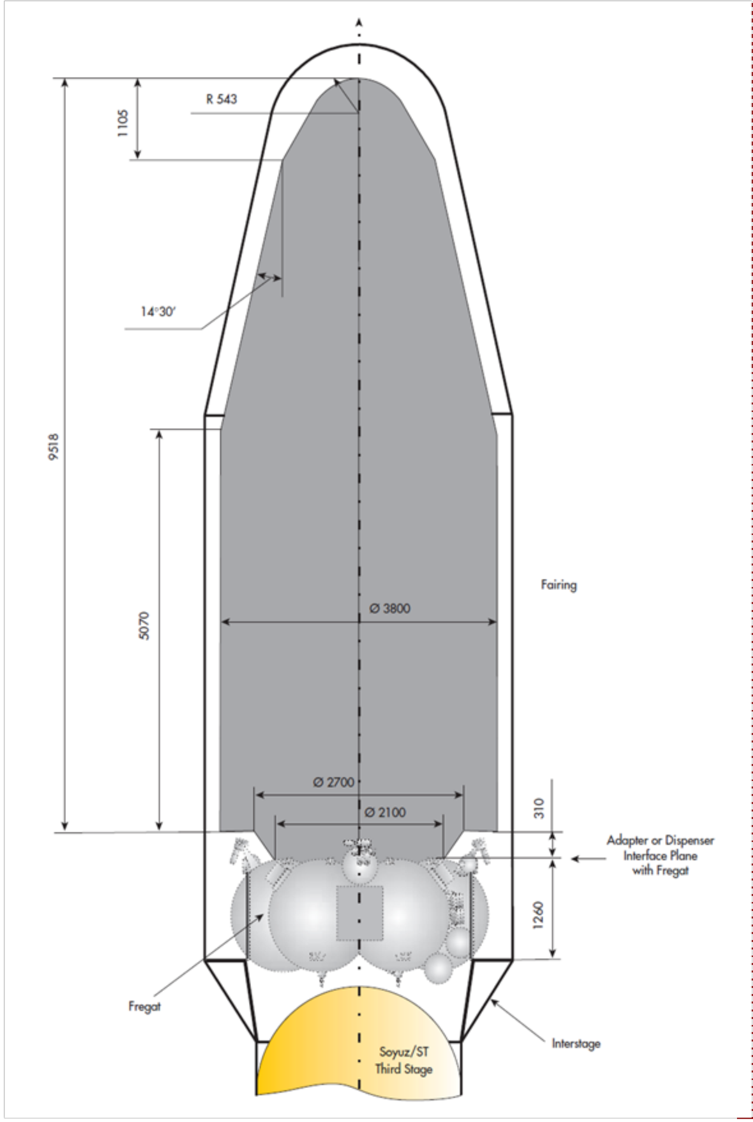
Launchers

- Many expendible launch vehicles available.
  - Launcher design not part of mission design (”only” selection)
- Main factors to consider:
  - Cost
  - Orbit (ΔV requirements)
  - Spacecraft mass
  - Spacecraft size
  - Reliability
  - Vibration envelope
  - Availability and politics

Mission Design

Launchers

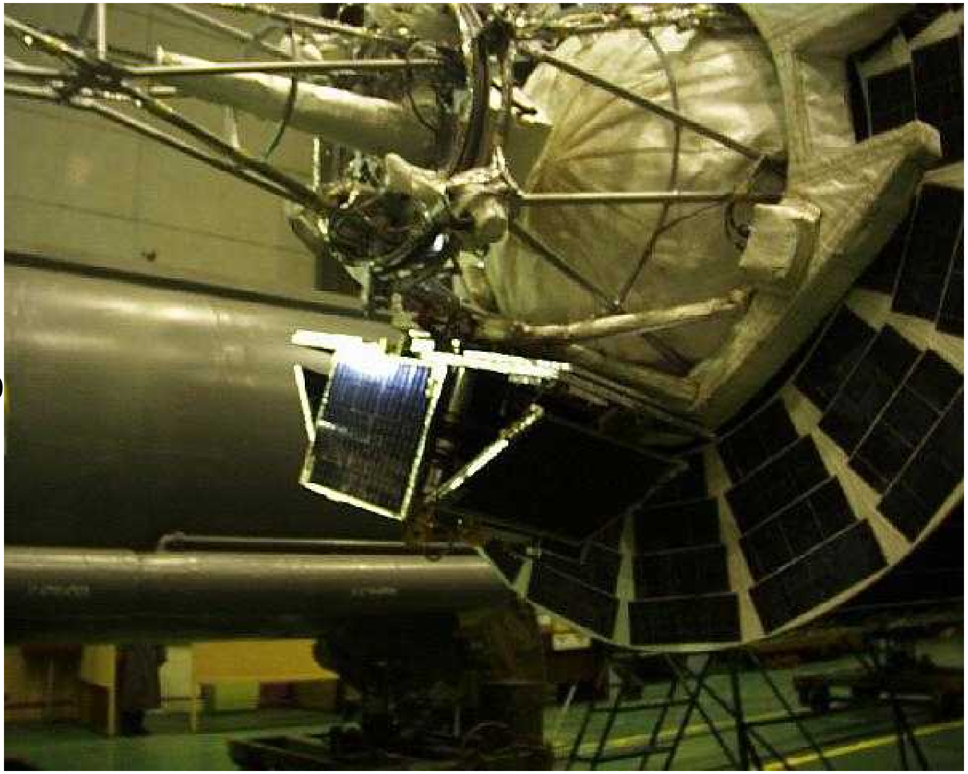
- Launcher alternatives
  - Europe
  - Russia
  - Ukraine
  - USA
  - Japan
  - India
  - China
- Note that Sweden has no launches to orbit
  - Suborbital sounding rockets and satellites/payloads
- User's manuals sometimes available online



Fairing dimensions from Soyuz user's manual

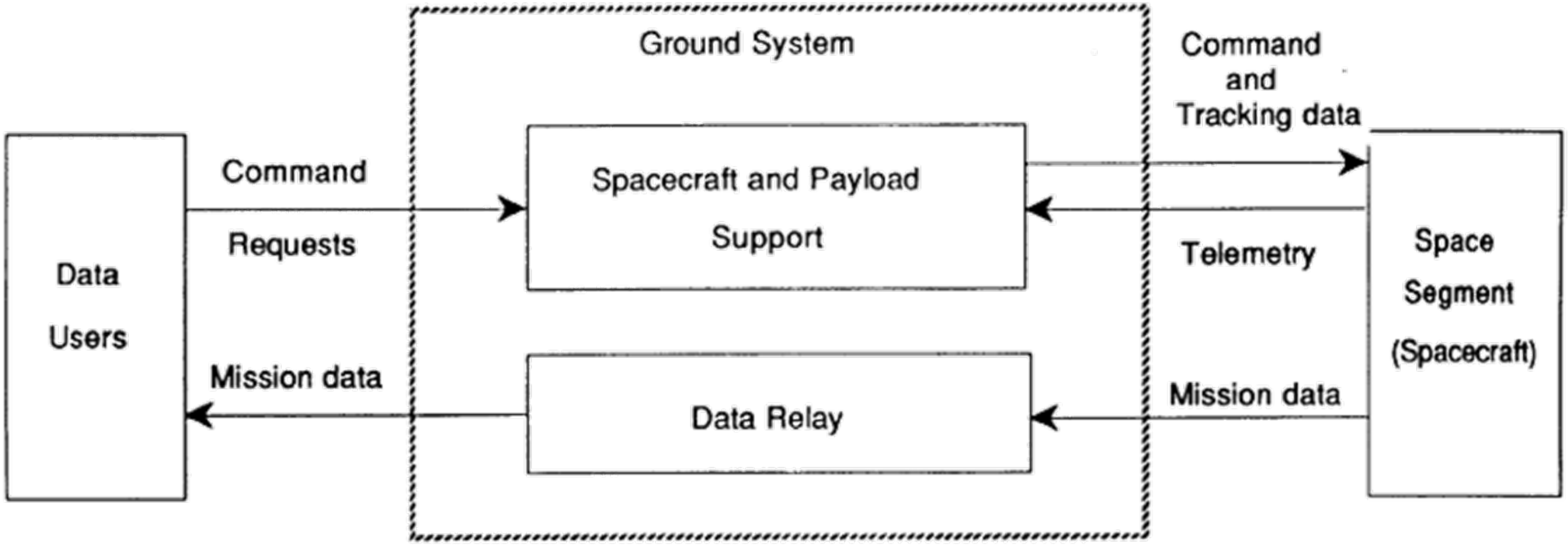
Inexpensive launch options

- Common issue
  - Launchers often sized for large GEO sats
  - Launch cost significant part of total budget
  - ESA's Vega designed to address this
- Some alternatives:
  - Piggybacking
    - ASAP-5
  - Hitchhiking
  - Russian ICBMs
  - Test launches



Swedish Astrid-2 Piggybacked on Russian Launcher "Kosmos"

Ground Segment: General principle



Mission Design

UPPSALA UNIVERSITET

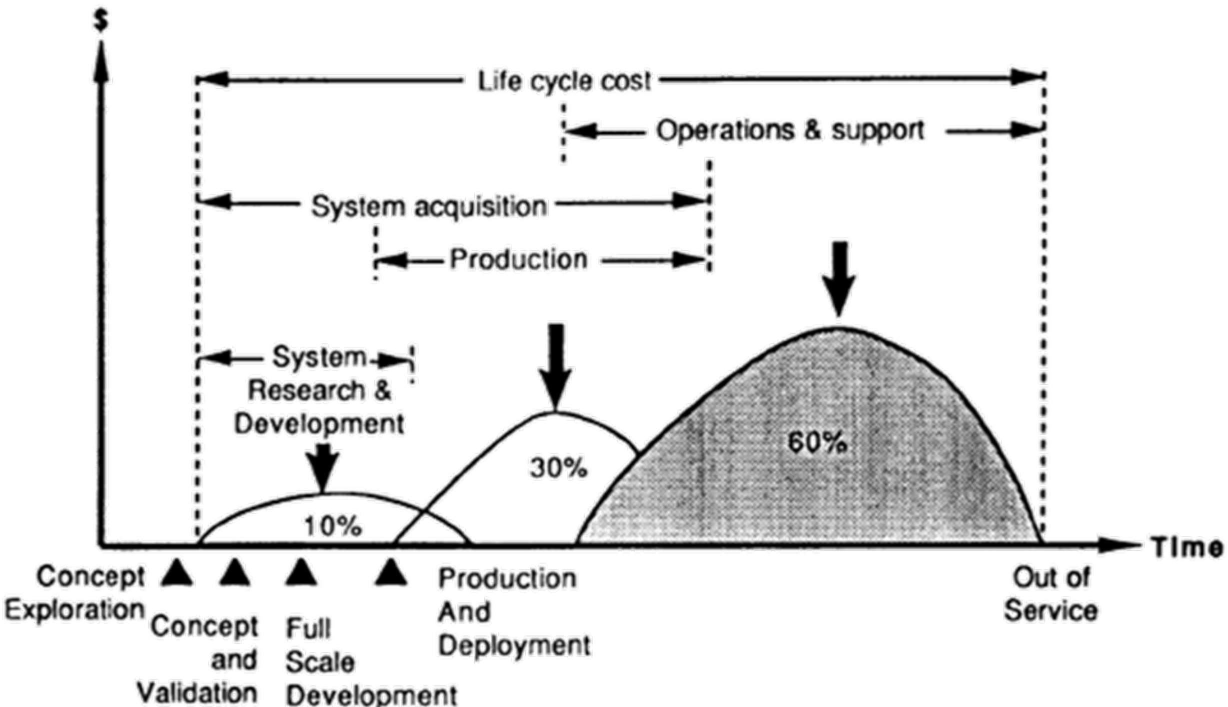
Communications

- Your only contact with your treasure
  - Commanding
  - Telemetry
- Ranging
  - Position and Doppler shift of carrier
- Large number of architectures and design parameters
  - Frequency
  - Capacity (bitrate)
  - Content of communication (think of the average bitrate of SMS!)

ESOC's groundsation in Villafranca, Spain, usable for deep space missions

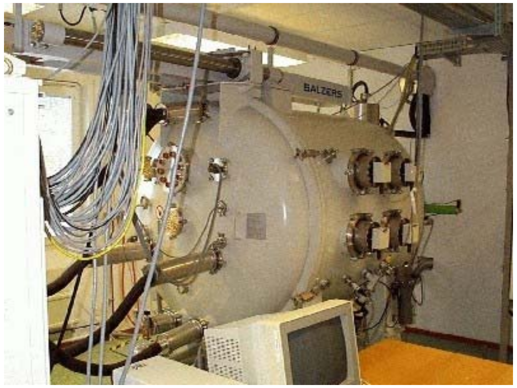
Mission Operations

- Large part of mission cost is related to mission operations and ground support



From Wertz

Testing

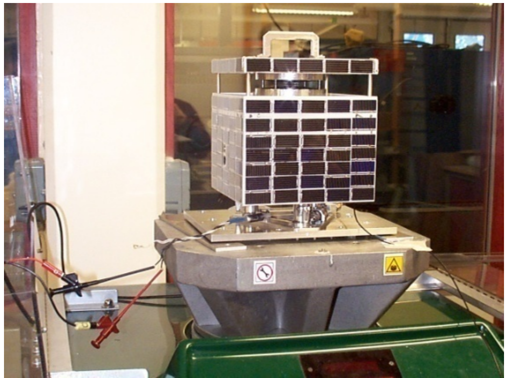


Vaccum chamber for space environment Thermal, outgassing tests, IRF Kiruna

Themis magnetic tests

- Vibration tests
- Shock tests
- Thermal / vacuum tests
- Magnetic, electrostatic tests
- Swedish facilities
  - Packforsk
  - Saab Ericsson space
  - others
- Some tests are up to spacecraft prime contractor, others are hard requirements from the launcher (especially if piggyback)

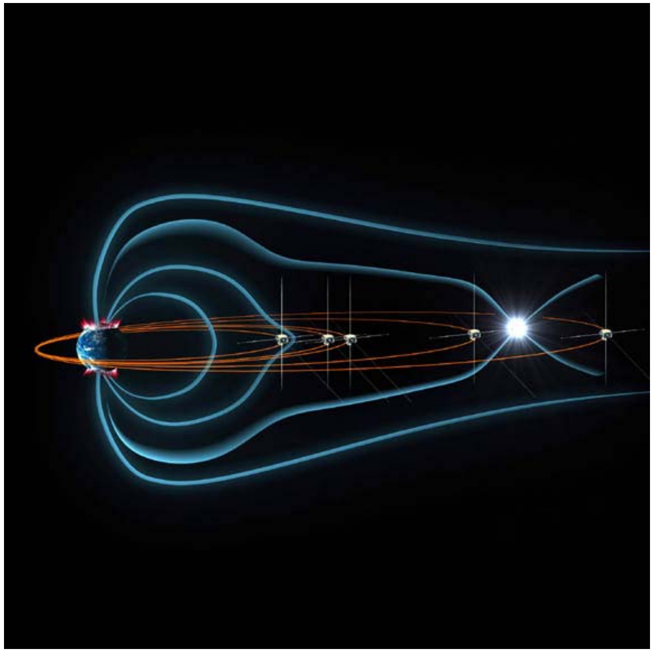
Munin Vibrational test

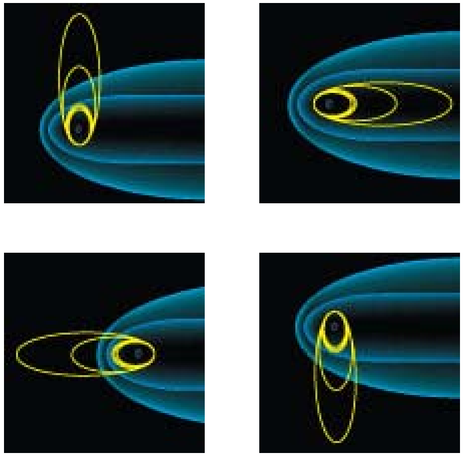


Case Study: Themis

- Designed to study the cause of auroral processes known as substorms
  - Plasma disturbance that occurs on the night side at 10-30 R_E altitude ($1R_E$=6378 km)
  - 2 major models
- Plasma observations at multiple locations
- Alignment over Northern Hemisphere during winter nights to simultaneously observe aurora from ground

Themis Orbit Design



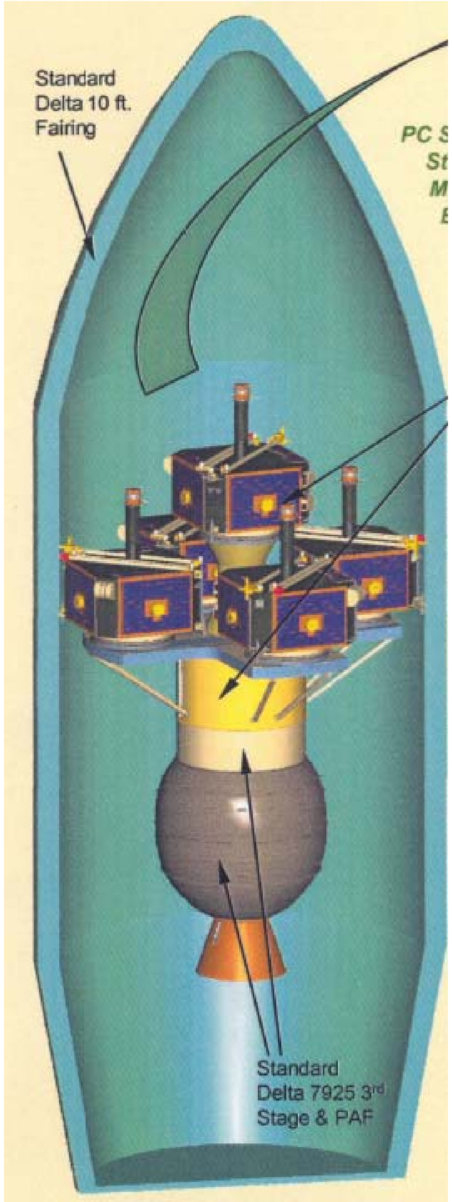


- 5 Probes
- Near-equatorial orbits, highly elliptic
  - Perigees ~1000 km
  - Apogees: 3 sats at 10 R_E,1 at 20 R_E,1 at 30
  - Inclination: 9 deg
- All orbits are integer multiples of 1 day (1,2,4)
- In Earth-fixed frame, line of apsides rotates ~once per year (13 months)

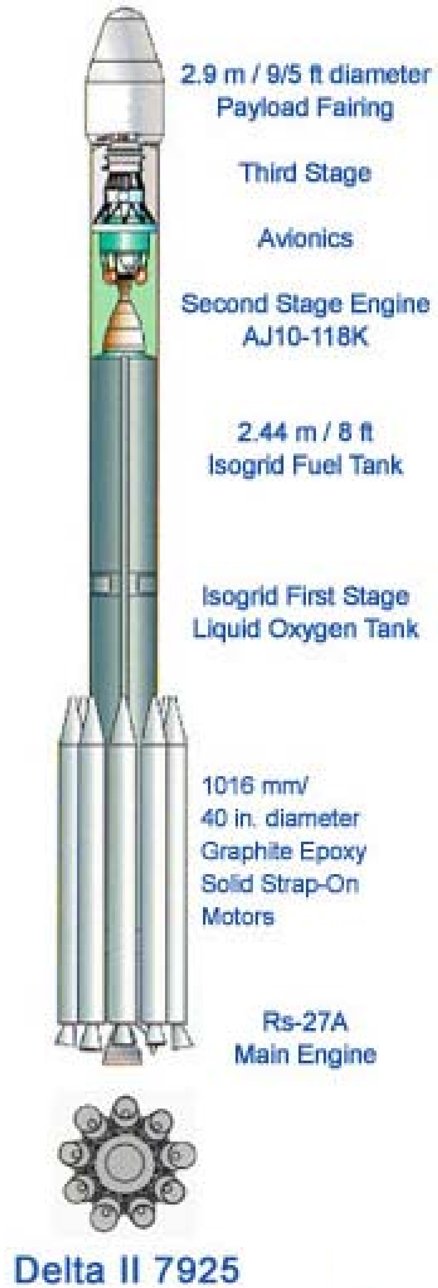
Mission Design

UPPSALA UNIVERSITET

Themis Launcher



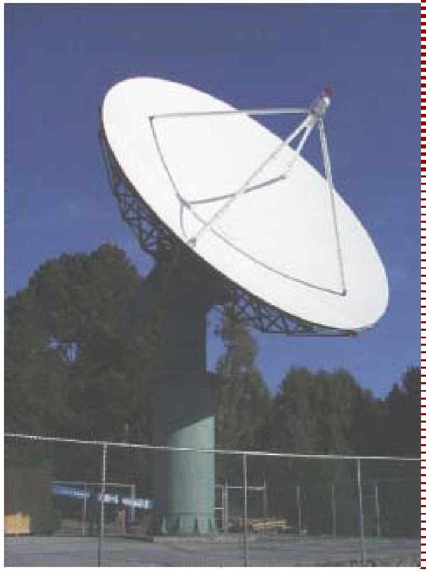
- Delta-II launch vehicle
  - Spacecraft wet mass:5 x 130 kg
  - 3-stage, 9 strap-ons
- Probe Carrier Assembly attached directly to 3rd stage solid motor
  - Eliminates need for kick motor; 3rd stage reaches required parking orbit



Mission Design

UPPSALA UNIVERSITET

Themis Ground support



- Mission Operations Center: Berkeley
- S-band (2-4 GHz) communications
  - 400 kbit/s down, 1 kbit/s up
- Ground stations:
  - Main: Berkeley
  - Secondary: Universal Space Network (USN) at Australia, Hawaii
  - Contingency: NASA TDRS spacecraft, NASA Deep Space Network
- Orbit determination from angle and Doppler tracking at ground stations
  - NORAD radar tracking backup

THEMIS LAUNCH VIDEO

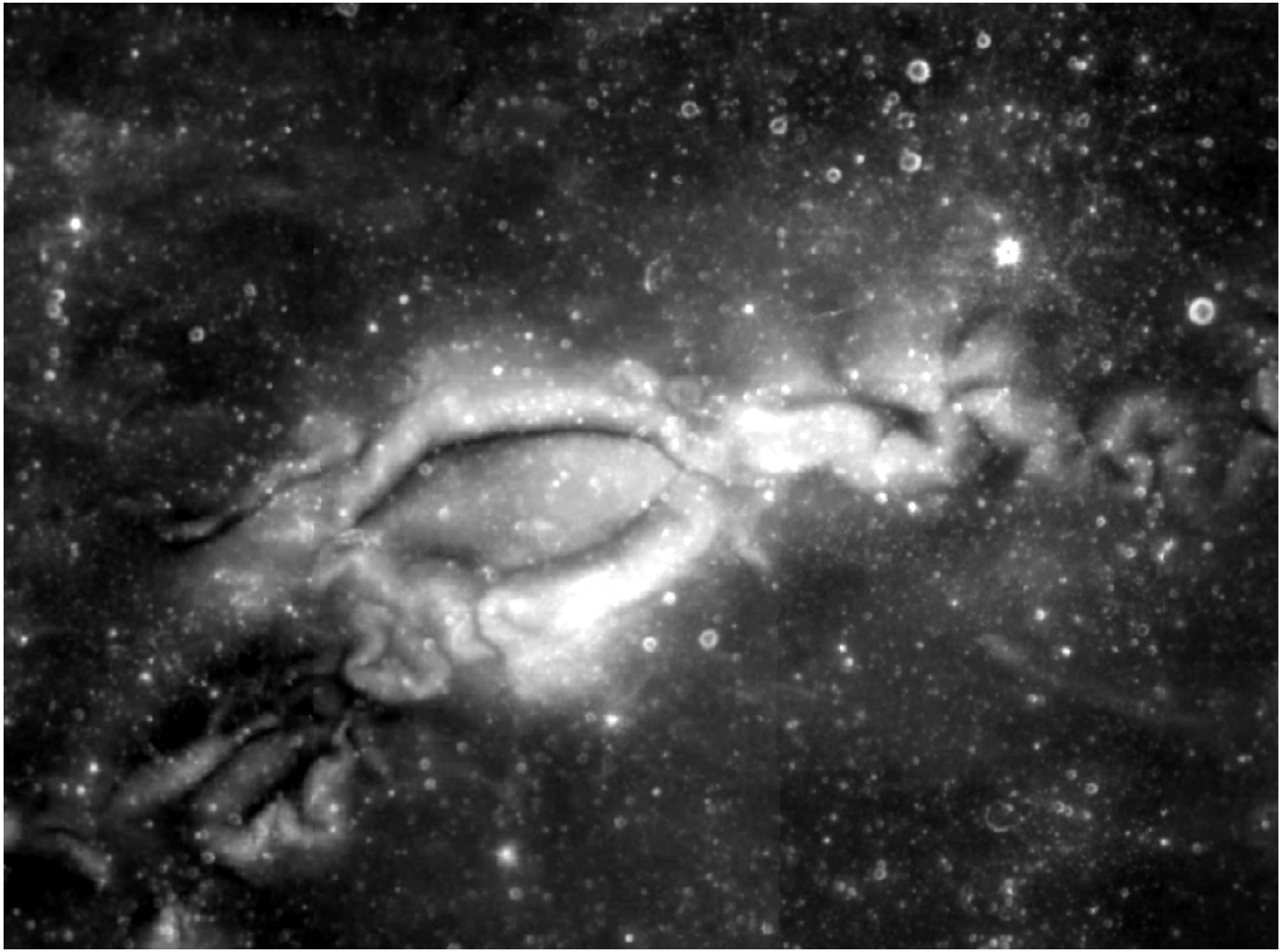
Today’s Lecture

- System Engineering:
  - Need to examine the system and processes **as a whole**
  - Engineering process is iterative, not linear
- Orbits:
  - Elliptic orbits are perturbed by small forces
  - Velocity change ΔV is the fundamental parameter when changing orbits
- Launchers
  - Many available launchers to choose from, but not many inexpensive ones
- Ground Support:
  - Communications link is vital for command and control, as well as for orbit determination

Tomorrow: The spacecraft itself...

Chris Cully
chris@irfu.se

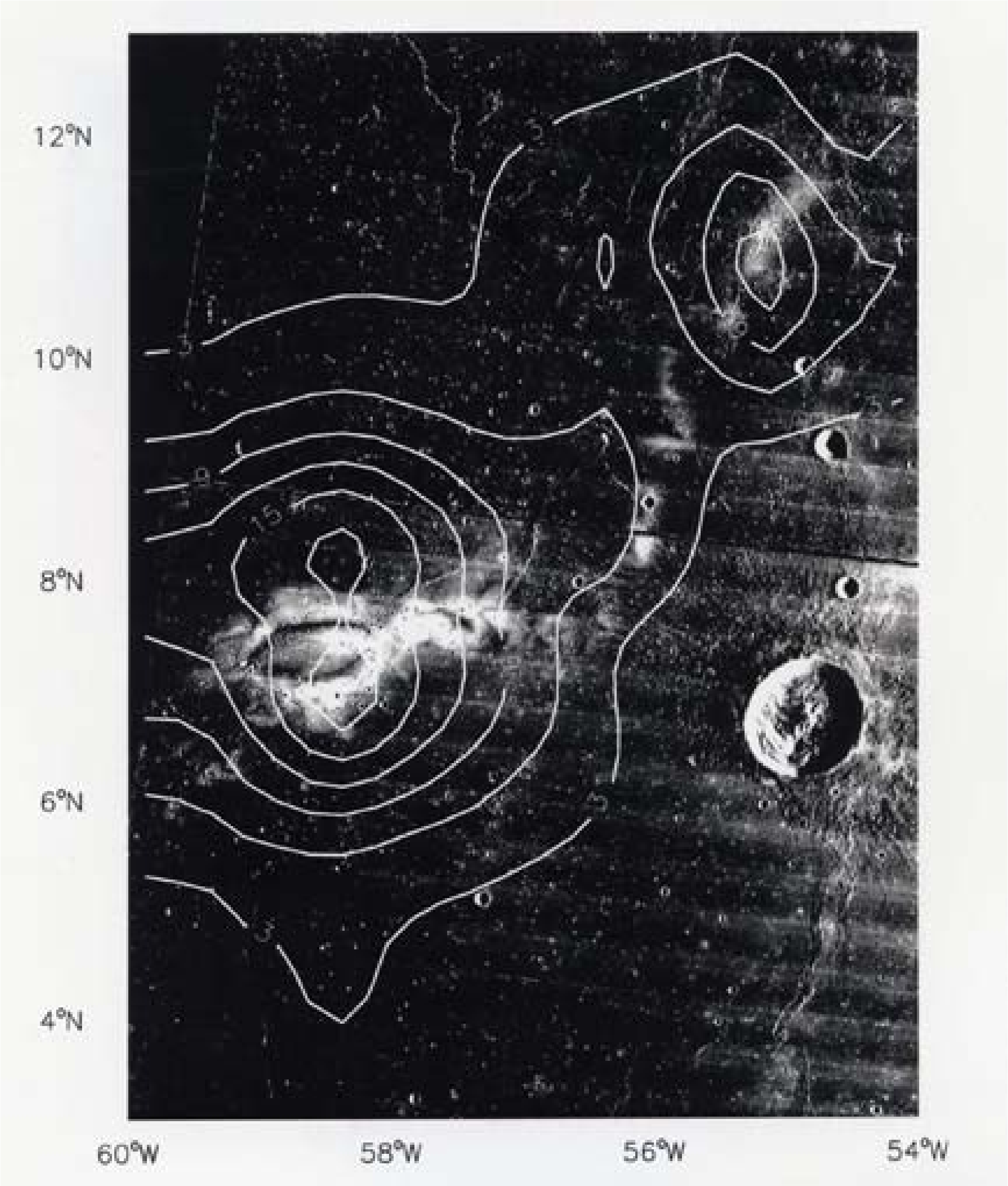
Mission Design



~70 km

UPPSALA UNIVERSITET

Mission Design



UPPSALA UNIVERSITET