16.89J / ESD.352J Space Systems Engineering
Spring 2007

MINERVA

Critical Design Review

Mission Statement

Establish an enabling space infrastructure that will support the exploration of Mars.

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May 8, 2000
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology

Agenda

- Introduction
- General mission overview
- Detailed design
- System level issues
- Lessons learned and conclusions

Introduction

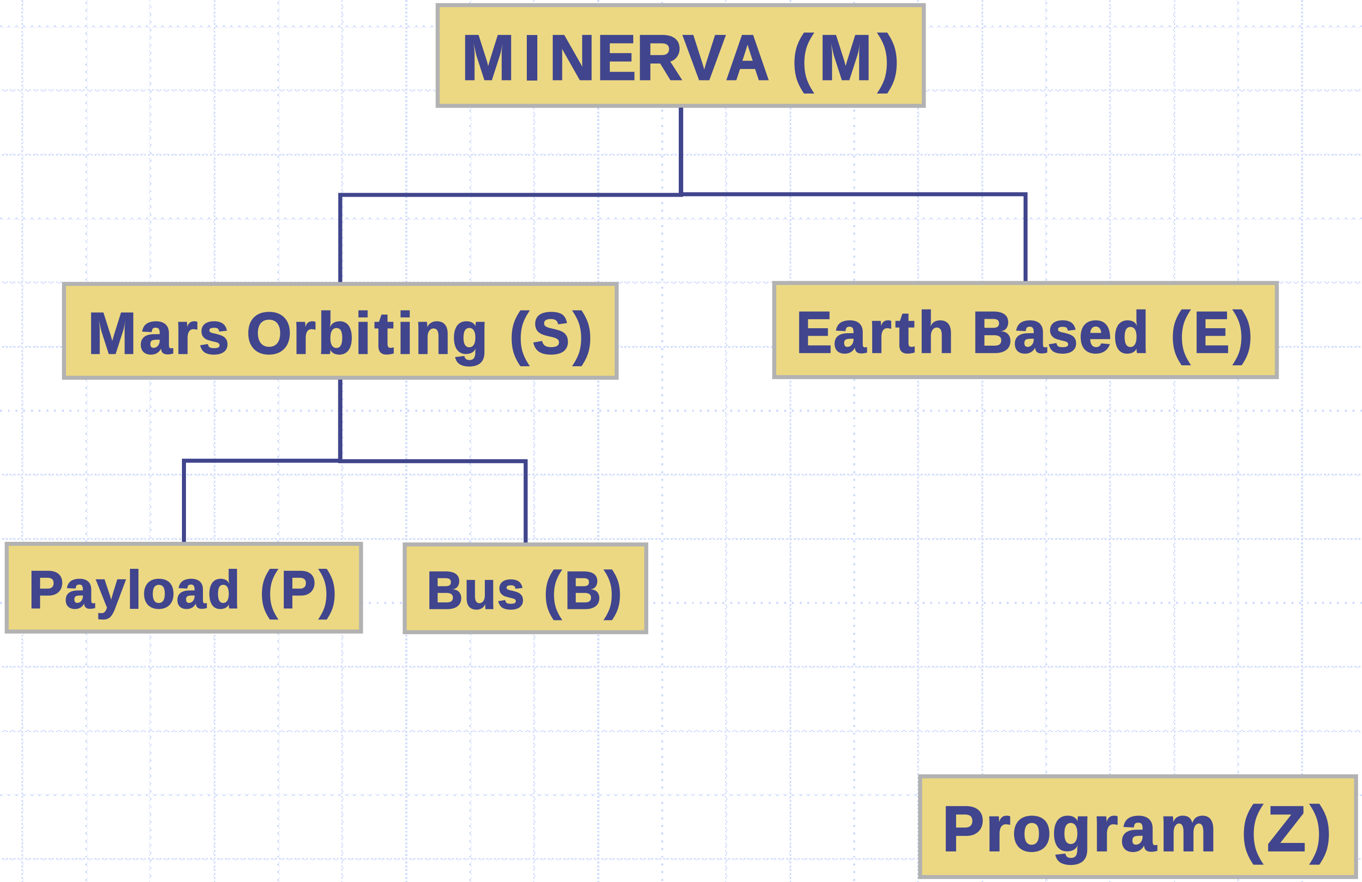
Motivation for Mission

- **Dramatically enhance the value of future Mars missions**
- Infrastructure at Mars provides major increase in science return
  - Pathfinder: 30 MB/sol → **MINERVA: 10 GB/sol**
  - Support for up to 10 Mars Surface Elements (MSEs)
  - Accurate location information
- Robotic mission designers can focus on science mission
- Enhanced probability of mission success
- **More science for the taxpayer's dollar!**

User Needs

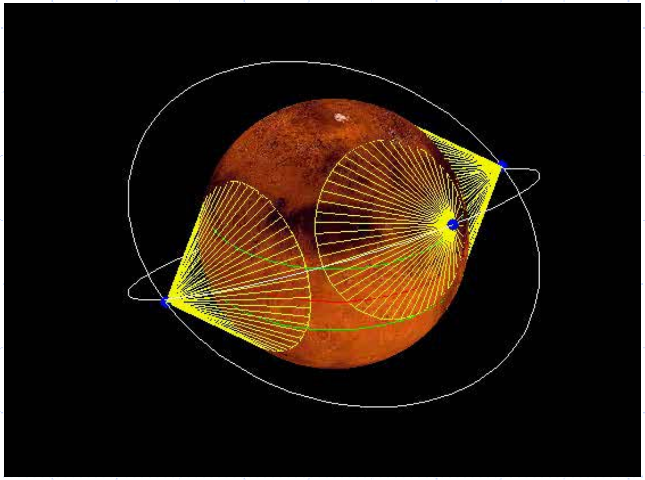
- MINERVA system shall provide enabling infrastructure to support exploration of Mars.
- The infrastructure shall provide Mars Surface Elements (MSEs) with:
  - Communication services between Mars surface and Earth Ground Stations (EGS)
  - Their position on the surface of Mars, without imposing additional design constraints on MSEs.

Requirements Flow Down



General Mission Overview

Design Summary



- Mars-orbiting constellation
  - Number of spacecraft: 4
  - Number of orbit planes: 2
  - Altitude: 2000 km
  - Inclination: 27°
- Spacecraft wet mass: 470 kg
- System cost: $297.9 M
  - Drivers: software development, launch

Launch

Launch date	18 Aug 2007
Launch window	± 1 sec, every 1 sidereal day from 3–18 Aug 2007
Launch site	Cape Canaveral Air Station
Launch vehicle	Delta III
Vehicle provider	Boeing
Total mass	1974 kg
Shared payload	Possible, but not necessary
Configuration	Four stacked spacecraft

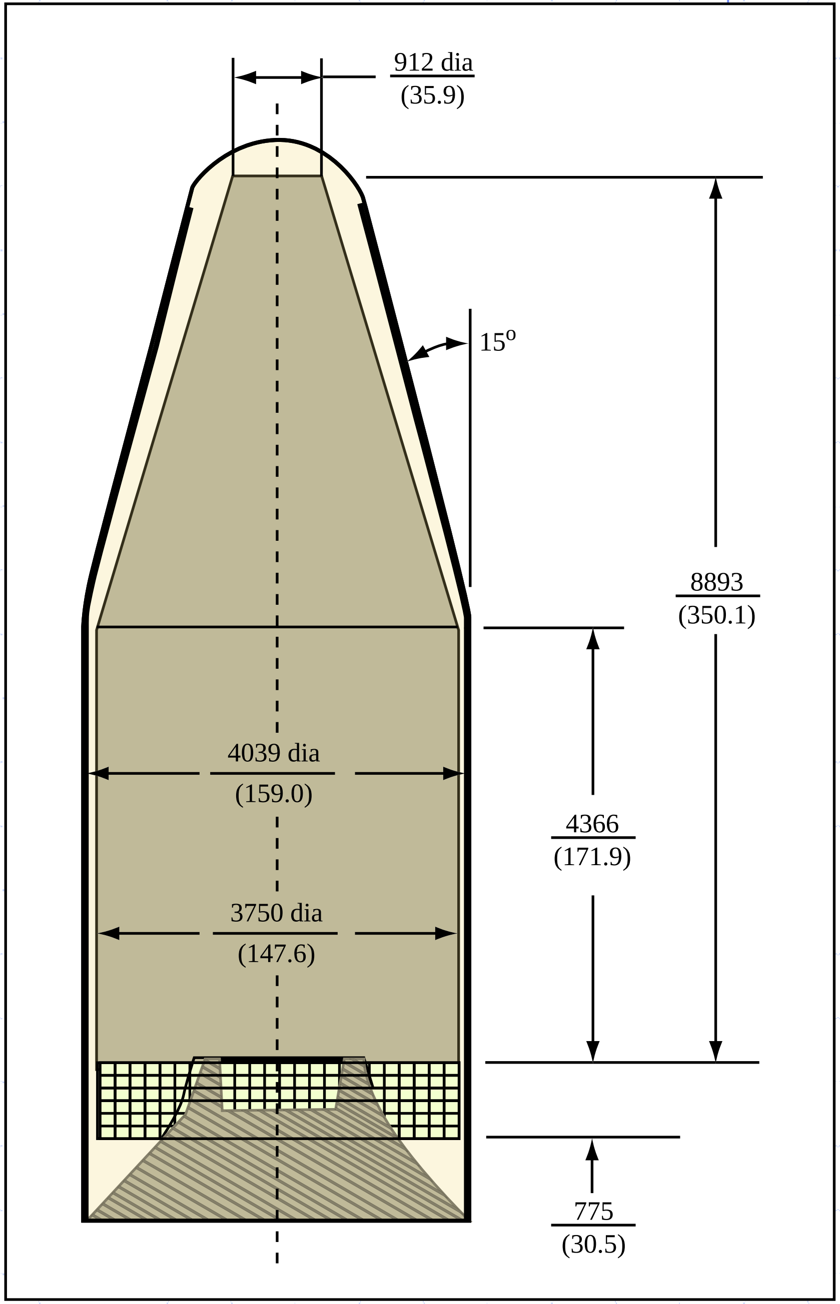
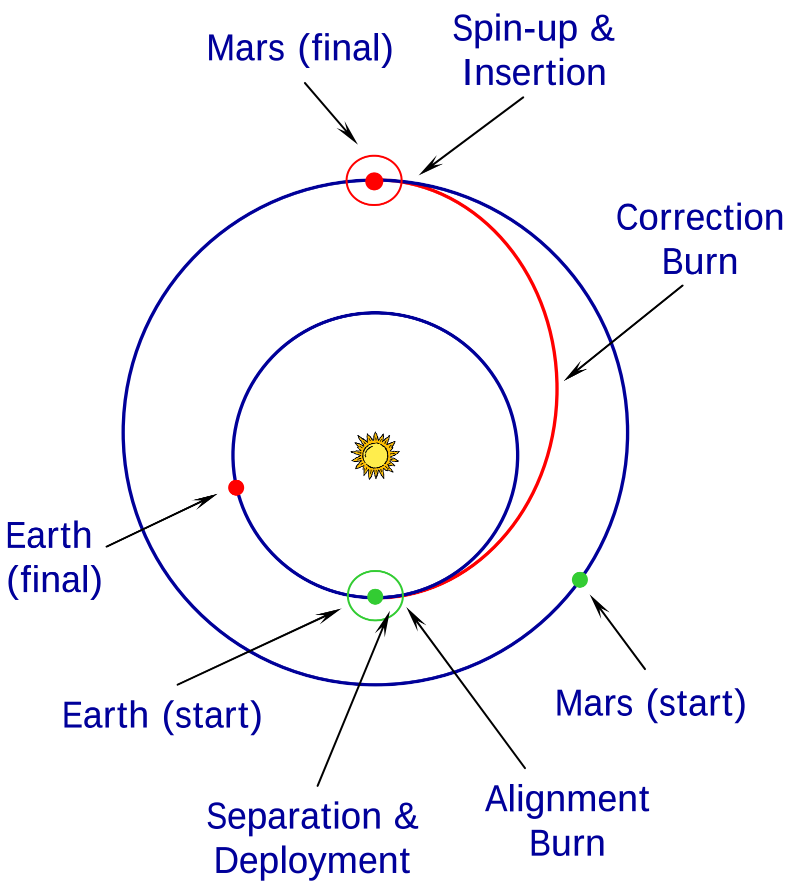


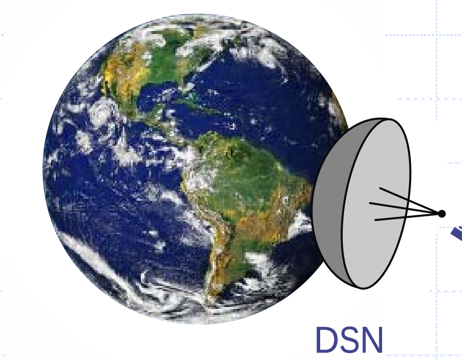
Image by MIT OpenCourseWare.

Transit Overview

Launch	18 Aug 2007
Departure burn	T+ 0d 3:23
Separation	T+ 0d 3:29
Deploy arrays	T+ 0d 6:01
Initial checkout	T+ 0d 6:05
Alignment burn	T+ 2d 16:39
Correction burn	T+ 122d 16:00
Insertion burn	T+ 285d 14:29
Circularization	T+ 290d 8:22
Deploy antenna	T+ 290d 8:24
Test/calibration	T+ 296d 12:00
IOC	10 Jul 2008

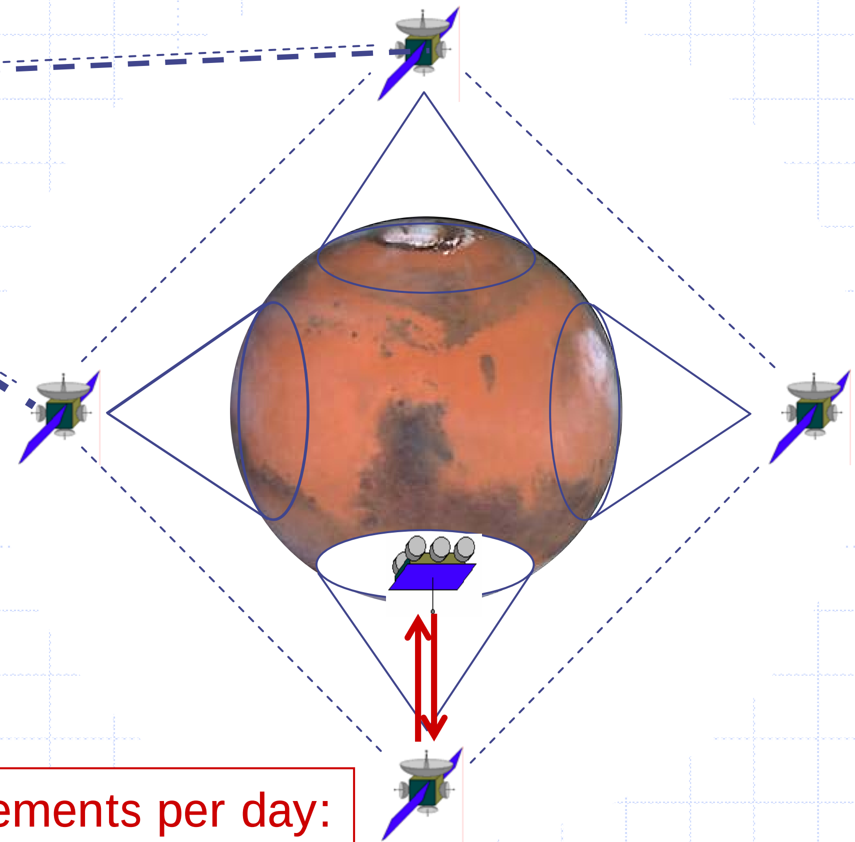


Day in the Life: Positioning



Two-way Doppler tracking over 10-hour DSN pass

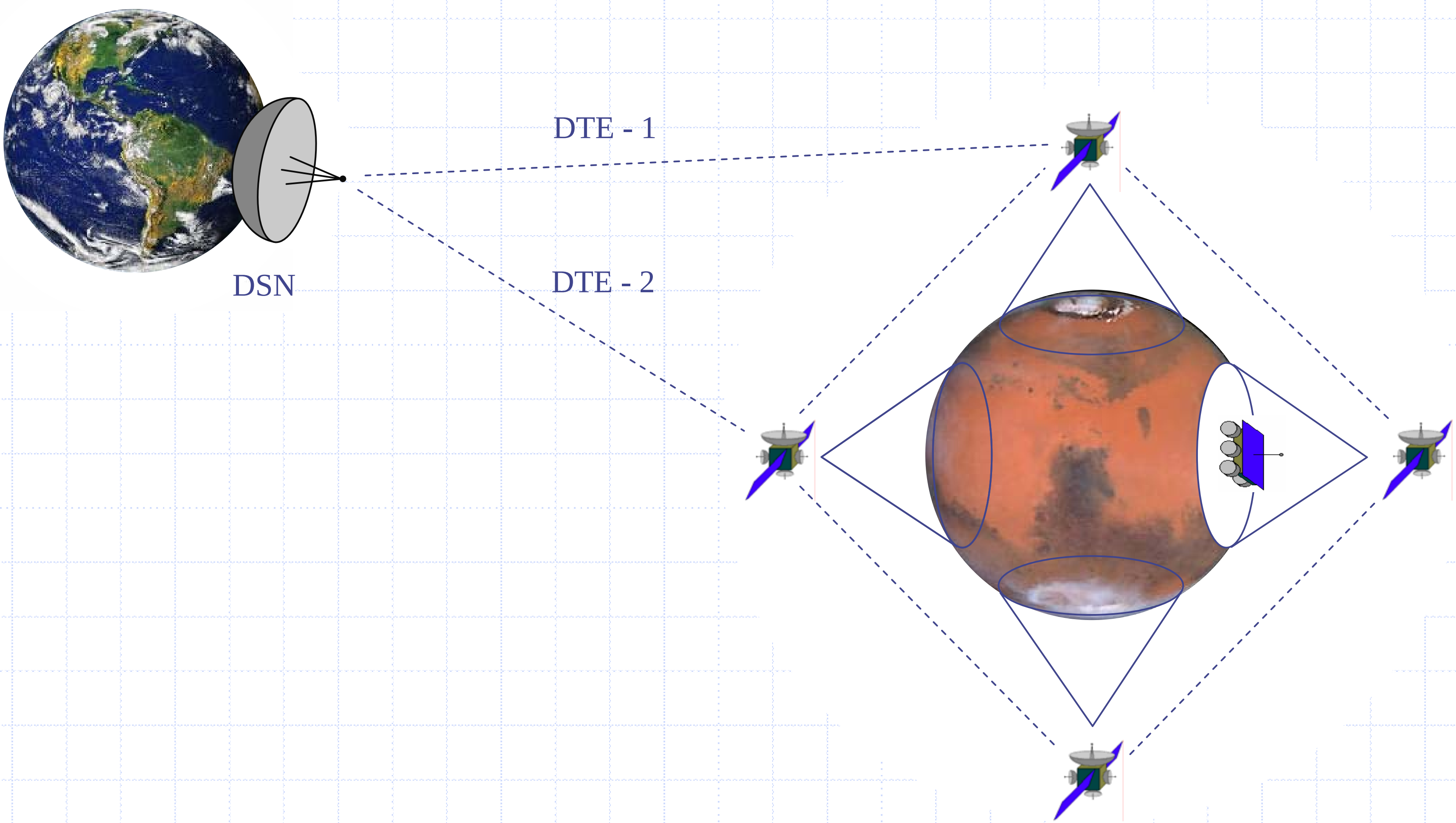
Daily post-processing:
- 100 m accuracy
- 35 min update rate



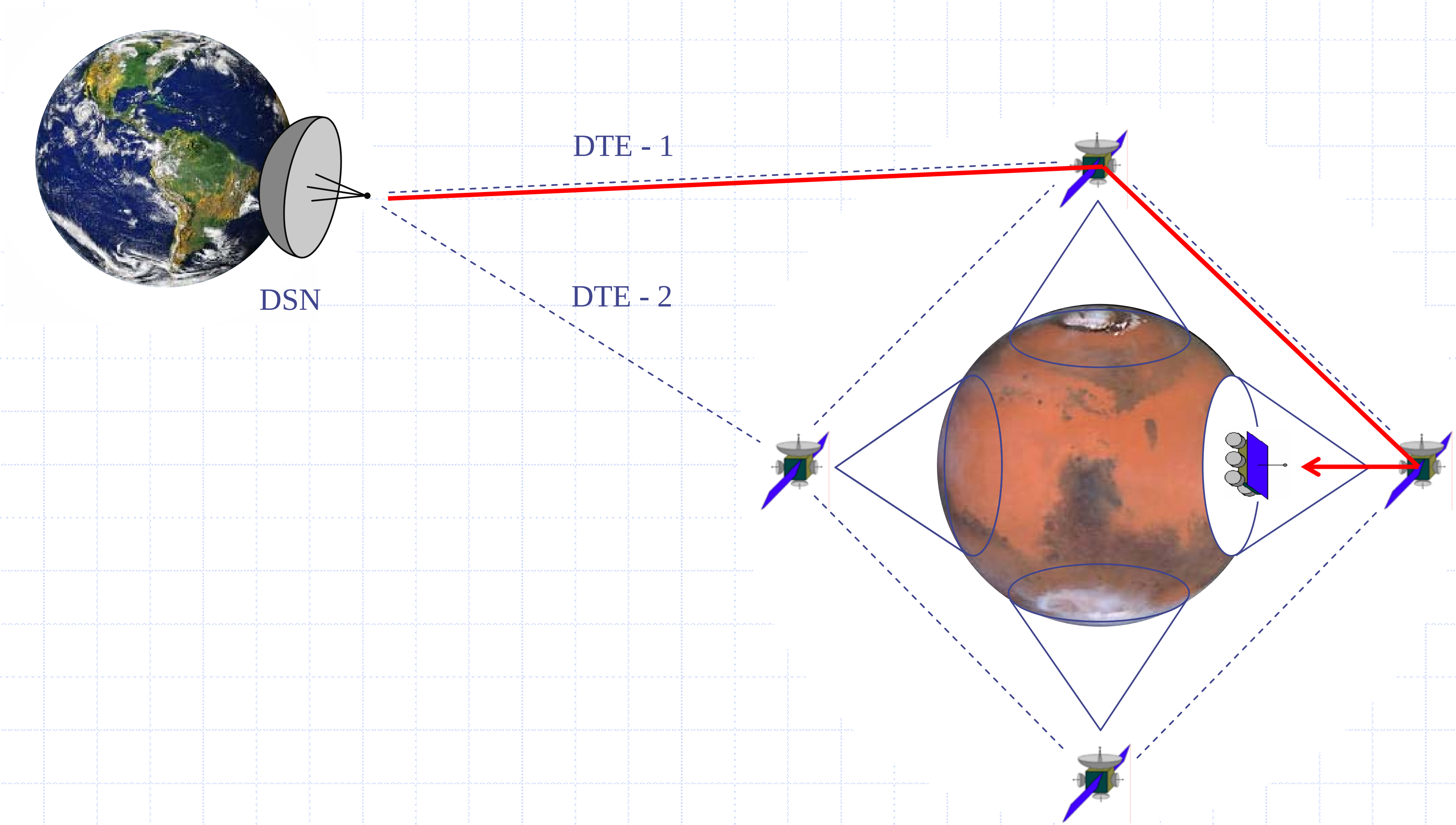
180 measurements per day:
- Two-way ranging
- Two-way Doppler tracking

Coarse estimate:
- 10s km immediate
- Best estimate >1 km
- Best obtained in 3 hr
- Update period 35 min

Day in the Life: Communication



Day in the Life: Communication



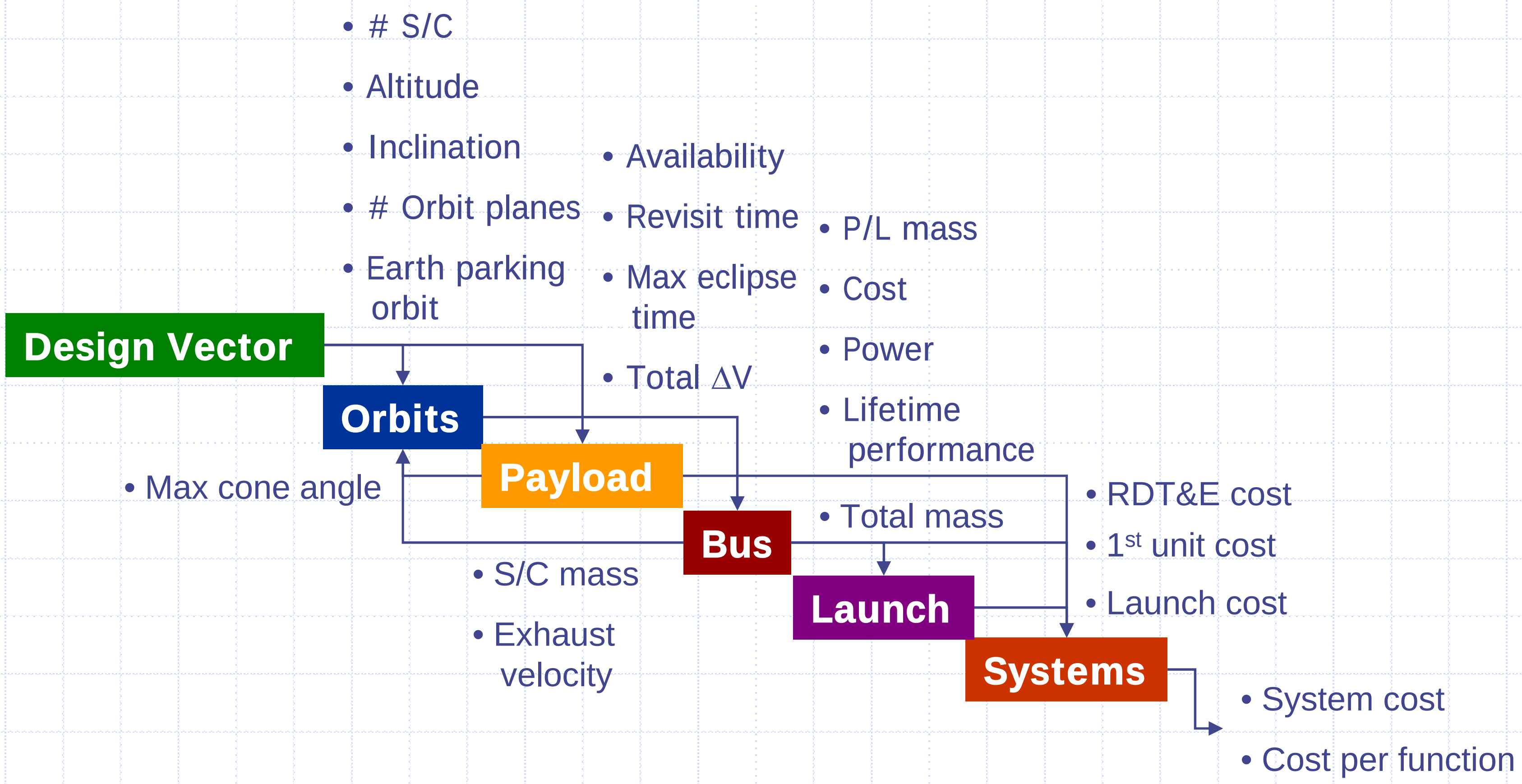
End of Life: Disposal

- Satellite has capability to insert into a disposal orbit
  - Boost to 2150 km altitude
  - Requires only 40 m/s ΔV
- Allows constellation replenishment

Detailed Design

Design Iteration Process

- Integrated Concurrent Engineering (ICE)



ICE Design Sessions

- Identified best launch scenario
  - Direct to Mars transfer over LEO parking orbit
  - Switch to chemical propulsion over electric
- Identified best constellation altitude
  - 2000 km for four spacecraft
  - Minimizes system cost
- Discovered minimal cost saving with three spacecraft
  - Sacrificing availability and robustness
- Tweaked inclination orbit
  - Significantly reduces maximum revisit time

Detailed Design: Orbit Analysis

Orbits Requirements

- M004 MINERVA shall have a maximum revisit time of less than 3 hours.
- M005 MINERVA shall provide a coverage of ± 15° latitude band around the equator.
- S001 Constellation shall have a minimum of 2 spacecraft in view of the Earth at all times.
- S007 MINERVA shall have a crosslink availability of 90%.

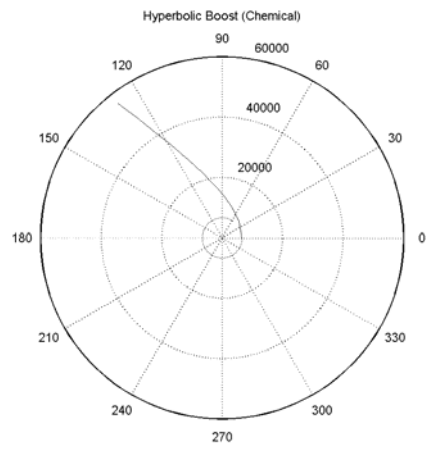
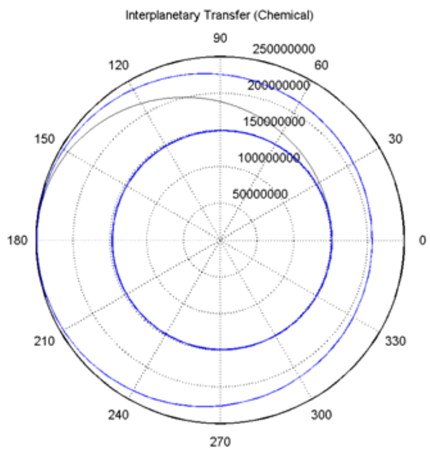
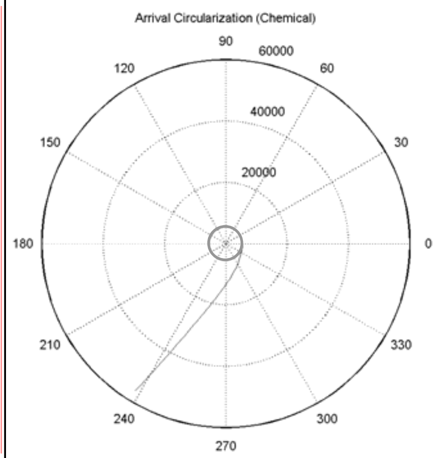
Transit Method Trade Study

- Proposed methods for the interplanetary segment
  - Chemical propulsion
  - Electric propulsion
- Design discriminators from an orbit standpoint
  - Total ΔV for all phases of the mission
  - Time of flight for transit to Mars

	Earth		Interplanetary		Mars	
	ΔV (km/s)	Time (d h)	ΔV (km/s)	Time (d h)	ΔV (km/s)	Time (d h)
Chemical	3.80	2d 17h	0.17	282d 23h	1.60	3d 17h
Electric	7.38	421d 14h	5.66	323d 3h	2.63	150d 1h

Using 185km parking orbit

Transit Method Trade Study

<table>
<tr><th></th><th>Earth</th><th>Interplanetary</th><th>Mars</th></tr>
<tr><td>Chemical Propulsion</td><td>
</td><td>
</td><td>
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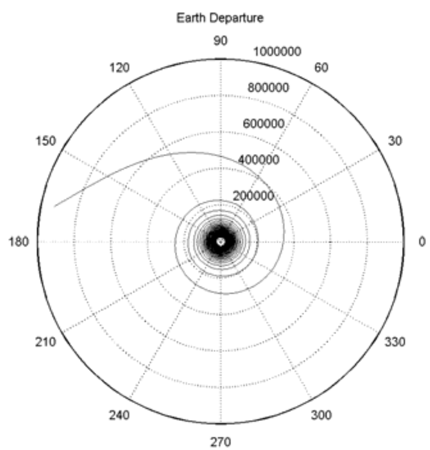
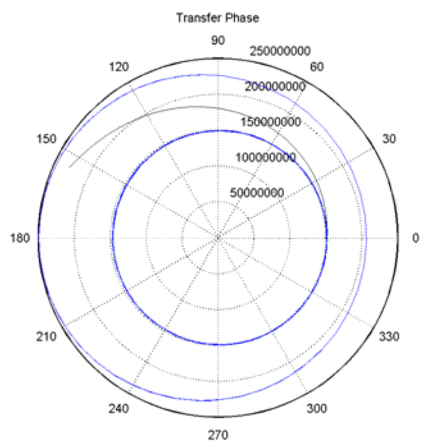
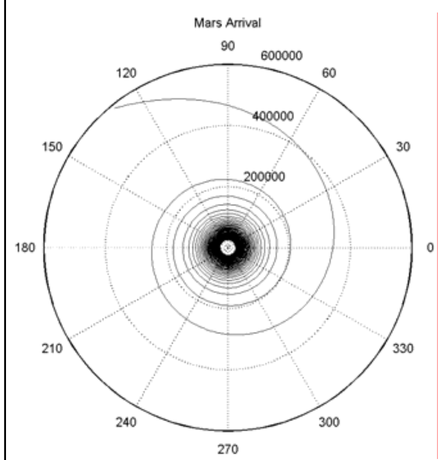
<tr><td>Electric Propulsion</td><td>
</td><td>
</td><td>
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Transit Method Selection

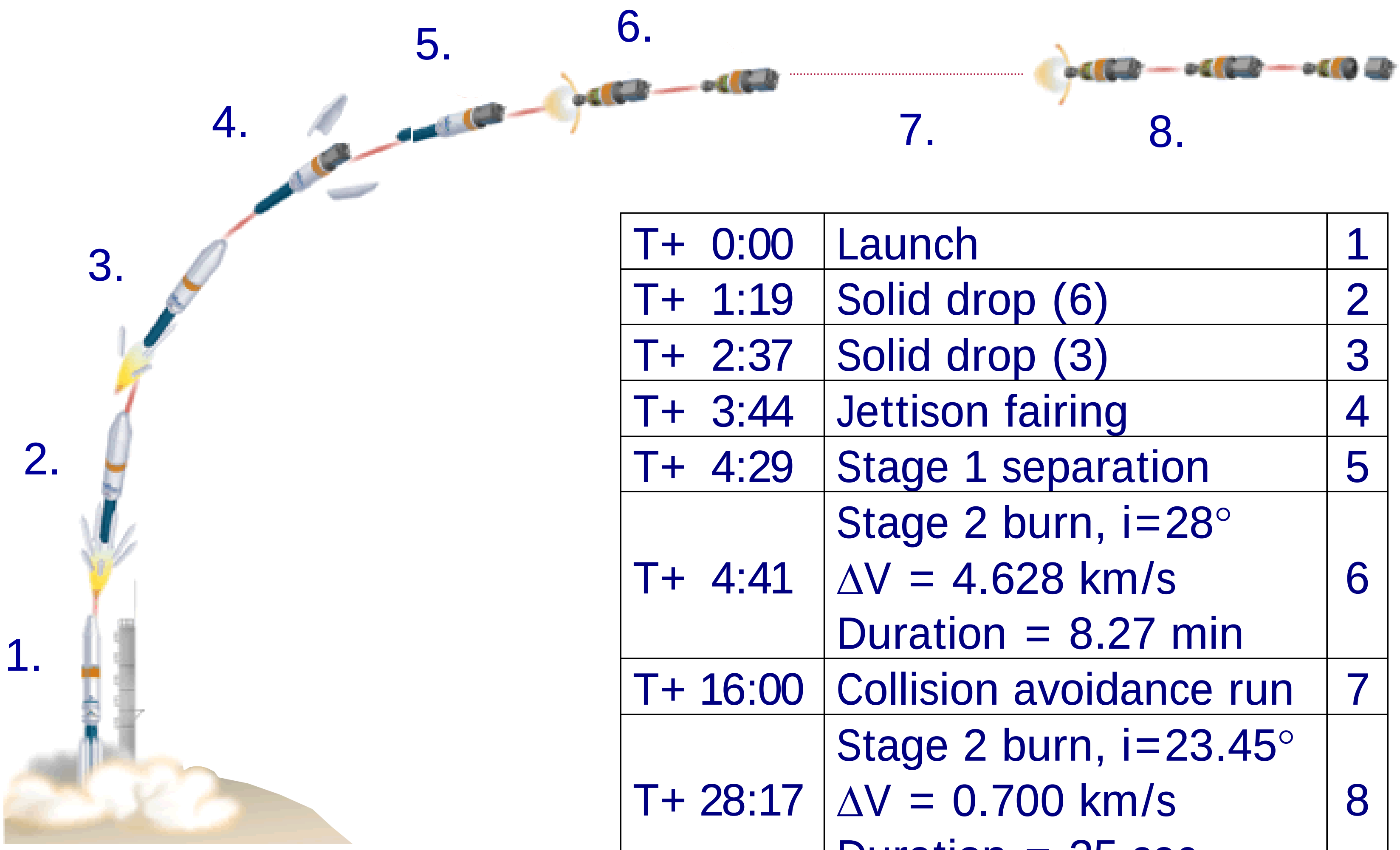
- Considerations
  - Chemical propulsion provides fast transfer for smaller ΔV
  - Electric propulsion is more benign
    - More time to react to problems
    - Smaller forces exerted during maneuvers
- Conclusion: from orbit standpoint, chemical propulsion is recommended
- Other groups are involved in this trade
  - Bus Group
  - System Group (Cost)

Launch Opportunities

- Each Earth-Mars launch window has a slightly different ΔV requirement
- The MINERVA design can accommodate all three launch opportunities investigated
- The launch window in 2009 may be used as a backup opportunity, with system IOC on 23 Sep 2010

Launch	Departure ΔV	Capture ΔV	Time of Flight
2005	3.726 km/s	1.742 km/s	278d 15h 35m
2007	3.799 km/s	1.601 km/s	290d 8h 22m
2009	3.712 km/s	1.753 km/s	278d 21h 54m

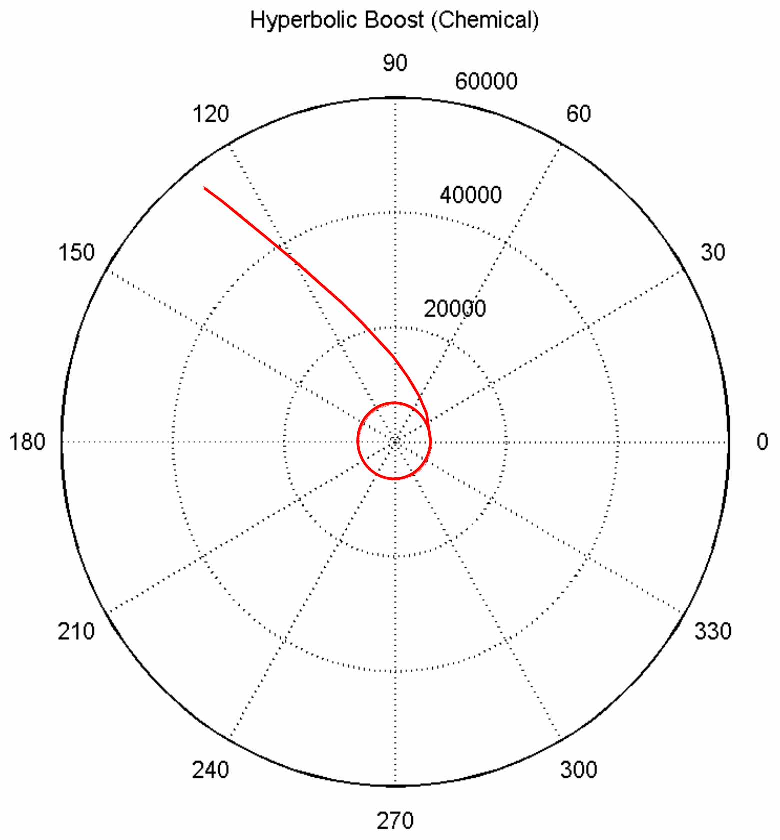
Delta III Launch Sequence



T+ 0:00	Launch	1
T+ 1:19	Solid drop (6)	2
T+ 2:37	Solid drop (3)	3
T+ 3:44	Jettison fairing	4
T+ 4:29	Stage 1 separation	5
T+ 4:41	Stage 2 burn, i=28° ΔV = 4.628 km/s Duration = 8.27 min	6
T+ 16:00	Collision avoidance run	7
T+ 28:17	Stage 2 burn, i=23.45° ΔV = 0.700 km/s Duration = 35 sec	8

Transit - Departure

T+ 3:23:20	Departure burn (second stage) ΔV = 3.799 km/s Duration = 5.59 min
T+ 3:29:30	Start release sequence Interval = 50.15 min
T+ 6:01:00	Despin maneuver
T+ 6:01:50	Deploy solar arrays
T+ 6:05:00	Initial checkout
T+ 2d 16:39	Depart Earth SOI



Fairing Jettison

Satellite Separation

Solar Array Deployment

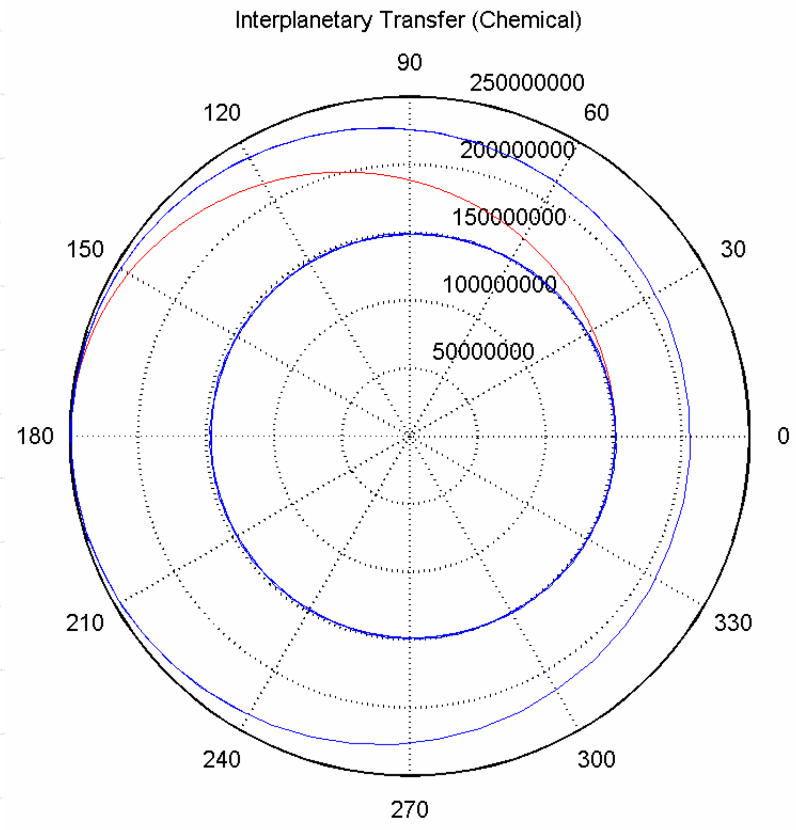
- Solar Arrays gimbaled about North-South axis

Cross-Link Deployment

- Deploys on hinged boom

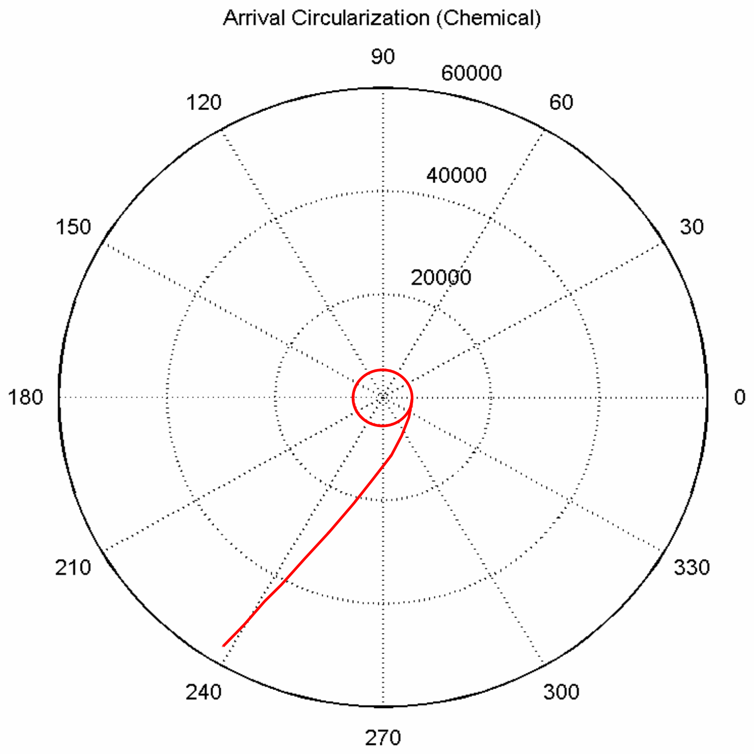
Transit - Rendezvous

T+ 2d 16:39	Alignment burn (four ACS thrusters) ΔV = ~0.020 km/s Duration = 48.2 sec
T+ 2d 16:45	Functional testing
T+ 122d 16:00	Correction burn (four ACS thrusters) ΔV = ~0.005 km/s Duration = 12.0 sec
T+ 285d 00:00	Upload precise position
T+ 285d 01:00	Spin-up maneuver
T+ 285d 14:29	Arrive Mars SOI (29 May 2008)



Capture and Deployment

T+ 285d 14:29	Injection burn (main kick motor) ΔV = 0.167 km/s Duration = 2.1 sec
T+ 290d 08:22	Circularization burn (main kick motor) ΔV = 1.602 km/s Duration = 19.1 sec
T+ 290d 08:23	Despin maneuver
T+ 290d 08:24	Deploy large antenna
T+ 290d 10:54	All satellites in place
T+ 291d 12:00	Correction maneuvers (as necessary)
T+ 296d 12:00	Test and calibration
T+ 326d 01:40	IOC: 9 July 2008



Earth-Antenna Deployment

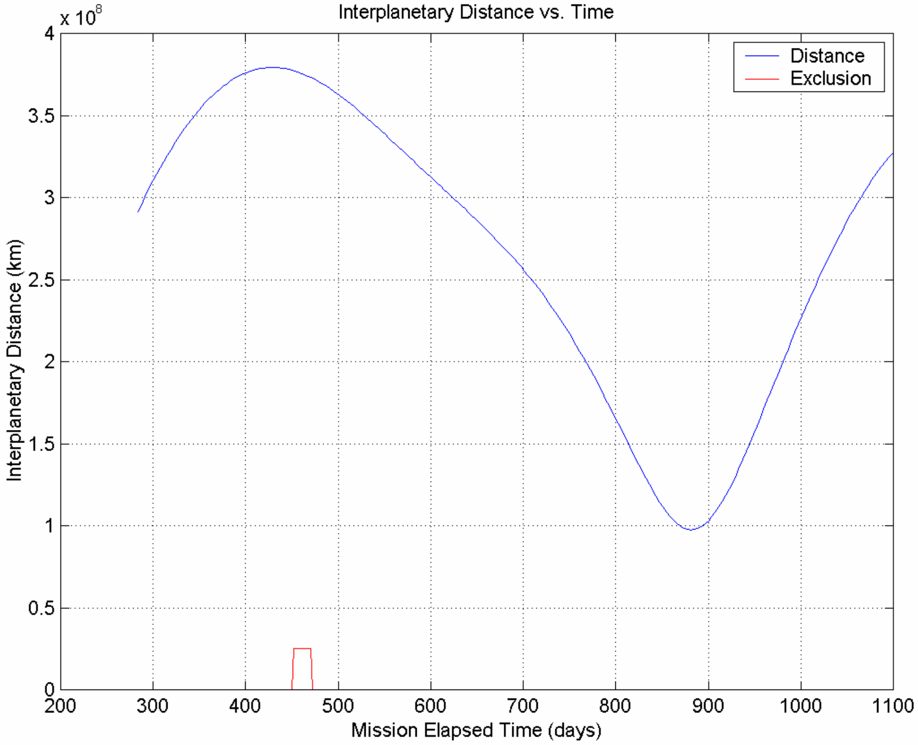
- Full pointing capabilities using 2 DOF boom

Fully Deployed Satellite

- Nominal mission configuration

Lifetime Visibility

- Earth-Mars distance is periodic over 2.2 years
- Exclusion zone of 19 days caused by line-of-sight intersection with the sun and its corona



Constellation Constraints

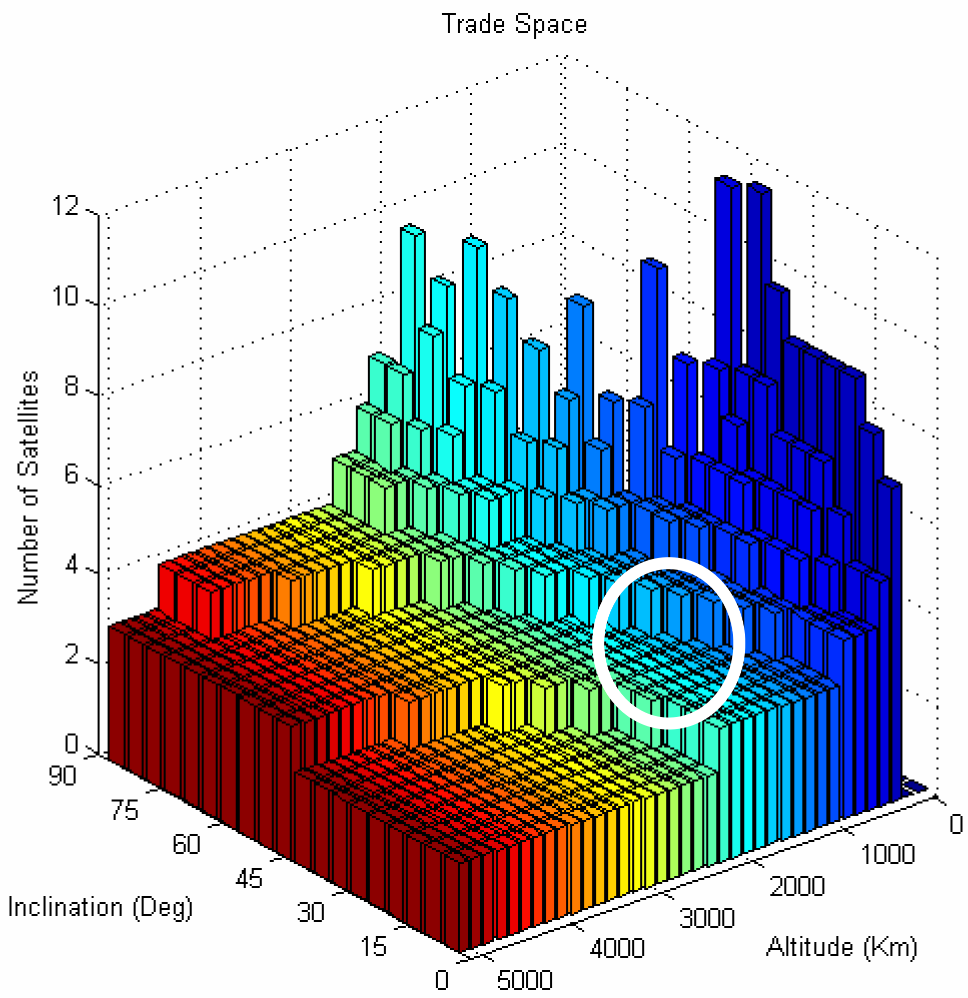
- Recap of requirements
  - Provide coverage to a ± 15° latitude band
  - Minimum MSE to satellite availability of 50%
  - Maximum revisit time of 3 hrs
- Architecture constraints
  - Allow for line of sight communications between satellites
  - Minimum inclination of ≈ 30°

Trade Spaces

- Coverage requirements
  - Altitude
  - Number of satellites
  - Inclination (restricted by the position determination requirement)
- Constrained by the cross-link requirements
  - Altitude
  - Number of satellites
- Cost (looked at in ICE sessions)
  - Altitude
  - Number of satellites

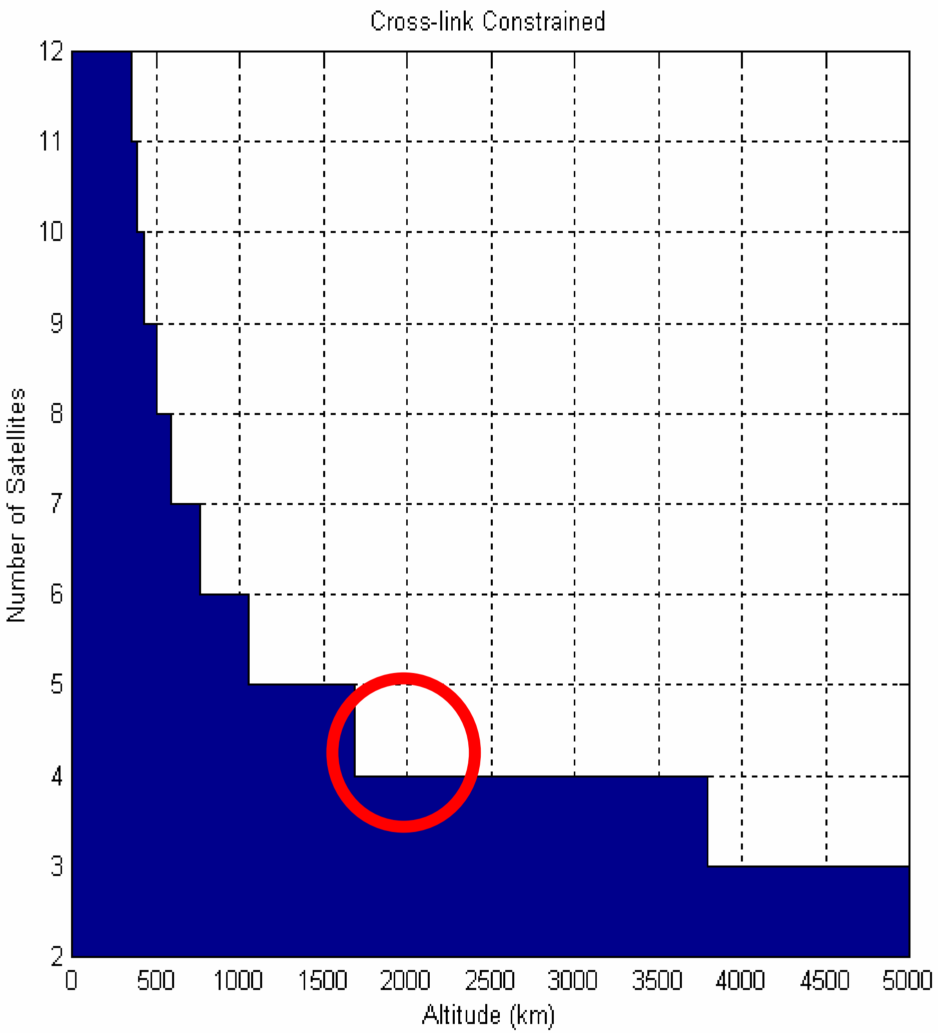
Coverage Trade Space

- Constrained by:
  - Revisit time < 3 hrs
  - 50% availability
- Variables:
  - Number of satellites
  - Inclination
  - Altitude

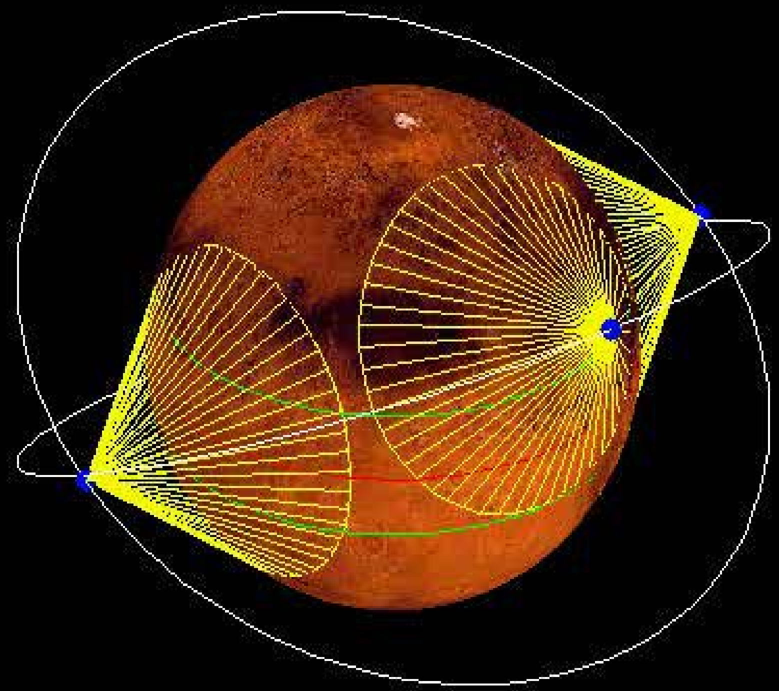


Cross-link Trade Space

- Minimum altitude required for cross-links
- Signal beams pass at least 200 km above the surface of Mars



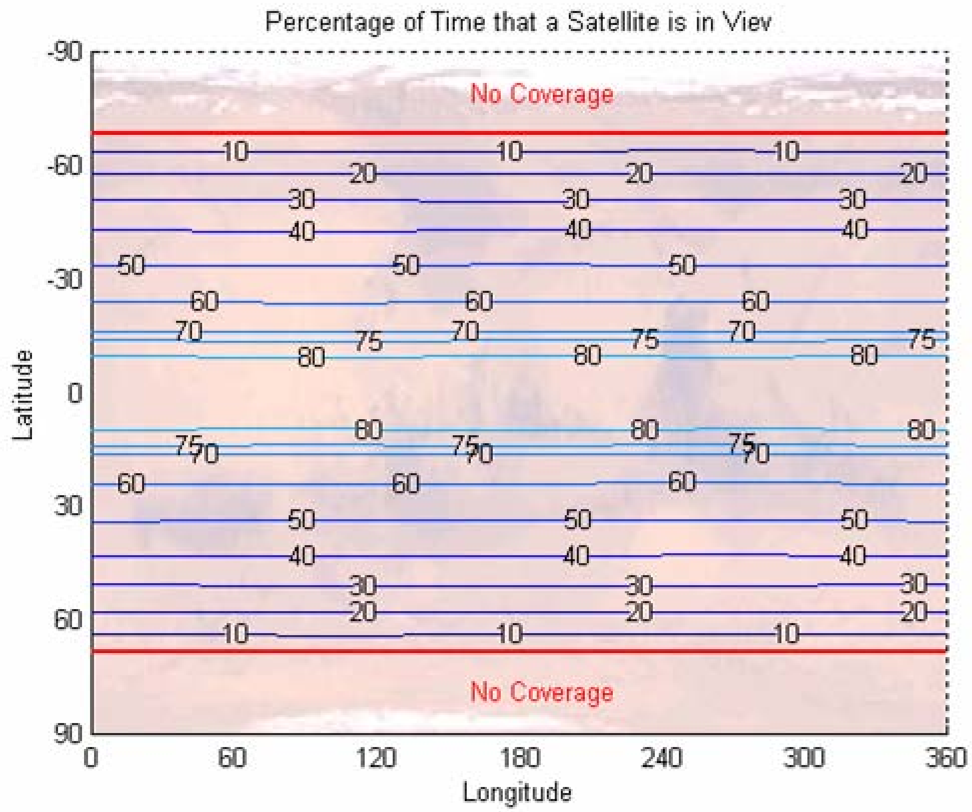
Final Constellation Design



- Walker-Delta pattern
- Circular orbits
- 2 Planes
- 4 Satellites
- 27° Inclination

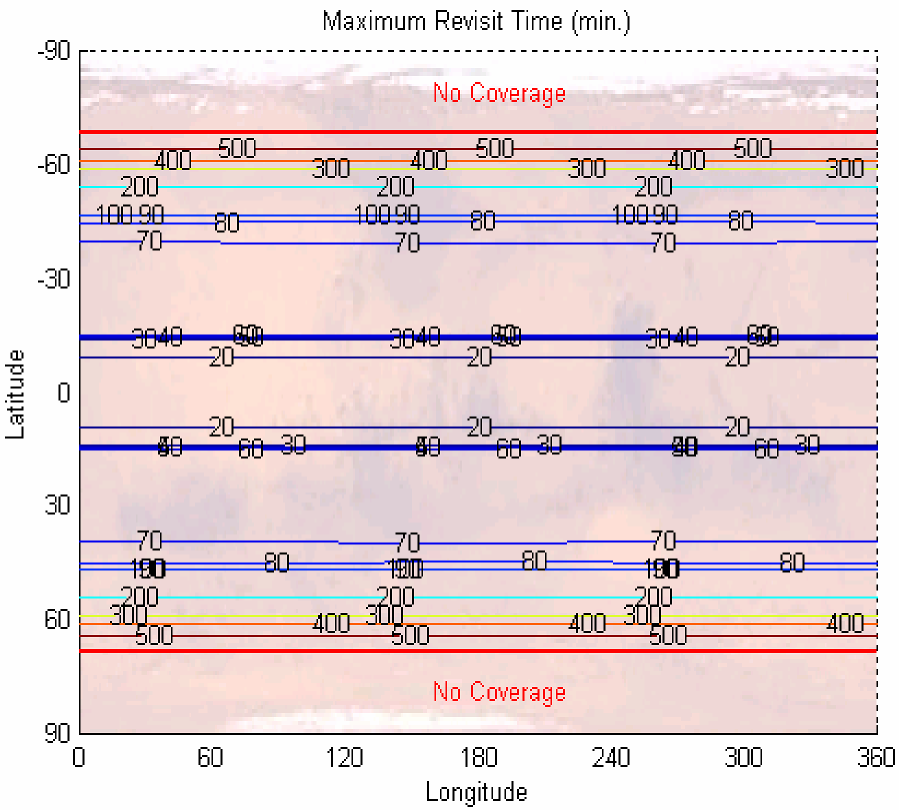
Percentage of Time in View

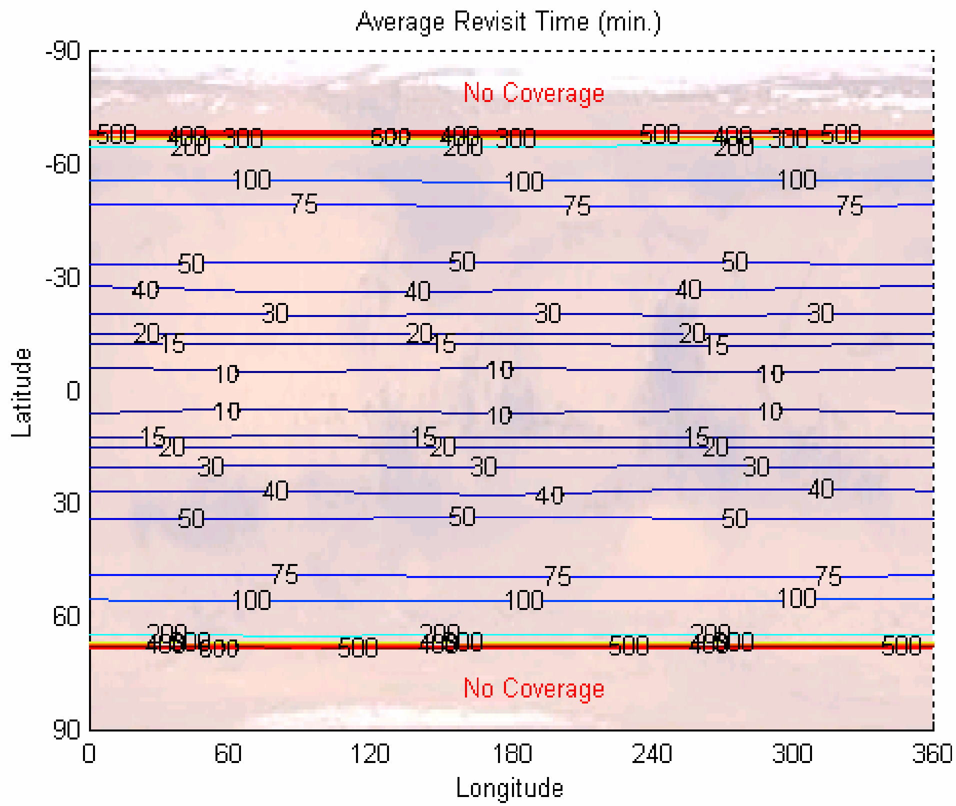
- Constellation provides >70% coverage in the $\pm 15^0$ latitude band
- Reduced coverage up to $\pm 65^0$



Revisit Time

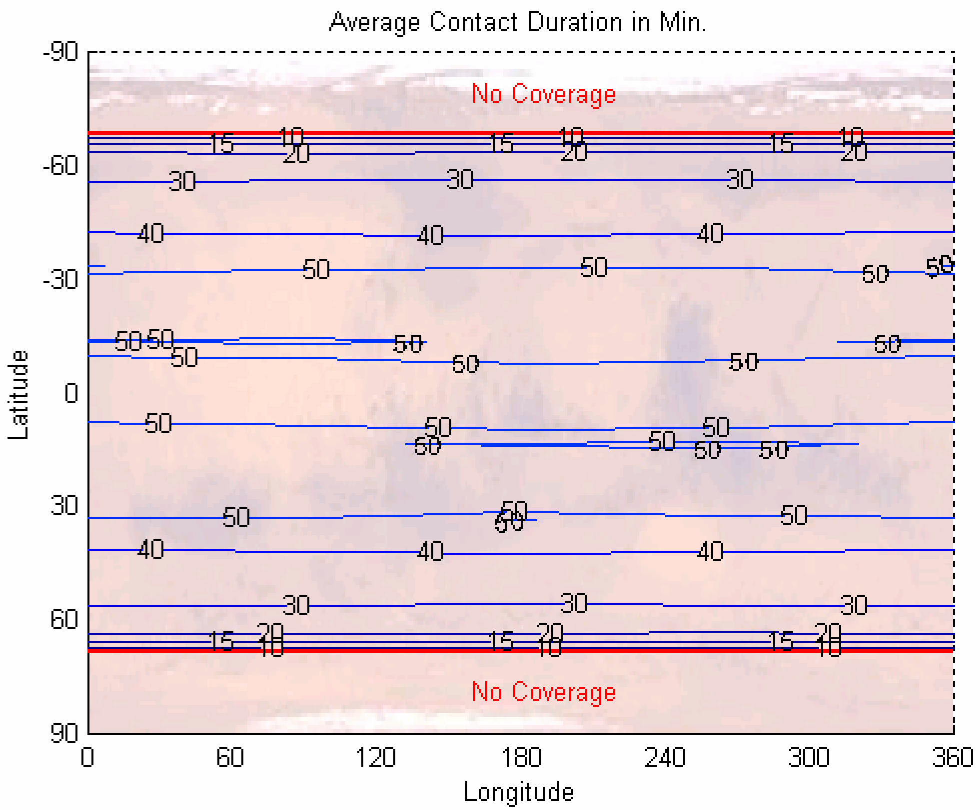
- The maximum time between satellite passes is <30 min
- The average time is <20 min





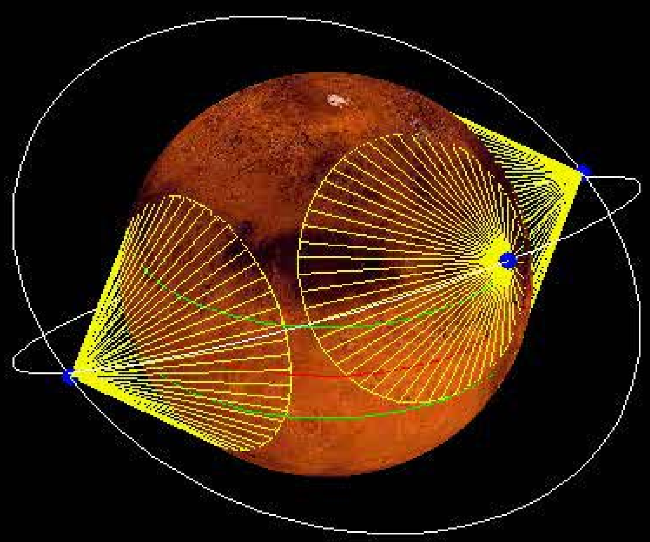
Contact Duration

- On average, a satellite will remain in view for 50 minutes.



Final Constellation Design

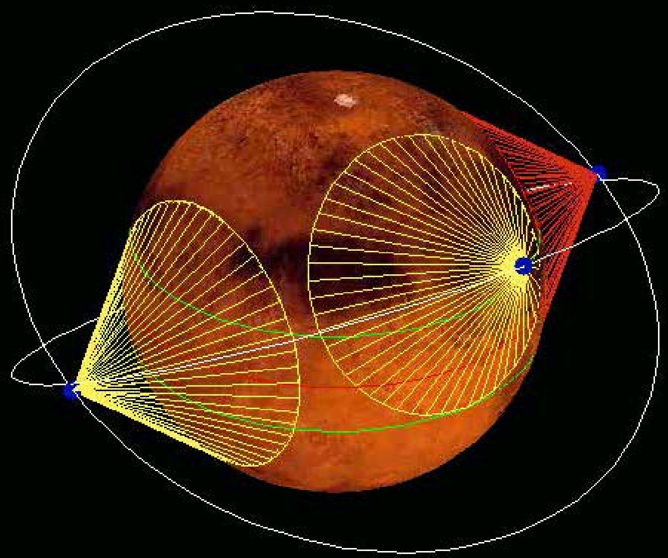
- Walker-Delta pattern
- 4 satellites in 2 planes
- Inclination of 27^0



- Provides ($\pm 15^0$ Lat)
  - Avg. revisit time < 20 min
  - Max. revisit time < 30 min
  - Contact duration ≈ 50 min
  - Availability > 70%
  - 3 satellites in view of Earth
  - Reduced coverage up to ($\pm 60^0$ Lat)

Single Satellite Failure

- In the event of a single satellite failure, the constellation will be able to provide communication and navigation at a diminished level



- Provides ($\pm$ 15^0 Lat)
  - Avg. revisit time $<$ 45 min
  - Max. revisit time < 100 min
  - Contact duration $\approx$ 50 min
  - Availability > 50%
  - At least 2 satellites in view of Earth

Detailed Design:
Payload Analysis

Payload Requirements

- M001 MINERVA shall provide communication capability between MSEs and EGS for at least 10 continuous hours per day.
- M002 MINERVA shall provide MSE position accuracy of 100 m (horizontal resolution) or less.
- M003 MINERVA shall return MSE position determination daily with an update every 3 hours.
- S005 Constellation shall return a minimum of 10 Gb/sol data rate to EGS.

Payload Requirements (cont.)

- E002 EGS shall be able to resolve spacecraft orbit to an accuracy of 20 m in radial, along-track, and cross-track directions.
- E003 EGS shall be able to upload spacecraft orbital element data and clock offsets at least once per day.
- E008 Uplink from EGS to MINERVA shall have a BER of no greater than 10^{-9}.
- E009 Uplink from EGS to MINERVA shall have a data rate of at least 500 bps.

Payload Requirements (cont.)

- P001 Payload mass shall not exceed 50 kg.
- P002 Payload shall use UHF for communication with MSEs.
- P003 Uplink from MSE to MINERVA shall have a BER of no greater than 10^{-6}.
- P004 Payload shall have a downlink BER no greater than 10^{-6}.
- P005 Each satellite shall have a downlink data rate of at least 150 kbps from MINERVA to EGS.

Payload Requirements (cont.)

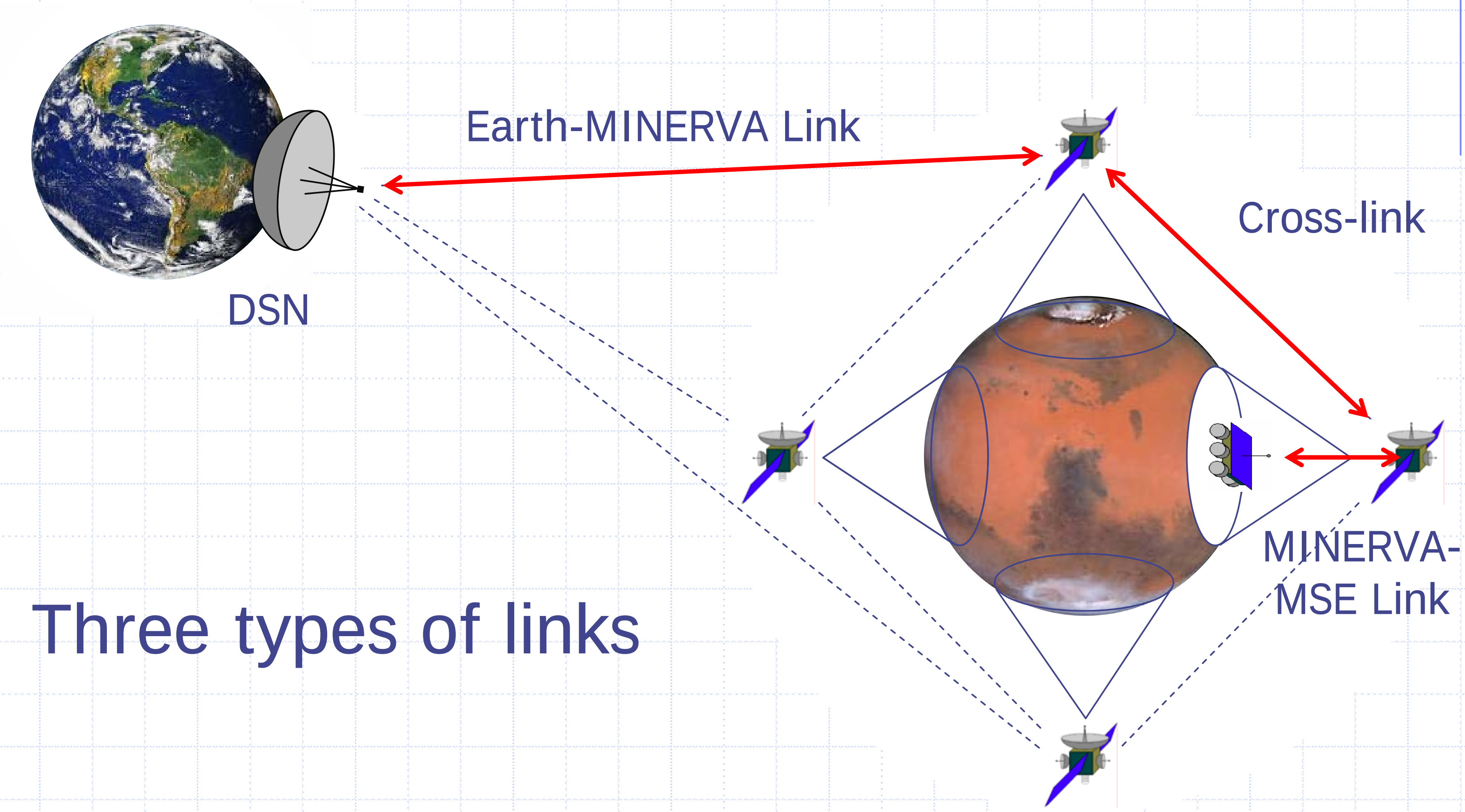
- P006 Payload shall dynamically allocate downlink data rate and uplink from MSE to constellation data rate.
- P007 Payload shall provide 30 Gb storage for communication data.
- P008 Payload subsystem shall use an on-board orbital propagator with an accuracy of 10 km for backup.

Payload Analysis: Communication

Communications Requirements

- Communication system
  - Relay between Mars Surface Elements (MSEs) in the ±15° latitude band and the Earth.
  - Exceed 10 Gb/sol of total data return

Communication System Overview



Three types of links

Antenna Types Analysis

Parabolic antenna

- Optimized for high gain (>20 dB) and low beamwidth (order of 15 deg or less)
- Has a lot of experience in space

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Helix antenna

- Optimized for frequencies below 2 GHz
- Best suited for low gain and high beamwidth
- Light mass

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Antenna Types Analysis

Phased array antenna

- Generates one or more beams simultaneously
- Changes direction of the beam rapidly
- Sweeps good gain over a large beamwidth (e.g. 14 over 120°)
- No moving mechanical parts

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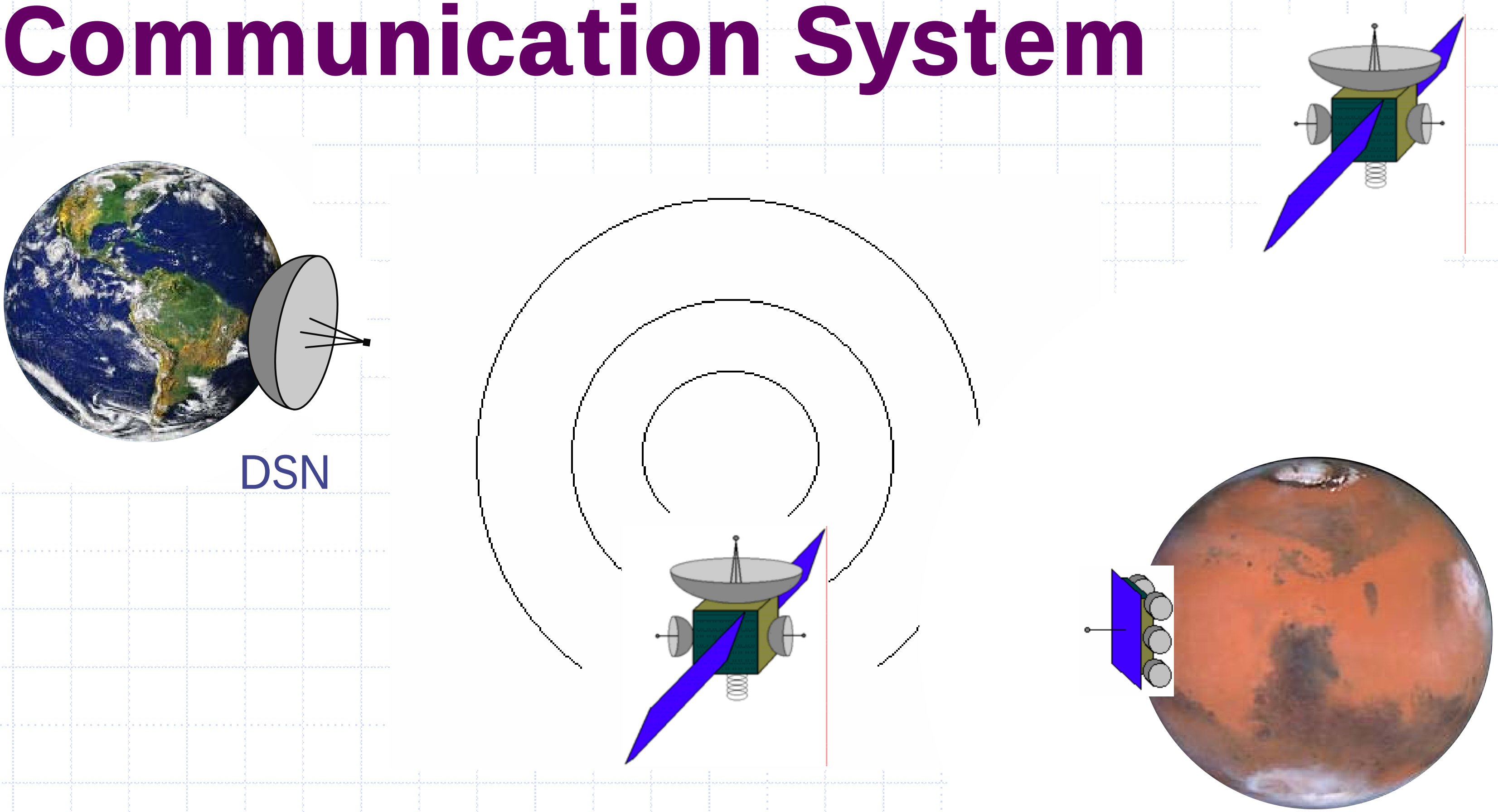
Horn antenna

- Optimized for frequencies of 4 GHz or higher
- Best suited for low gain and high beamwidth
- High weight

Top Level Trade Analysis for the Communication System

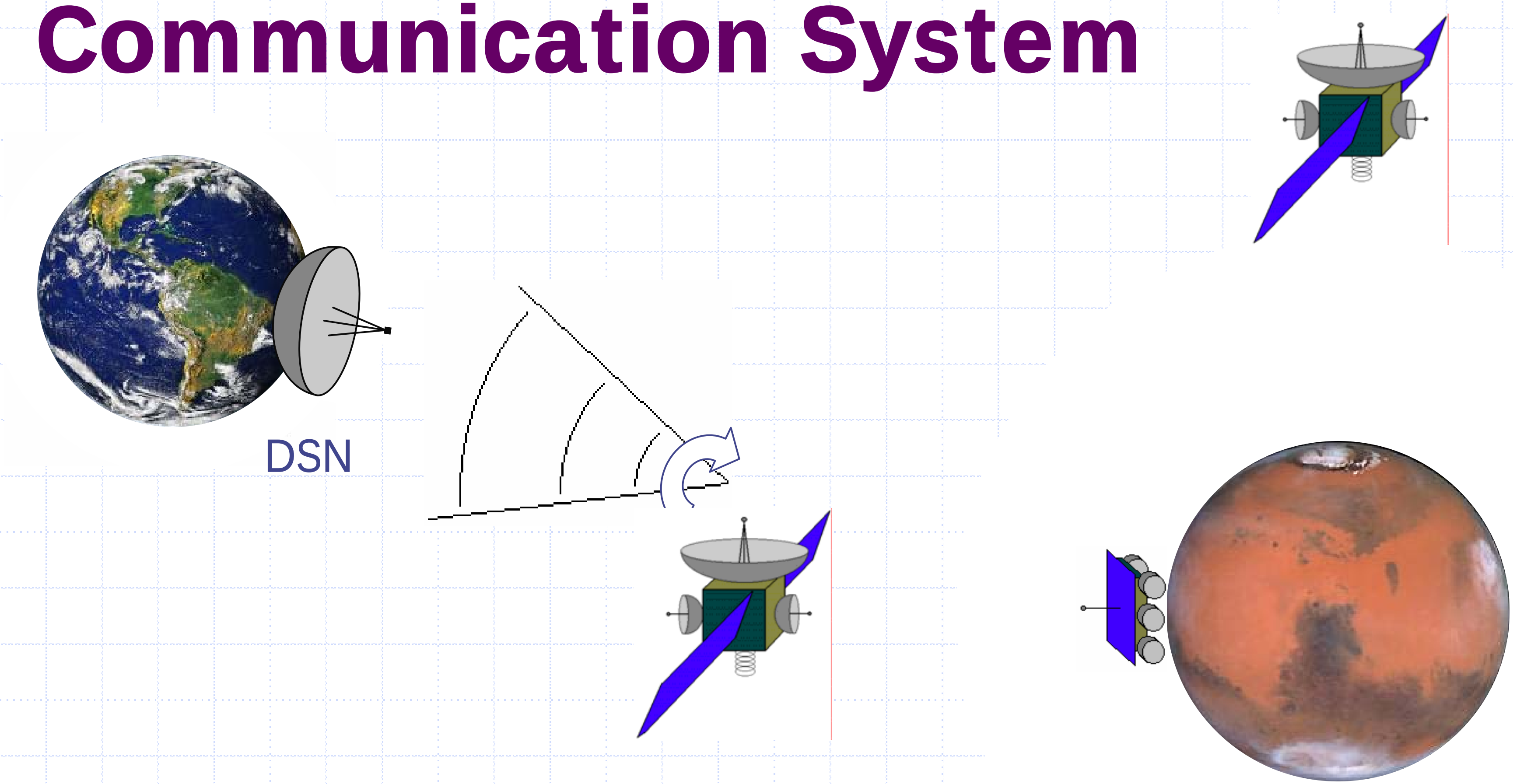


Case 1: Integrating all links together in one antenna

1) Omnidirectional antenna

- Inefficient use of available power

Top Level Trade Analysis for the Communication System

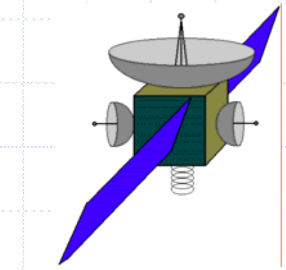


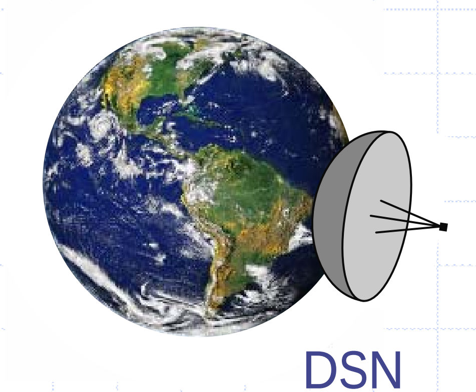
Case 1: Integrating all links together in one antenna

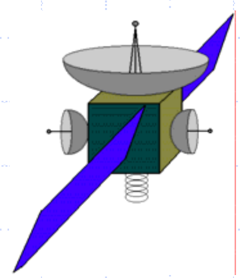
2) Directional antenna

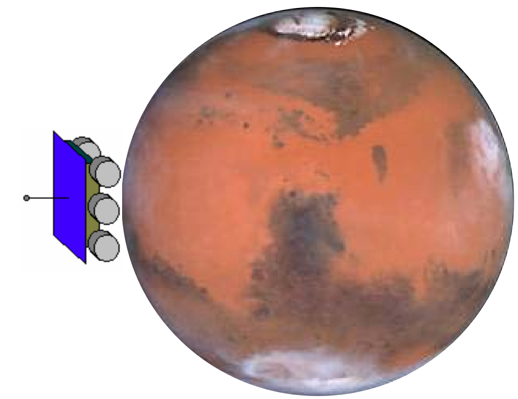
- Impossible to communicate between Mars and Earth at the same time (parabolic reflector and phased array antenna)

Top Level Trade Analysis for the Communication System







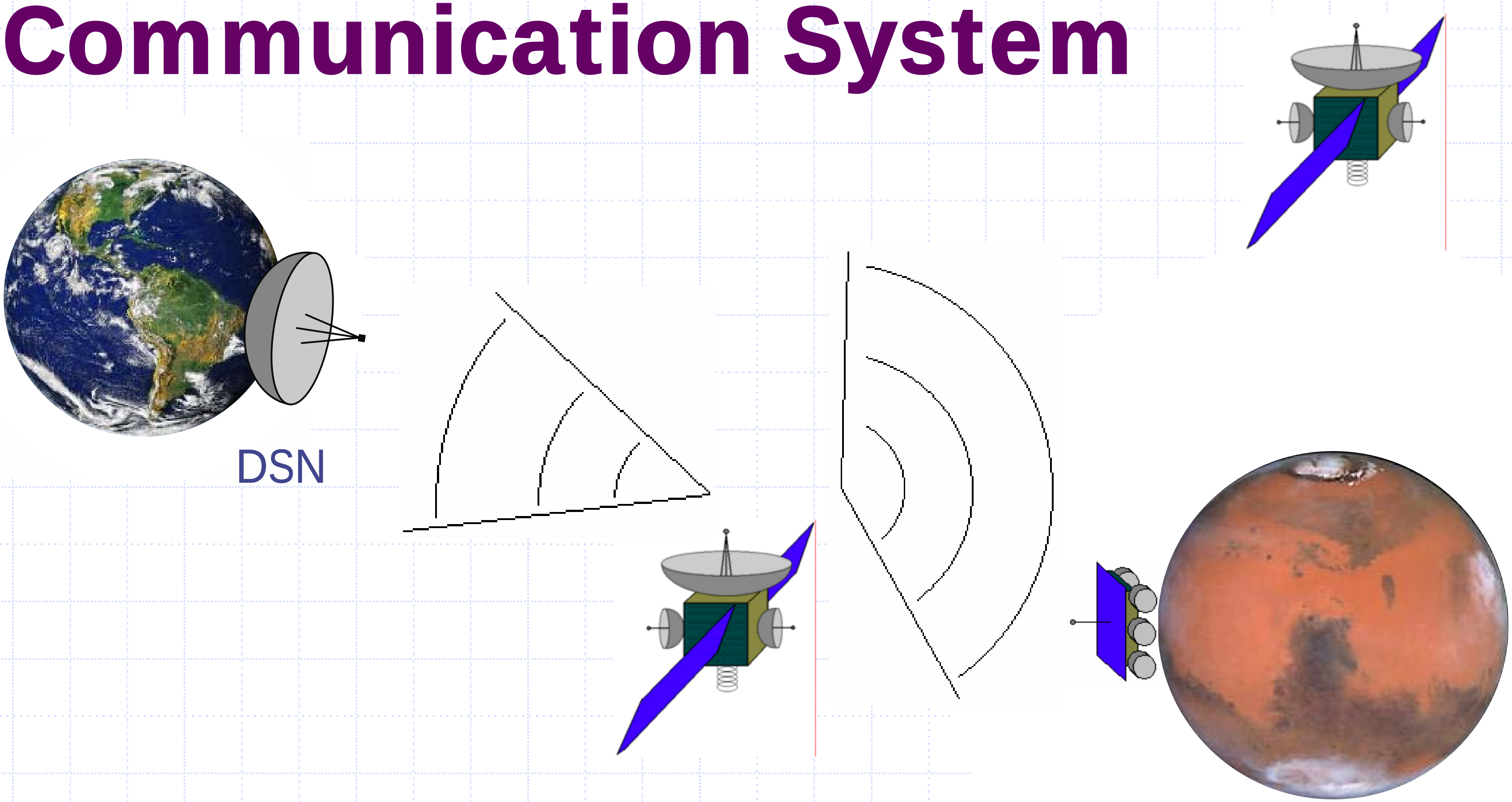


Case 1: Integrating all links together in one antenna

Conclusion:

- Integrating all links together is not the optimal solution

Top Level Trade Analysis for the Communication System

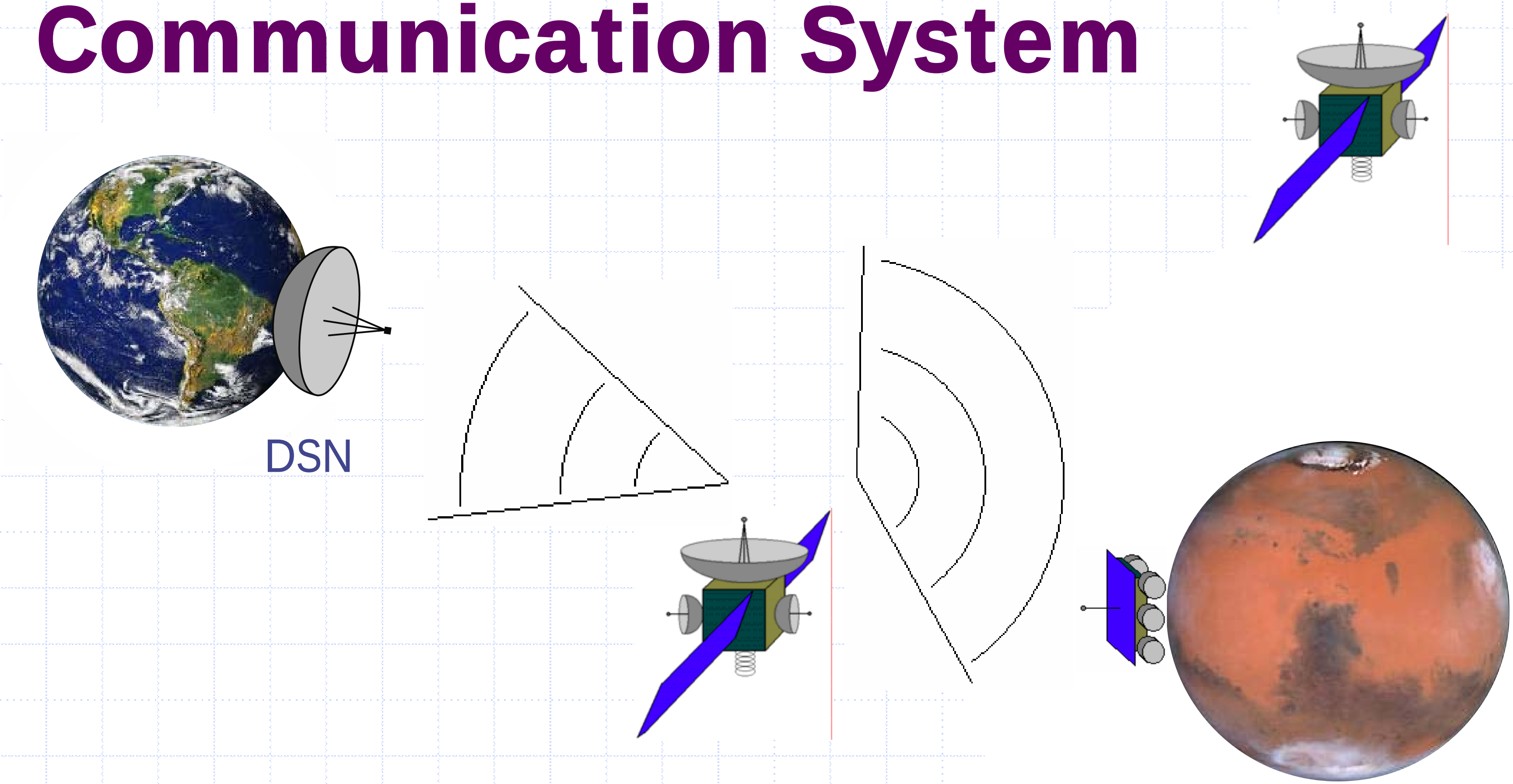


Case 2: Integrating cross-link and MINERVA-MSE

1) Using a helix type antenna or a parabolic antenna

- Not enough gain for that large beamwidth

Top Level Trade Analysis for the Communication System

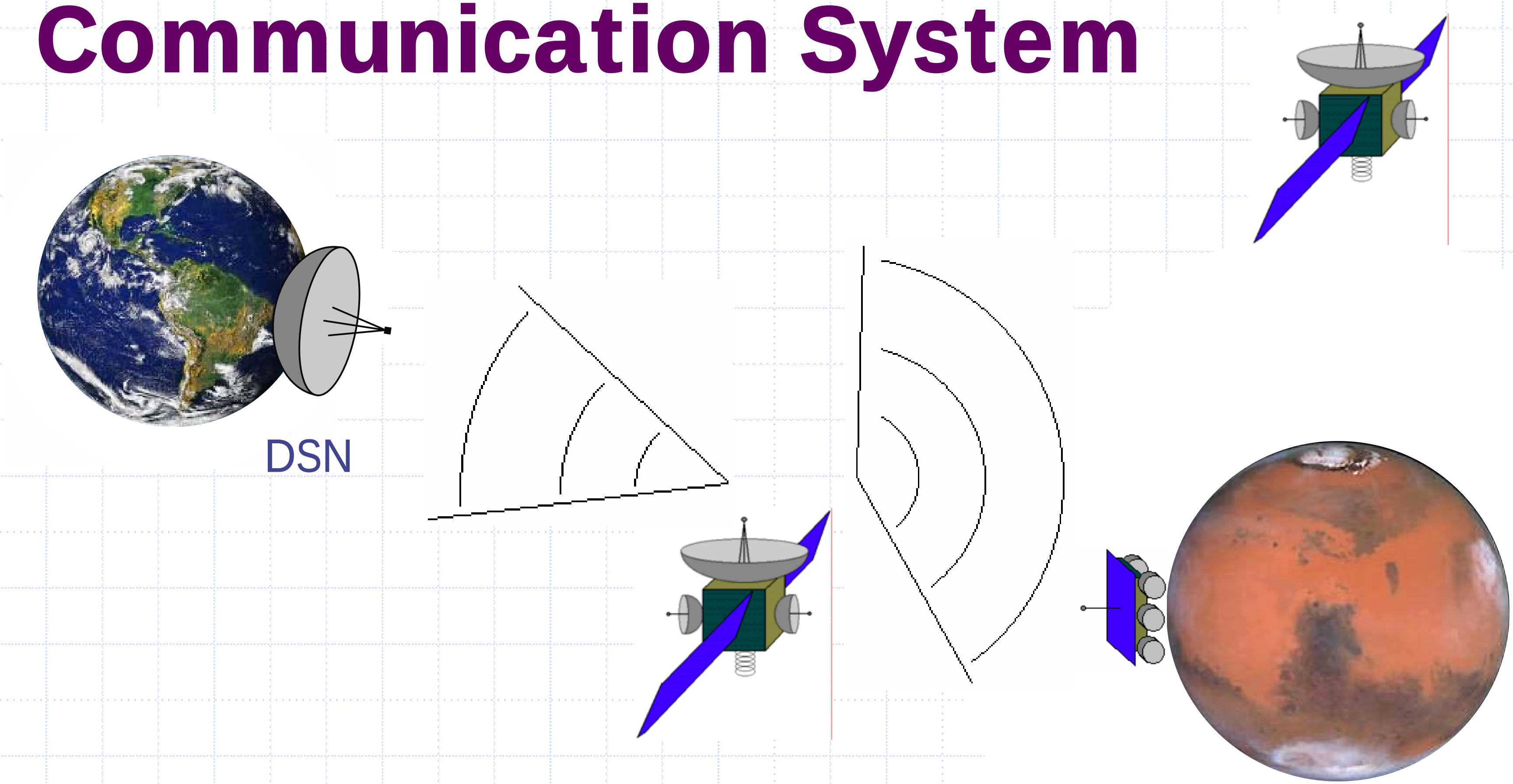


Case 2: Integrating cross-link and MINERVA-MSE

2) Using a phased array antenna

- UHF phased array antenna have not been used for space communication

Top Level Trade Analysis for the Communication System

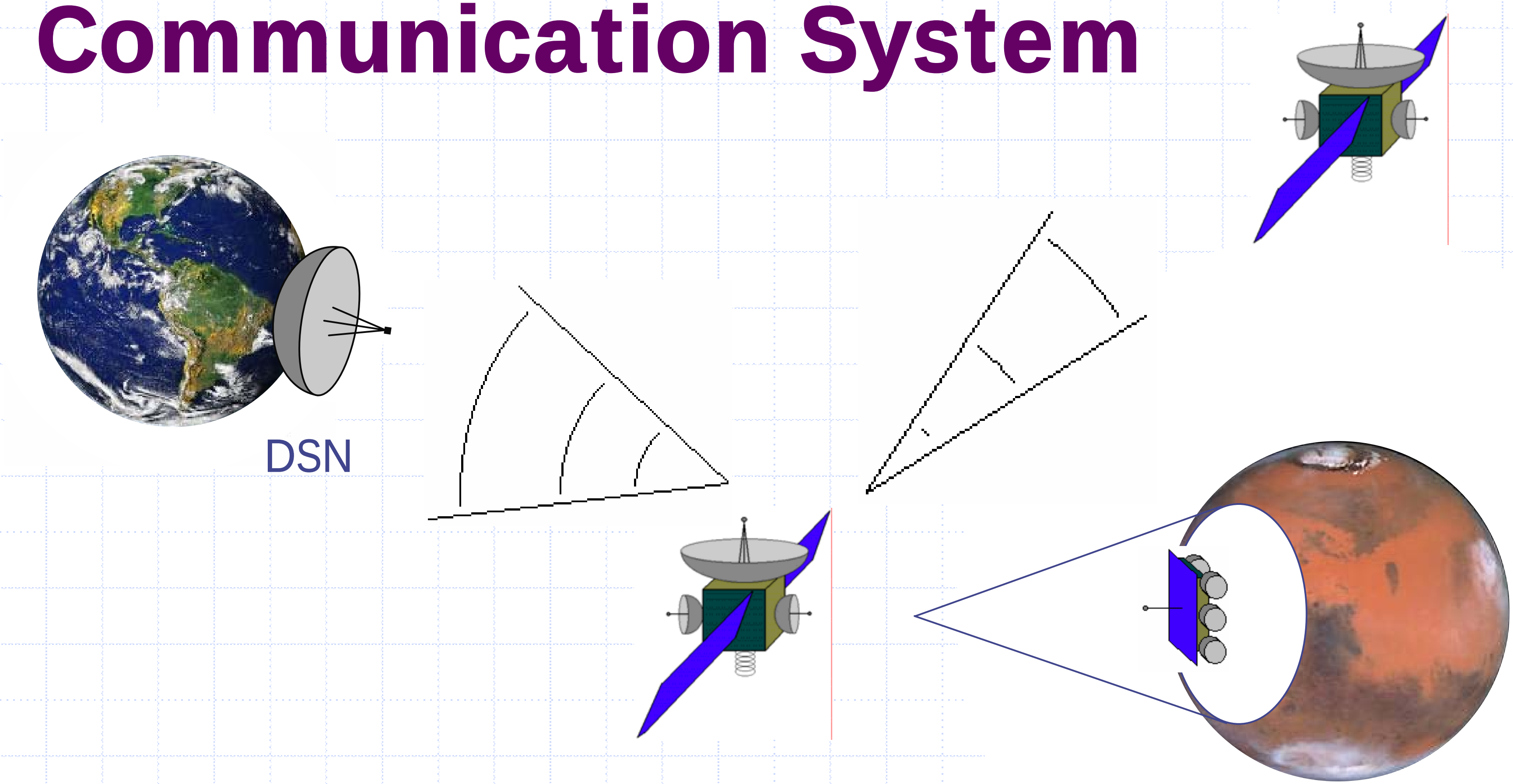


Case 2: Integrating cross-link and MINERVA-MSE

Conclusion:

- Integrating cross-link and MINERVA-MSE is not the optimal solution for this application

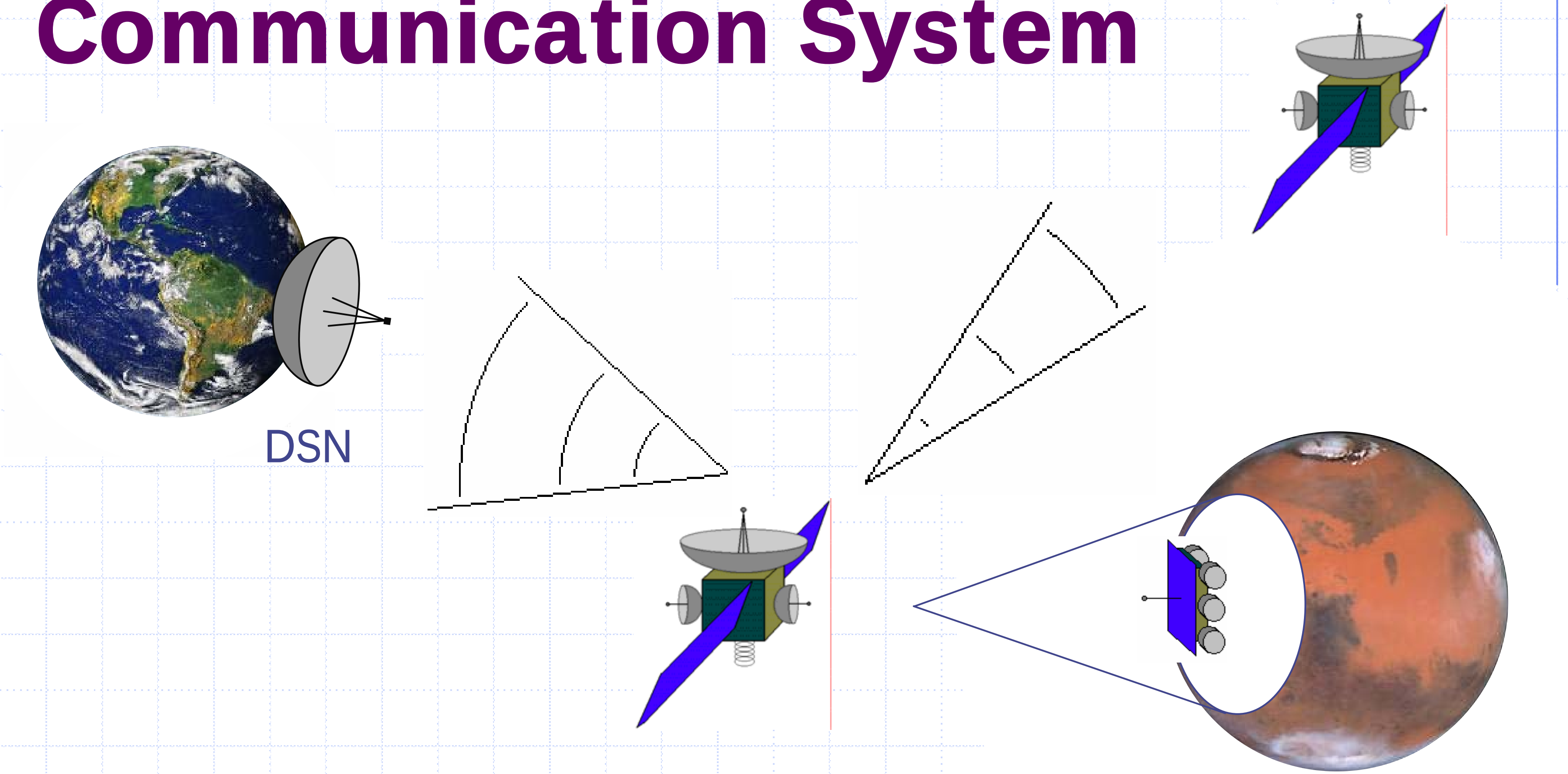
Top Level Trade Analysis for the Communication System



Case 3: Separating each type of link

One different type of antenna per link

Top Level Trade Analysis for the Communication System



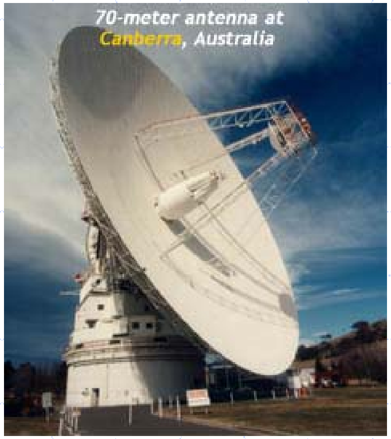
Case 3: Separating each type of link

Conclusion:

- Separating each type of link is the solution chosen

Earth Ground Station Interface

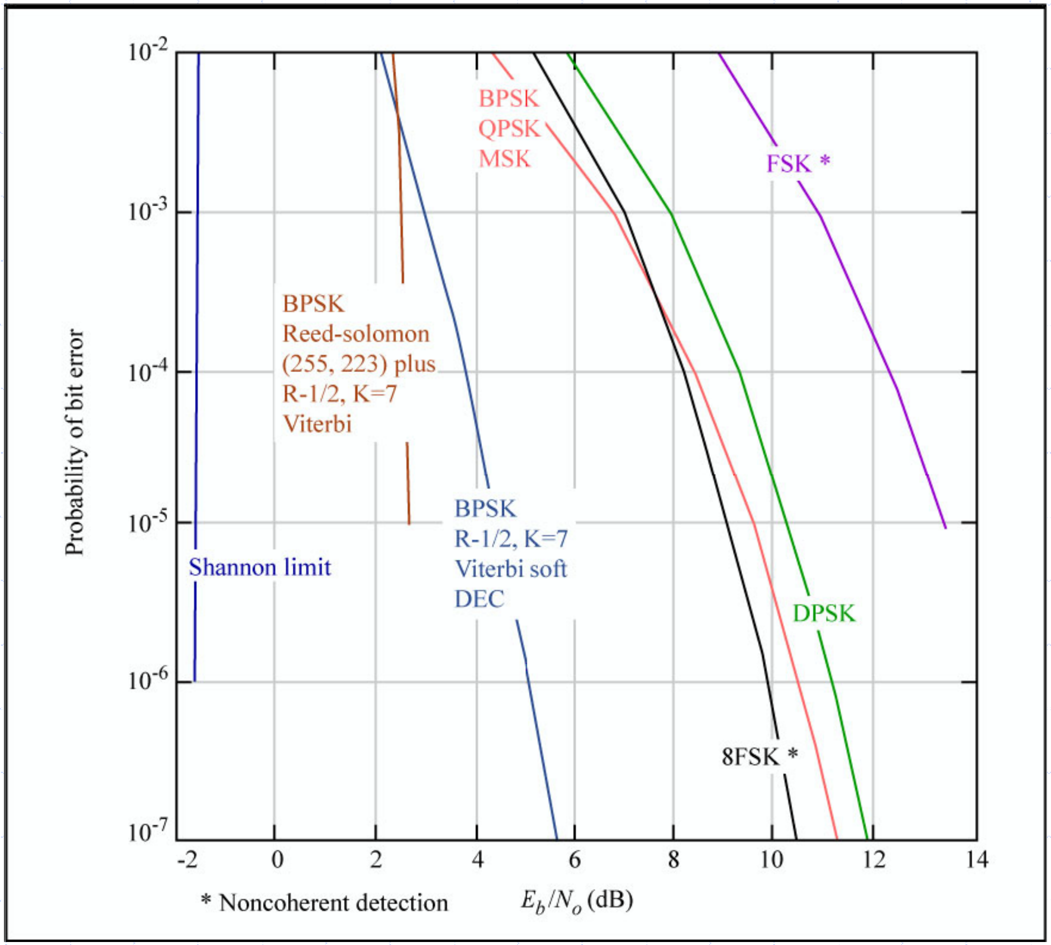
- Deep Space Network: 70-m vs. 34-m antennas



- 34-m: availability of Ka-band allows reduced satellite antenna size
- 34-m: processing facilities located on the ground
  - Better thermal control - reduced system noise
  - Smaller operation cost

Modulation used

- BPSK R-1/2 Viterbi software decoding
  - Standard deep space telemetry modulation format



Respects Shannon Limit

Figure by MIT OpenCourseWare.

Frequencies used

- Ka-band (32 GHz) for Earth-MINERVA link
  - Reduces the size of the antenna while keeping a high gain
  - Will be supported by DSN
  - Also used during Earth-Mars transit
- X-band (7 GHz) for cross-link
  - Provides good beamwidth without significantly influencing the antenna diameter (medium gain)
  - Widely used in deep space missions
- UHF (0.4 GHz) for MINERVA-MSE link
  - Good performance for omnidirectional antennas on Mars surface
  - Reduces necessary antenna mass on board MSE

Antenna Types Trade Analysis

- MINERVA - Earth link: Parabolic antenna
  - Mars Earth distance: 50 - 400 million km
    $\Rightarrow$ high gain required
- MINERVA - Mars link: Helix antenna
  - UHF 0.4 GHz to support existing assets
  - High beamwidth to improve coverage (77 deg at 2000 km altitude)
- MINERVA cross-links: Parabolic antenna
  - Necessity to use antenna for Earth link during Mars approach and as a backup

Payload Hardware

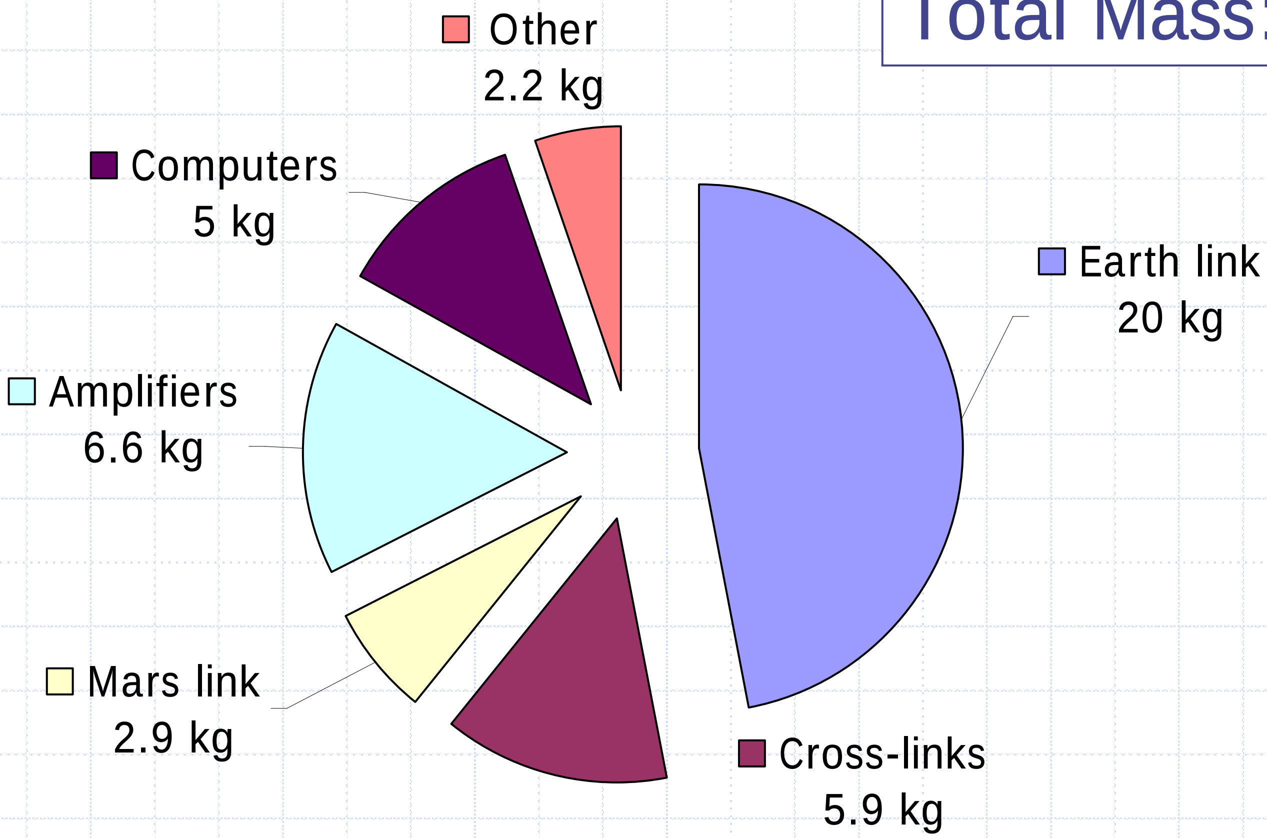
Antennas and Transponders
MINERVA-Earth Link: Ka-(X)-band 2.05 m parabolic, 130 W, 26.6 kg
MINERVA-Mars Link: UHF ø 25 cm x 31 cm helix, 21 W, 2.9 kg
MINERVA Cross-Link: X-(Ka)-band 2 x 50 cm parabolic, 5 W, 5.6 kg 2 Omni-directional, 5 W, 0.3 kg
Total Mass: 35.4 kg

Other Hardware
Computer: RAD 6000, 5 kg Used on Mars Pathfinder, Globalstar, ISS
Navigation Equipment: Ultra Stable Oscillator, 0.2 kg
Other equipment: Switches, etc. 2 kg
Total Mass: 7.2 kg

Total Payload Mass: 42.5 kg

Payload Mass Breakdown

Total Mass: 42.5 kg



Communications F.O.V. Verification

- Use model to verify clear “lines of sight” between satellites, Mars and Earth

Payload Analysis: Position Determination

Position Determination Requirements

- Position determination system
  - Gather information to determine position of Mars Surface Elements (MSEs) in the ±15° latitude band
  - With an accuracy of 100 m
  - With an average update period of less than 3 hours

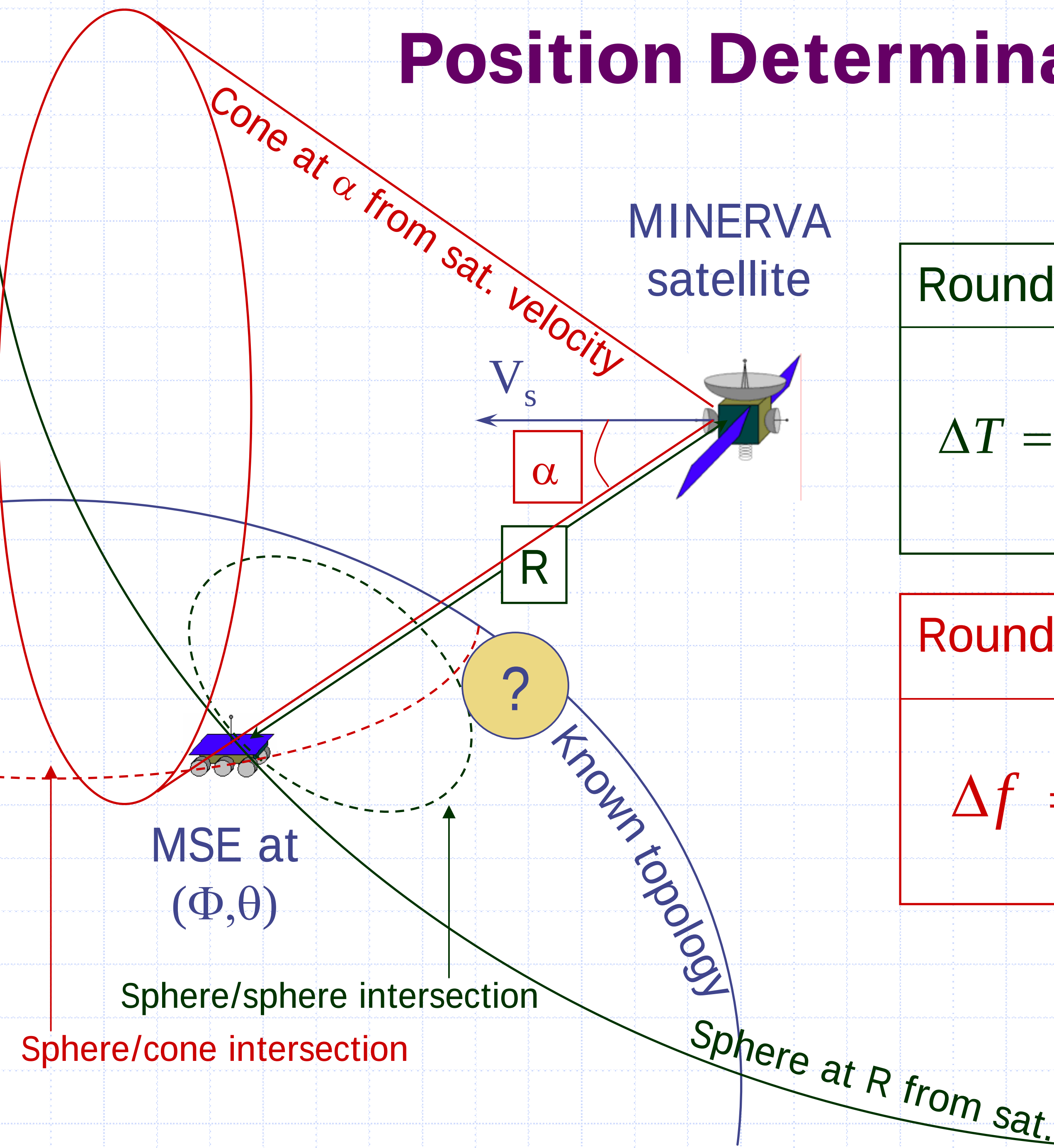
Positioning Design Trades

Position determination problem

- Passive
  - Radar
  - Infrared
- Active
  - One-way (GPS-like)
    - Range
    - Doppler
  - Two-way
    - Range
    - Doppler

Passive	One-way (GPS-like)	Two-way
Pros	**Pros**	**Pros**
No requirement on user	Unlimited #users	Quick 2-D positioning with single satellite
Single coverage for 2-D Double coverage for 3-D	Proven methods	Double coverage for 2-D Triple coverage for 3-D
Cons	**Cons**	**Cons**
Infrared not proven	Time offset Frequency offset	Limited #users
Computational load	Triple coverage for 2-D Quadruple coverage for 3-D	Transponders on user

Position Determination Method



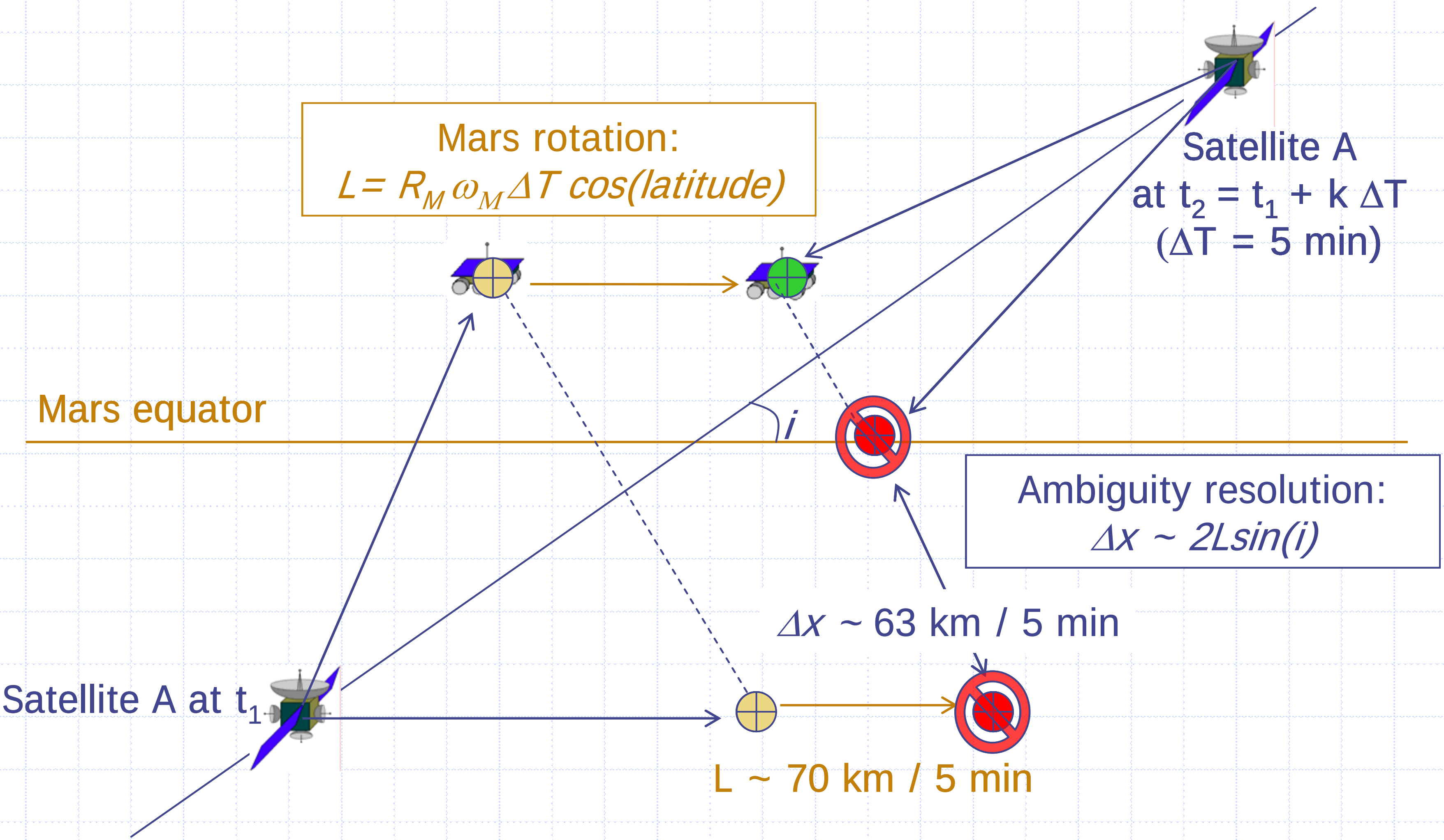
Roundtrip delay:

$$\Delta T = \frac{2R}{c} + \Delta t_{\text{processing delay}}$$

Roundtrip Doppler shift:

$$\Delta f = \frac{2V_s \cos(\alpha)}{\lambda}$$

Ambiguity Resolution



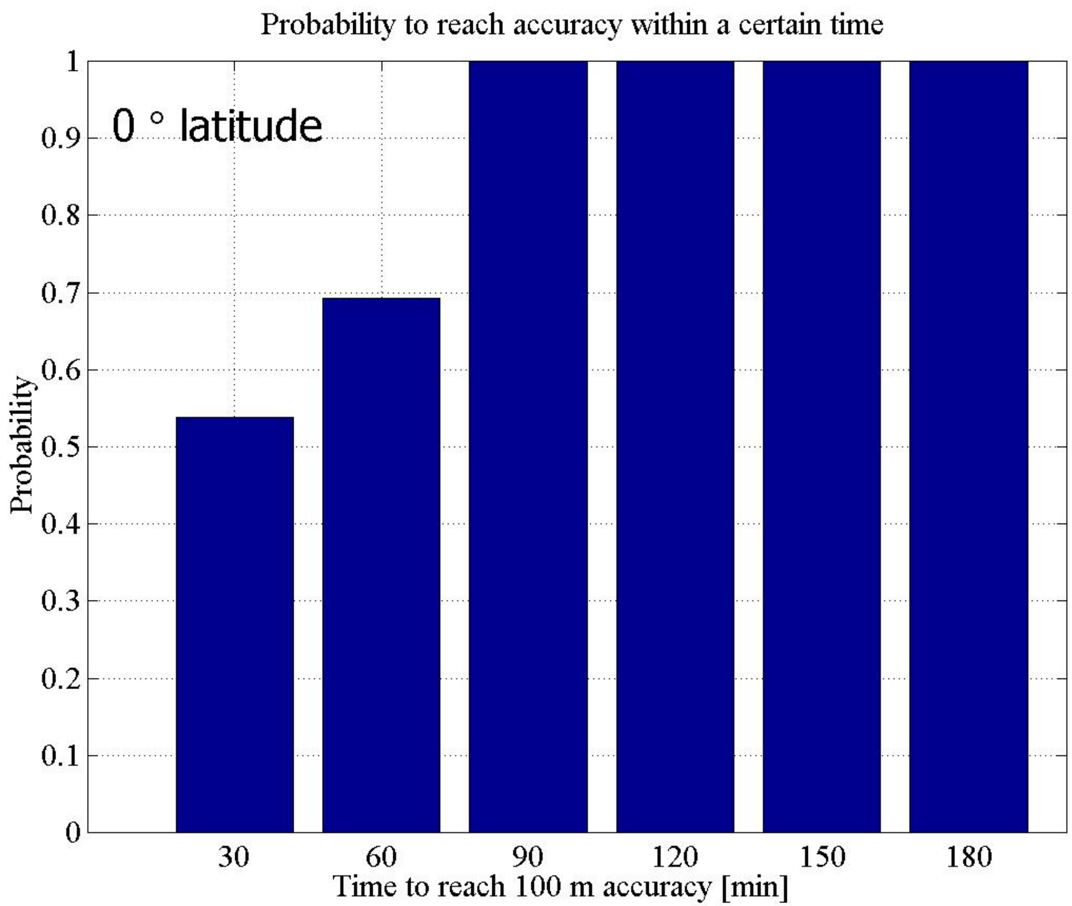
Sources of Error

Group		Properties	Magnitude	Effect
Internal	**Ranging error**	Code chip rate	10 m	Not limiting factor
Internal	**Doppler error**	Integration time	< 1 cm/s	Not limiting factor
		Sat. oscillator stability	< 1 mm/s	
External	**MSE altitude**	Mars topography	~ 200 m	Corrected with time
External	**MSE velocity**	Assumed very slow Measured with IMUs	< 1 cm/s	4 – 90 km error Per km/hr
External	**MINERVA orbits**	Quick positioning: orbit prediction	100 m – 10 km	Absolute upper bound on accuracy
		Post-processing: orbit determination	20 m	

Time to Get 100 m Accuracy

- Probability to reach 100 m accuracy (1 σ) within certain time:

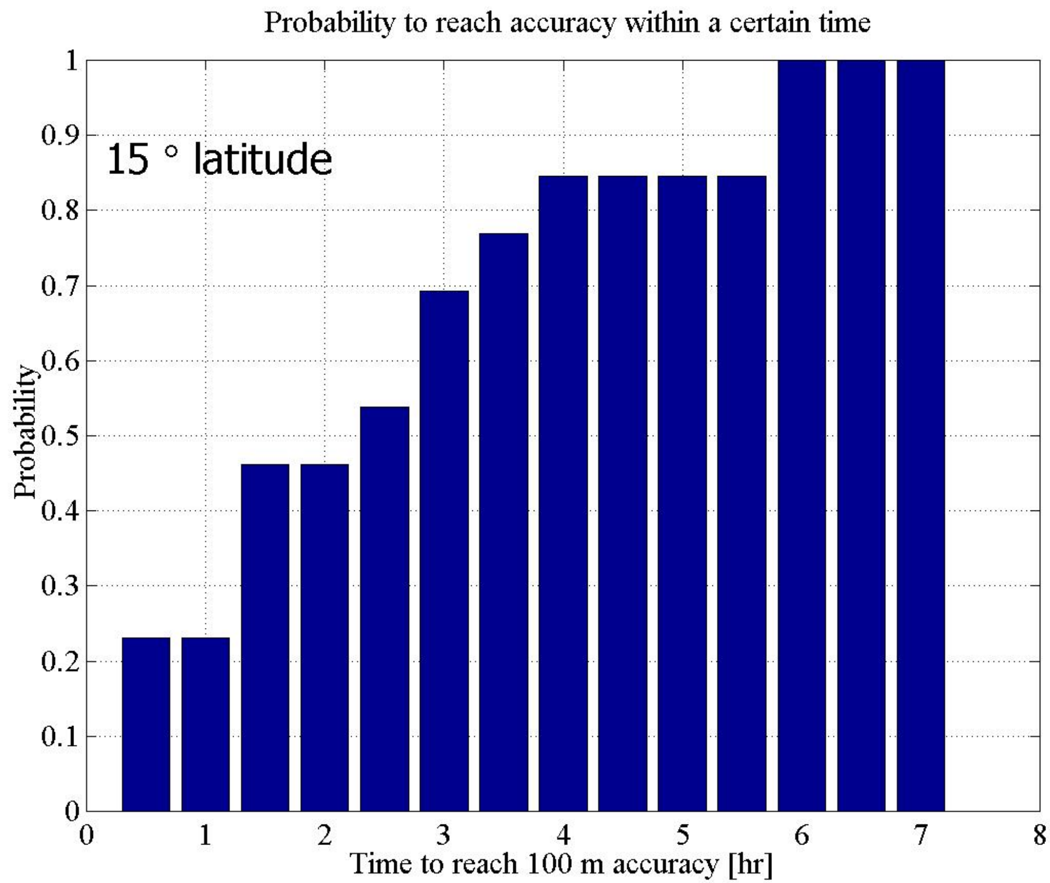
0° latitude



Time to Get 100 m Accuracy

- Probability to reach 100 m accuracy (1 σ) within certain time:

15° latitude



Detailed Design: Software Analysis

MINERVA Software Components

- Flight software
- Test, integration, and simulation software
  - Used to verify initial and updated flight software and during anomaly recovery
  - Cost modeled in CERs
- Operations software
  - Mission & activity planning
  - Mission control
  - Navigation & orbit control
  - Spacecraft operations
  - Data delivery, processing, and archiving

Flight Software

- ”Estimation by similarity" technique used to estimate:
  - Source lines of code (SLOC)
  - Software throughput requirements (MIPS)
  - Software memory requirements (MB)
- Flight software trades
  - Level of flight software autonomy
  - Programming language: C or Ada

Flight Software Autonomy Trade

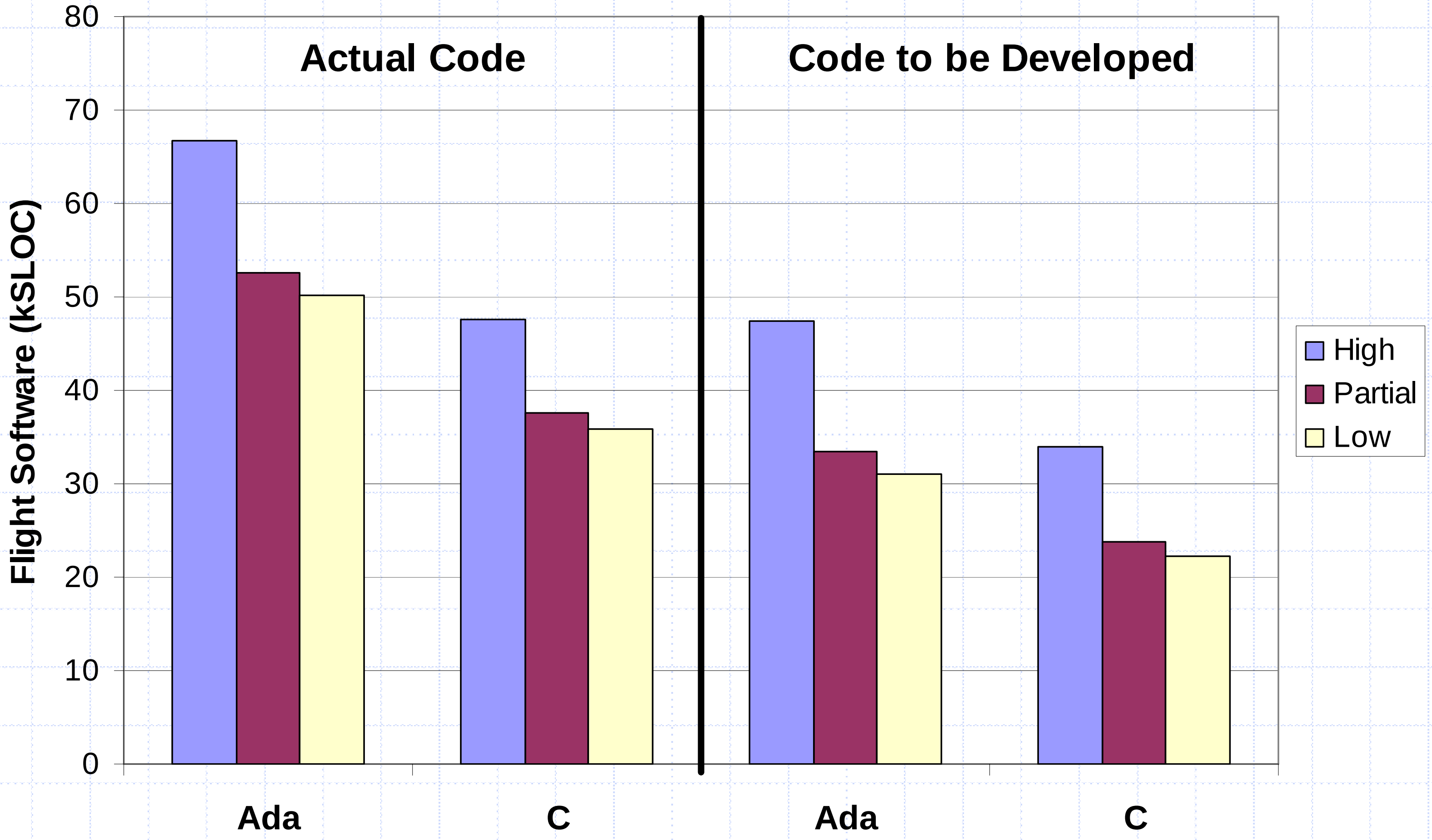
Level of Autonomy	MSE Position Determination	Communications	GN&C
High	◆ Calculated on-board ◆ Continuously tracks MSEs	◆ Automatic communications routing	◆ High precision orbit propagator ◆ Accurate position calculated on-board
Partial	◆ Calculated on-board with Earth input	◆ Preplanned communications routing ◆ Simple search	◆ Medium precision orbit propagator ◆ Earth provides accurate positions
Low	◆ Calculated on Earth		

Other Flight Software Autonomy

- Attitude determination and control
  - Includes momentum management
- Routine housekeeping
  - Thermal control
  - Power management
  - Data storage
- System monitoring
  - Detects anomalies
  - Controls safe modes

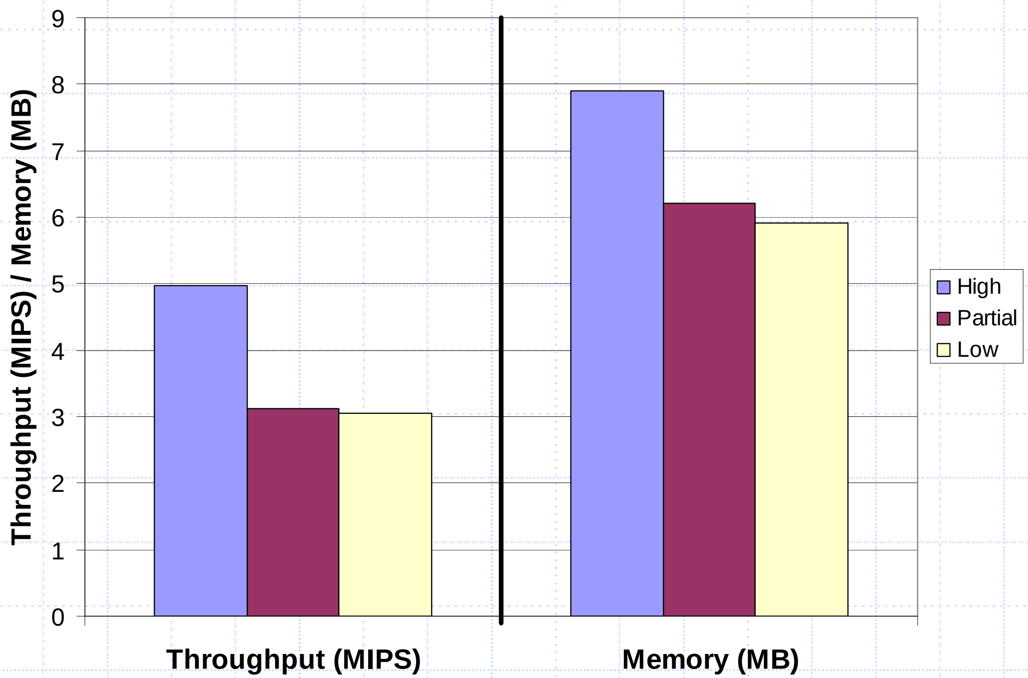
Flight Software Size

- Some I/O device handlers can be reused



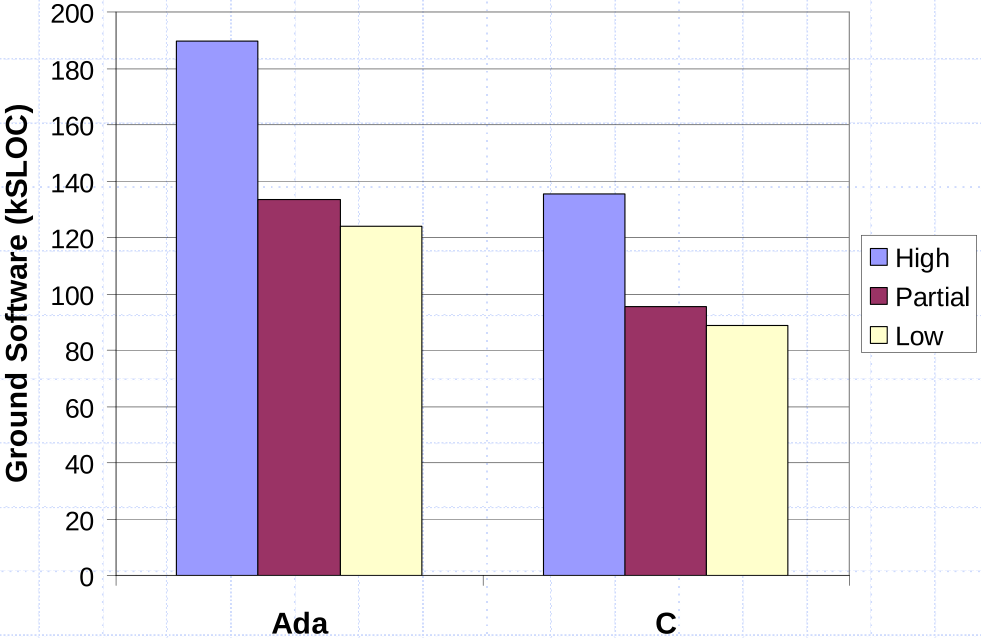
Flight Software Computer Requirements

- RAD 6000 Provides
  - Throughput: 10 to 20 MIPS
  - Memory: 16 GB
- Software computer requirements are met



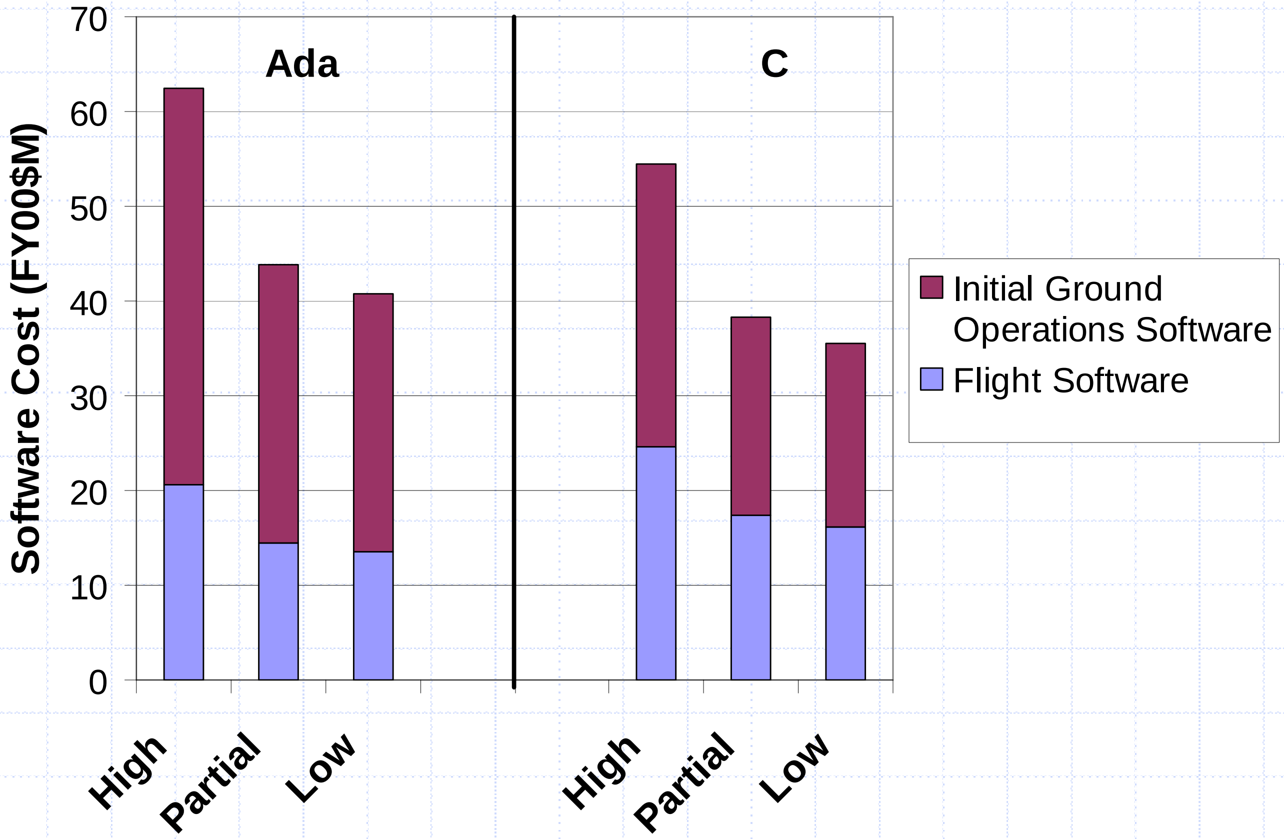
Ground Software Size

- Test, integration, and simulation software
  - Assumed to be 4x the size of the flight software
  - Modeled in CERs
- Initial operations software
  - Assumed to be 4x the size of the flight software



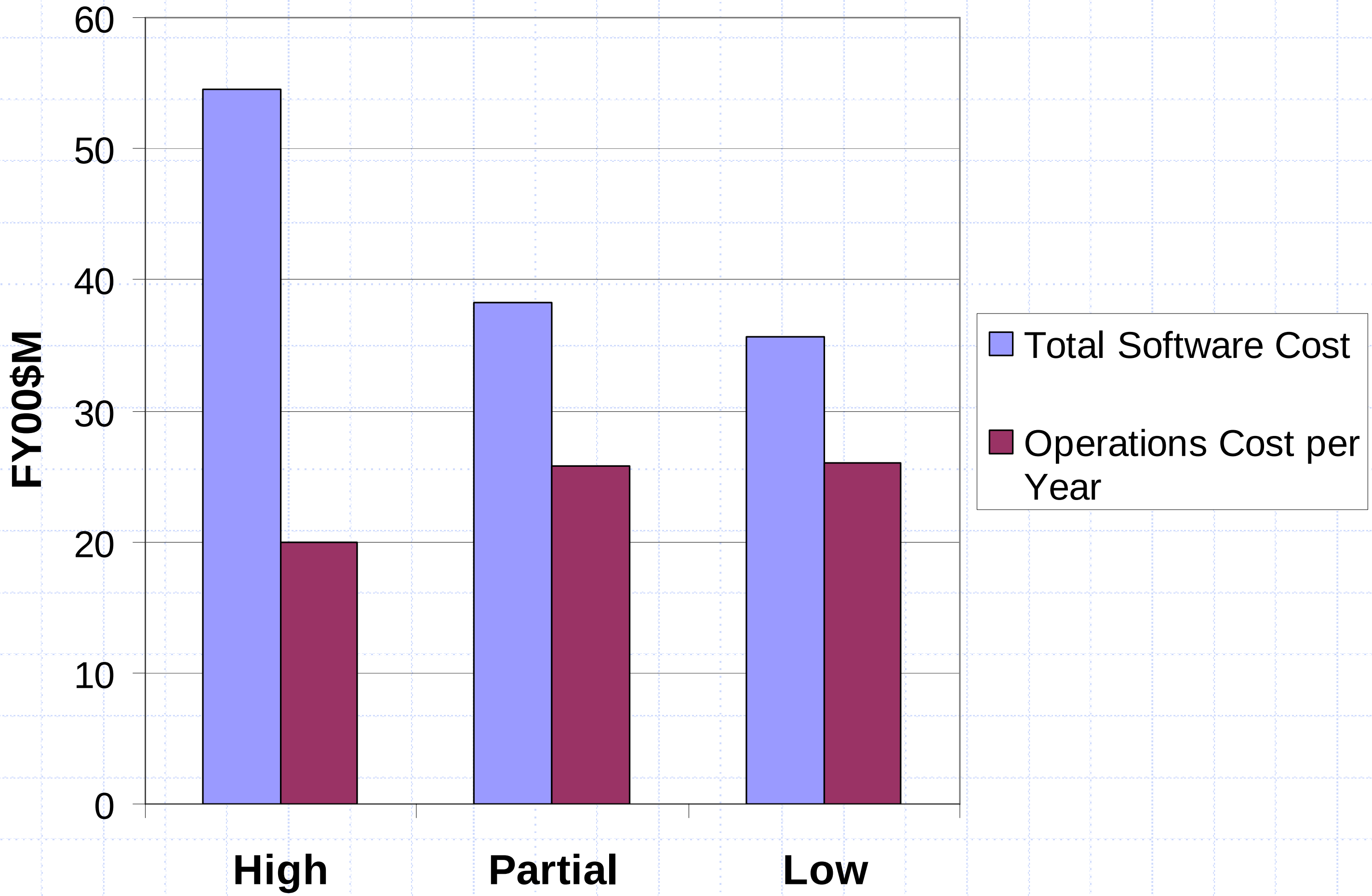
Software Cost

- Partial autonomy with C as the programming language was chosen to meet IOC cost cap



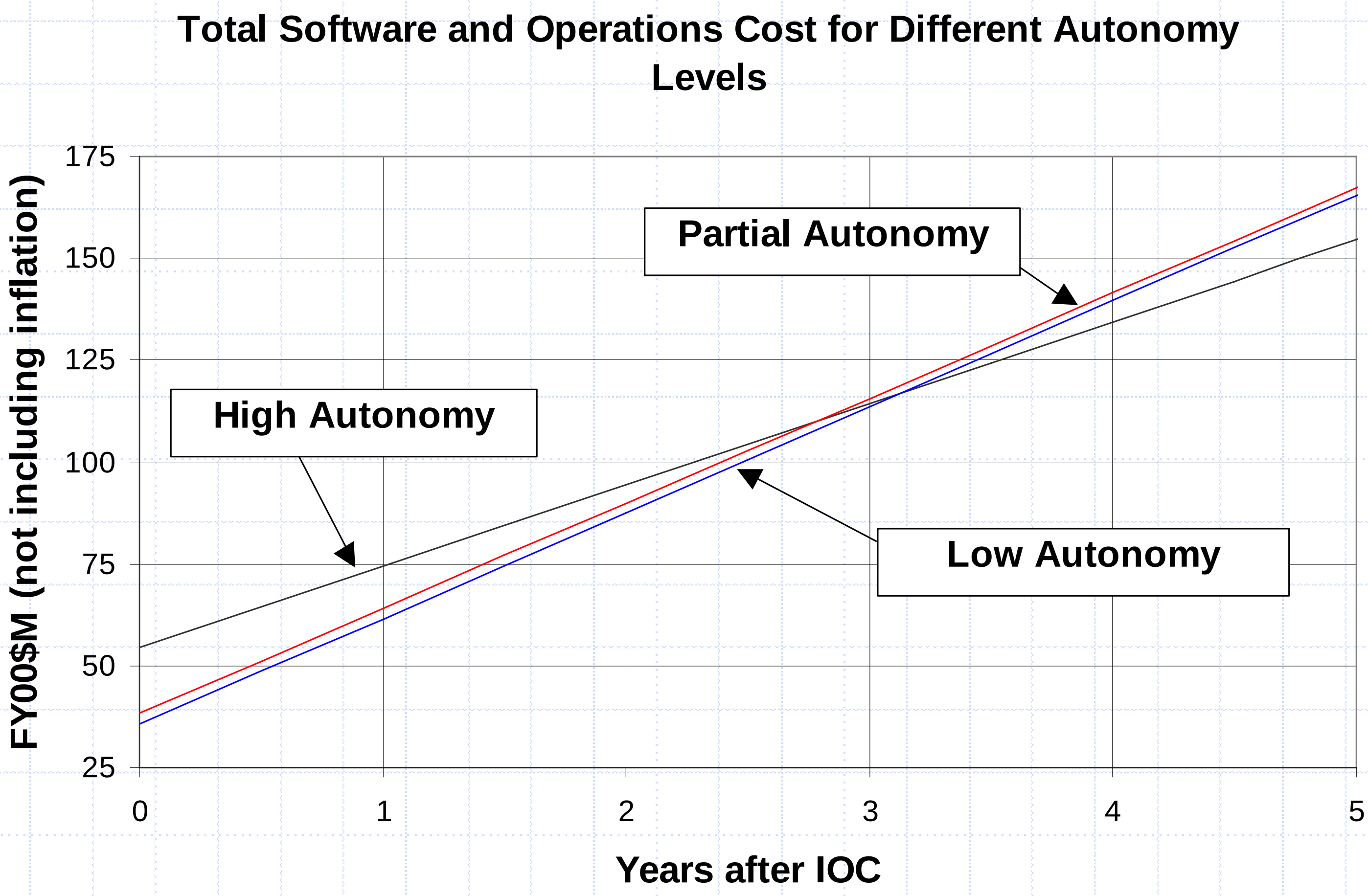
Autonomy vs. Operations Cost

- Autonomy reduces the yearly operations cost



Autonomy vs. Operations Cost

- High autonomy is cheaper in the long run



Detailed Design:
Bus Analysis

Bus Requirements

- M008 MINERVA shall have a design lifetime of at least 6 years.
- S002 Each spacecraft shall have power to support nominal operations of the spacecraft at all times, including eclipse periods.
- S003 Each spacecraft mass shall not exceed 575 kg.
- S011 Each spacecraft shall have the capability to boost to a disposal orbit.
- B001 ADCS subsystem shall maintain pointing accuracy of 0.1 degree.

Bus Requirements

- B002 ADCS shall provide orbit station keeping.
- B003 Thermal subsystem shall maintain spacecraft components within their operating temperature ranges.
- B004 Power subsystem shall provide 200 W of power during transit.
- B005 Power subsystem shall provide 400 W of power throughout the operational lifetime in Mars orbit.
- B006 Power subsystem shall provide 400 W-hr of energy storage.

Bus Requirements (cont.)

- B007 Propulsion subsystem shall provide at least 2400 m/s ΔV (total).
- B008 Propulsion subsystem shall provide sufficient ΔV for disposal.
- B009 Spacecraft structure shall survive launch environment for a Delta III.
- B010 Spacecraft structure shall survive radiation environment for the duration of the mission lifetime.

Bus Group Design

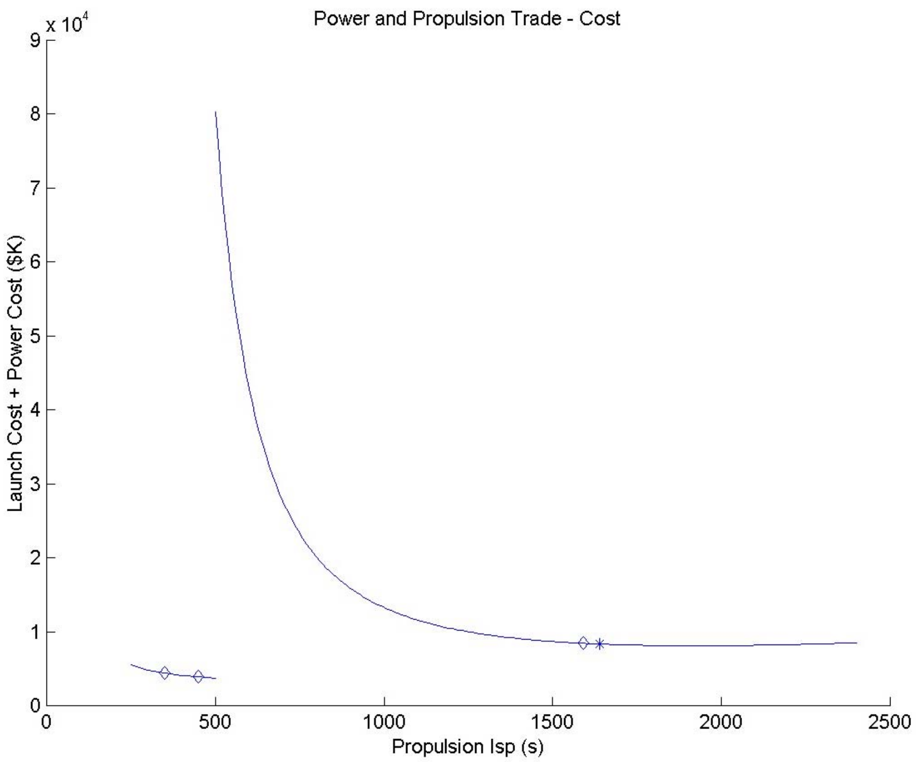
- MATLAB software model used to perform design trades
- Inputs
  - Payload characteristics
  - Orbit parameters
  - Mission requirements
- Outputs
  - Spacecraft budgets
  - Spacecraft cost

ADCS Sub-System Design

- Directed antenna requires 3-axis pointing stabilization
  - Gravity gradient/spin stabilized could not meet minimum requirements
- Sensors
  - Sun
  - Horizon
  - Gyros (safe mode)
  - Accelerometers
- Controllers
  - Reaction wheels
  - Thrusters

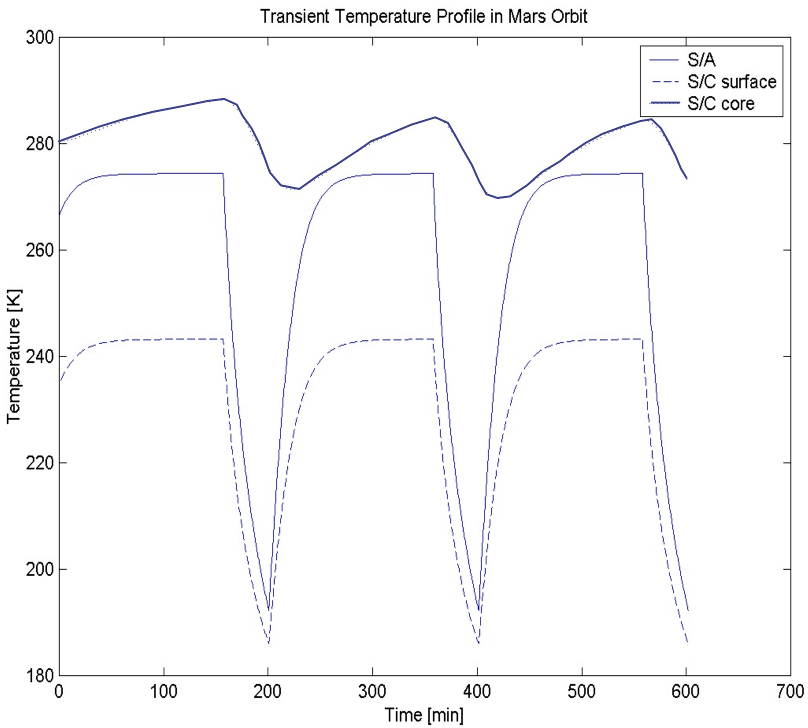
Propulsion Sub-System Design

- Launch decision allows Mars transfer ΔV to be done by launch vehicle
- Minimize cost - choose between EP, chemical propulsion
- NTO/MMH propellant
  - I_{sp} = 322.5 sec
  - Thrust = 4250 N



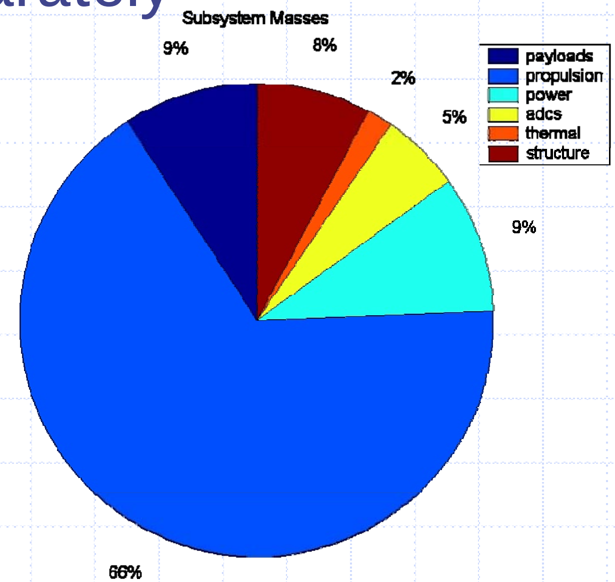
Thermal/Power Sub-System Design

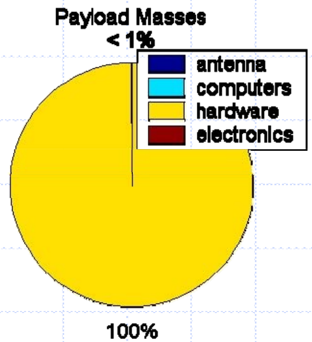
- Thermal module calculates the power needed to maintain thermal management
- Power module calculates solar array area/mass based on EOL
  - Solar Array Flight Experiment
- Batteries sized for mission life, eclipse period
  - Lithium-ion batteries

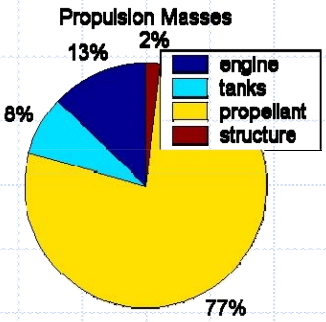


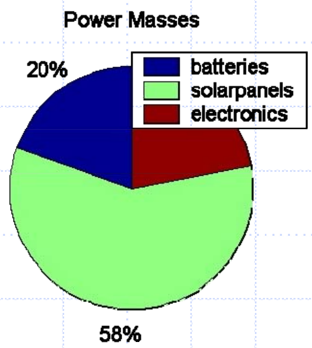
Structure Sub-System Design

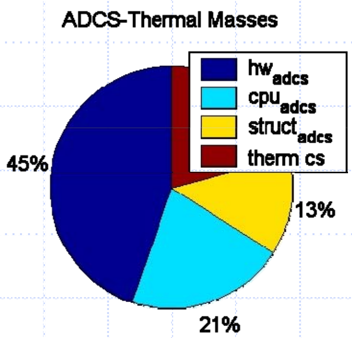
- 15% mass margin
- 20% structure mass factor
  - Power uses 30%
- Payload mass calculated separately











Spacecraft Bus Design

System Component	Number	Mass	Total Mass	Total Power	Critical Dim
Payload	**1**	37	**37**	**190**	Ant Diam = 2m
ADCS			**30.7**	**39.0**	
Sun sensor	6	1.2	7.0	0.8	
Horizon Sensor	4	0.7	2.8	5.0	
Gyroscope	2	0.7	1.3	10.0	
Accelerometer	2	0.1	0.2	1.2	
Reaction Wheel	4	3.8	15.0	22.0	
Structure	-	4.4	4.4	-	
Propulsion			**273.8**	**25.0**	
Propellant	-	177.4	211.8	-	
Main Engine	1	4.5	4.5	15.0	
ACS Engine	12	0.5	6.0	-	
Propellant Tank	2	10.6	21.2	-	Diameter = 0.6m
Blow dow n System	1	20.0	20.0	-	
Feed System	-	5.0	5.0	10.0	
Structure	-	4.4	5.3	-	
Thermal			**7.0**	**11.6**	
Heater	-	2.3	2.3	11.6	
Radiator	-	2.3	2.3	-	
Insulator	-	2.3	2.3	-	
Power			**50.1**	**418.0**	
Solar Arrays	2	11.0	22.0	418.0	Area = 4.00 m^2
Electronics	-	8.3	8.3	-	
Batteries	6	1.2	7.4	393 W-hrs	
Wiring	-	1.0	1.0	-	
Structure	-	11.3	11.3	-	
Launch Structure	-	10.5	**10.5**	-	
		Total Mass:	409		
		w / margin	**470**		

Launch Vehicle Fit-Check

- Four satellites fit in Delta-III fairing with 3 cm minimal clearance
- Bottom satellite mounts to launch vehicle adapter structure
- Satellite attachment rings part of satellite structure
  - Pyro-bolts lock rings together
  - Springs separate spacecraft after rings unlock

Stowed Satellite

- Stowed volume ~ 4 m^3

Spacecraft: Nadir Pointing Side

- Helix antenna
- Horizon sensors
- Primary sun sensors
- Sun-nadir steering maintains Mars-Earth-Sun pointing
  - Steerable main antenna
  - Steerable solar arrays

Satellite: Internal Components

- First iteration of ADCS and electronics layout
- Propellant tanks shown:
  - NTO/MMH
  - He pressure regulation
- Lithium/Ion batteries
  - 2 are redundant
  - Hidden in diagram
- Harnessing and plumbing not modeled

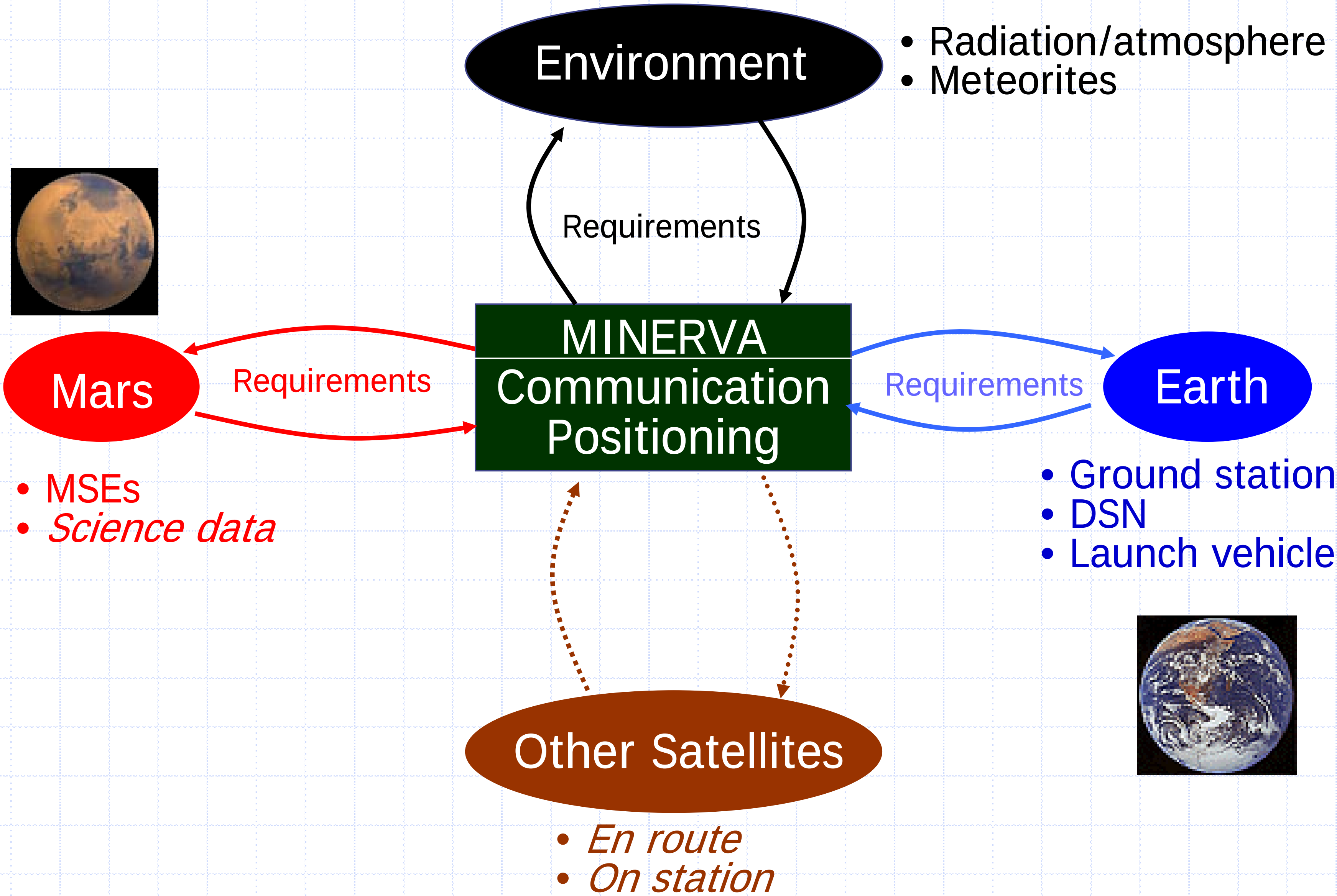
Image removed due to copyright restrictions.

Detailed Design: Operations Analysis

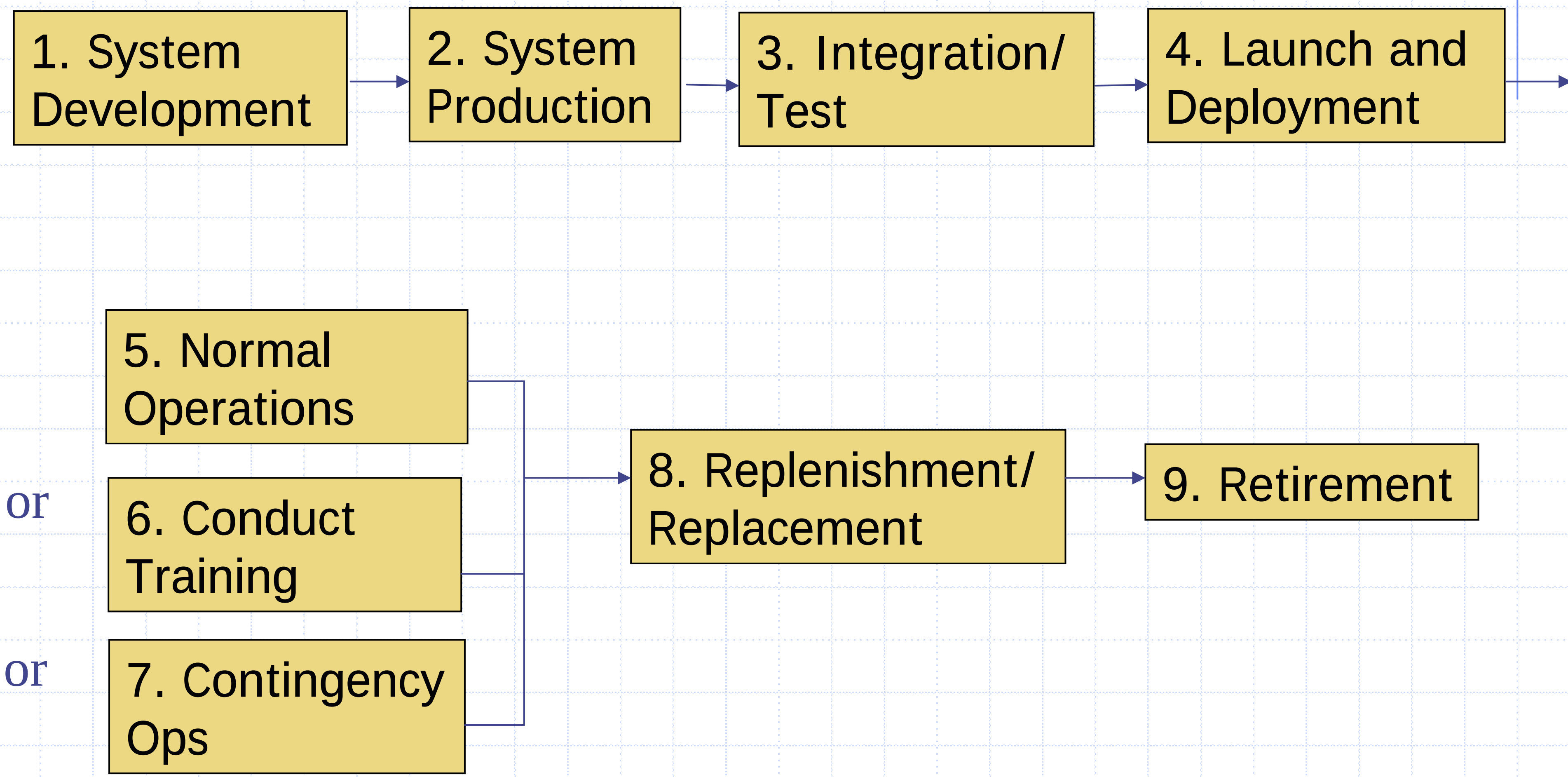
Operations Requirements

- Z002 System shall have an operational lifetime of at least 5 years.
- M006 At IOC the system shall be able to support at least 10 MSEs simultaneously.
- S005 Constellation shall have at least 90% probability of meeting the minimum requirements throughout its operational lifetime.
- S010 Each spacecraft shall have at least one recoverable safe mode.

Operations: System Context



Operations: Functional Analysis



Operations: Functional Analysis

- Earth Uplink
  - Data collection/processing at EGS
  - Segments are time/destination tagged
- Mars Uplink
  - MINERVA initiates communication per instructions
- Positioning Loop
  - MINERVA initiates positioning
  - On-board calculation with EGS updates
- Anomaly Resolution
  - Three Safe Modes, Tiger Team crisis resolution

System Reliability: Safe Modes

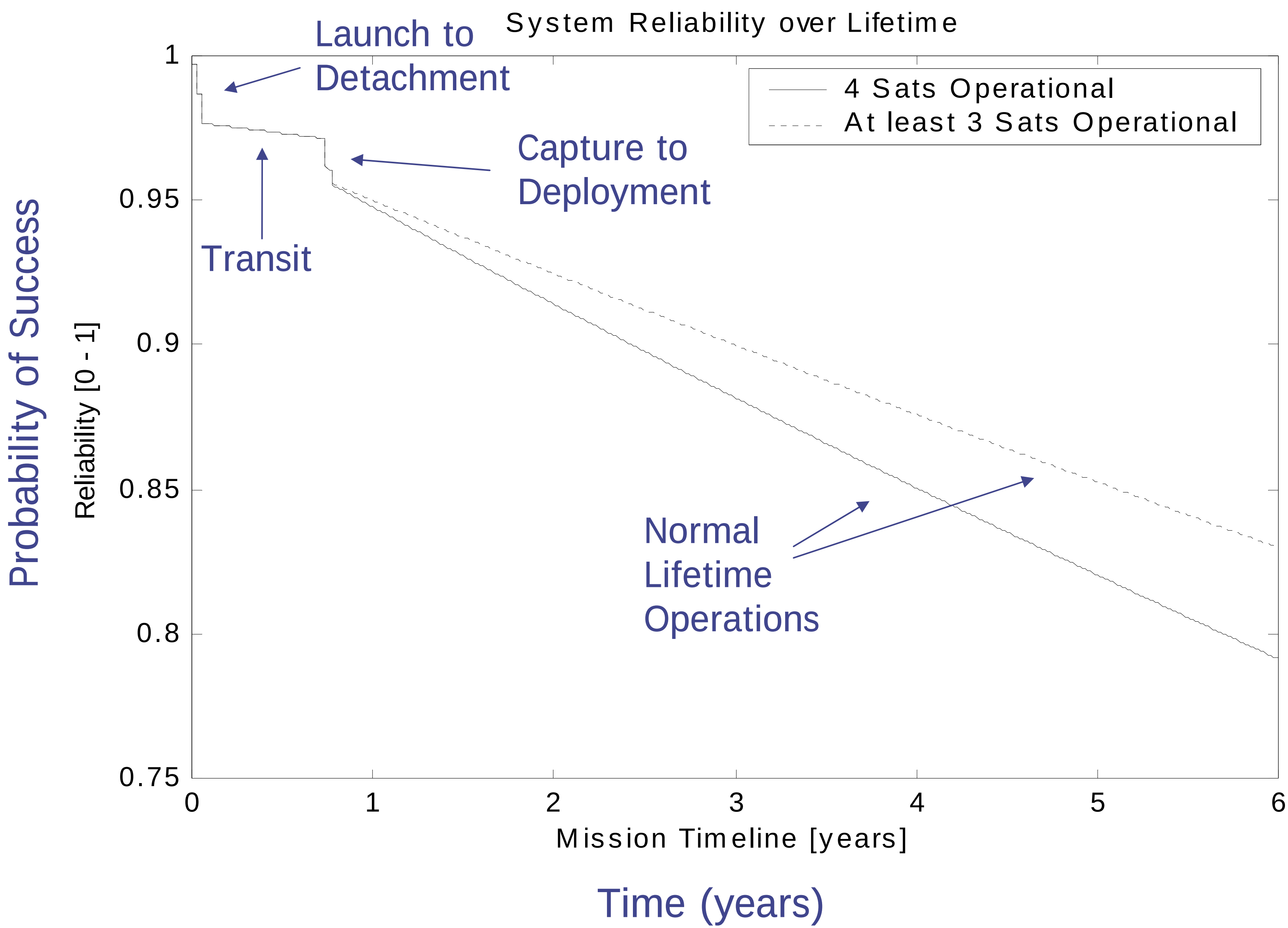
- Progressive levels of ops reduction
- Graceful degradation of spacecraft and availability

- **Safe Mode 1**: Anomaly flags or checkouts not ok, maintain high availability
- **Safe Mode 2**: Non-critical power or mechanical failures, EGS notification
- **Safe Mode 3**: Critical failure, spacecraft shutdown, 14 hour self-reliance window

System Reliability: Failure Tree

- Examination of critical failures
  - Result from lower level faults
  - Multi-path vs. complete redundancy
- Setup Phase
  - Binary: Launch, separation, transit
  - Partial: Detachment, deployment, capture
- Normal Operations Phase
  - No failure
  - External: Environment, interactions
  - Internal: Operators, software, hardware

System Reliability: Event Analysis

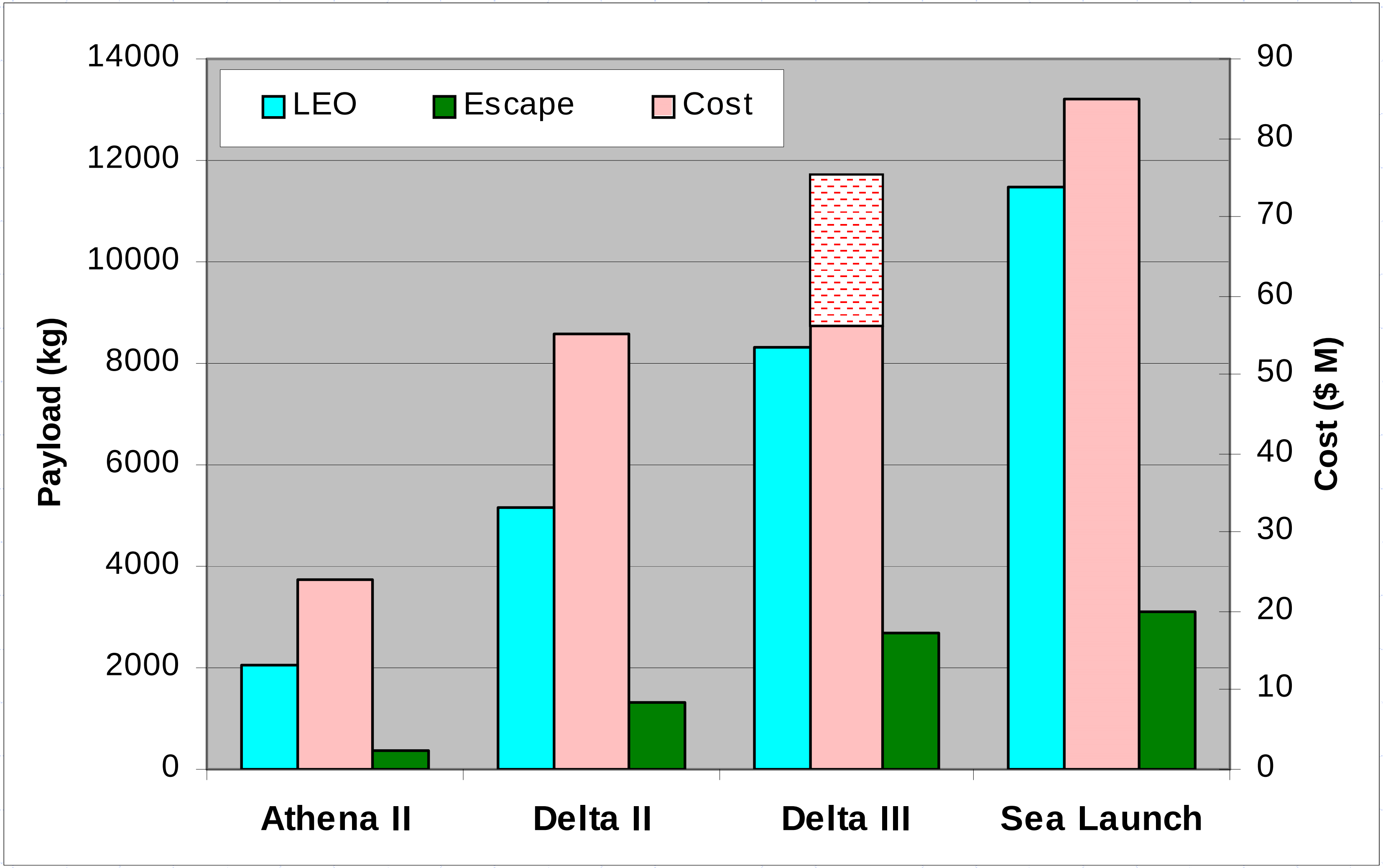


Detailed Design: Launch Analysis

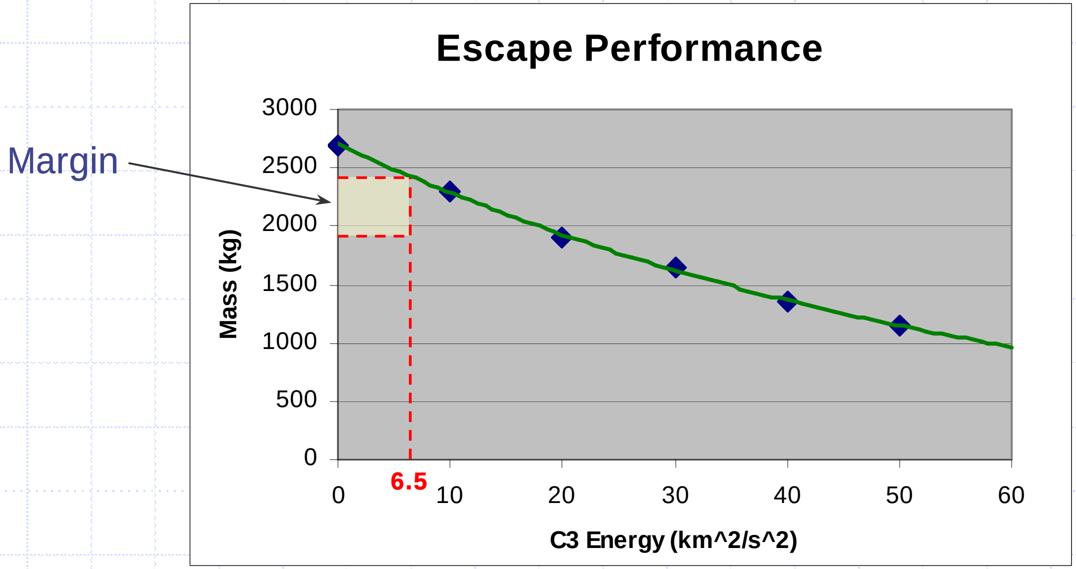
Launch Requirements

- Z001 System shall achieve initial operational capability by 2010.
- M007 Total system mass and supporting launch structure shall be no greater than what can be launched on a single launch vehicle to a Mars transfer orbit.
- S009 Launch vehicle shall be able to boost entire constellation mass to a Mars transfer orbit with a C3 energy of 6.46 km^2/s^2.

Launch Vehicle Trades



Launch Vehicle Performance



- The Delta III can provide more C3 energy than is needed for transfer
- Additional capability will be used to change the inclination of the parking orbit to 23.45°

Detailed Design:
Cost Analysis

Cost Requirements

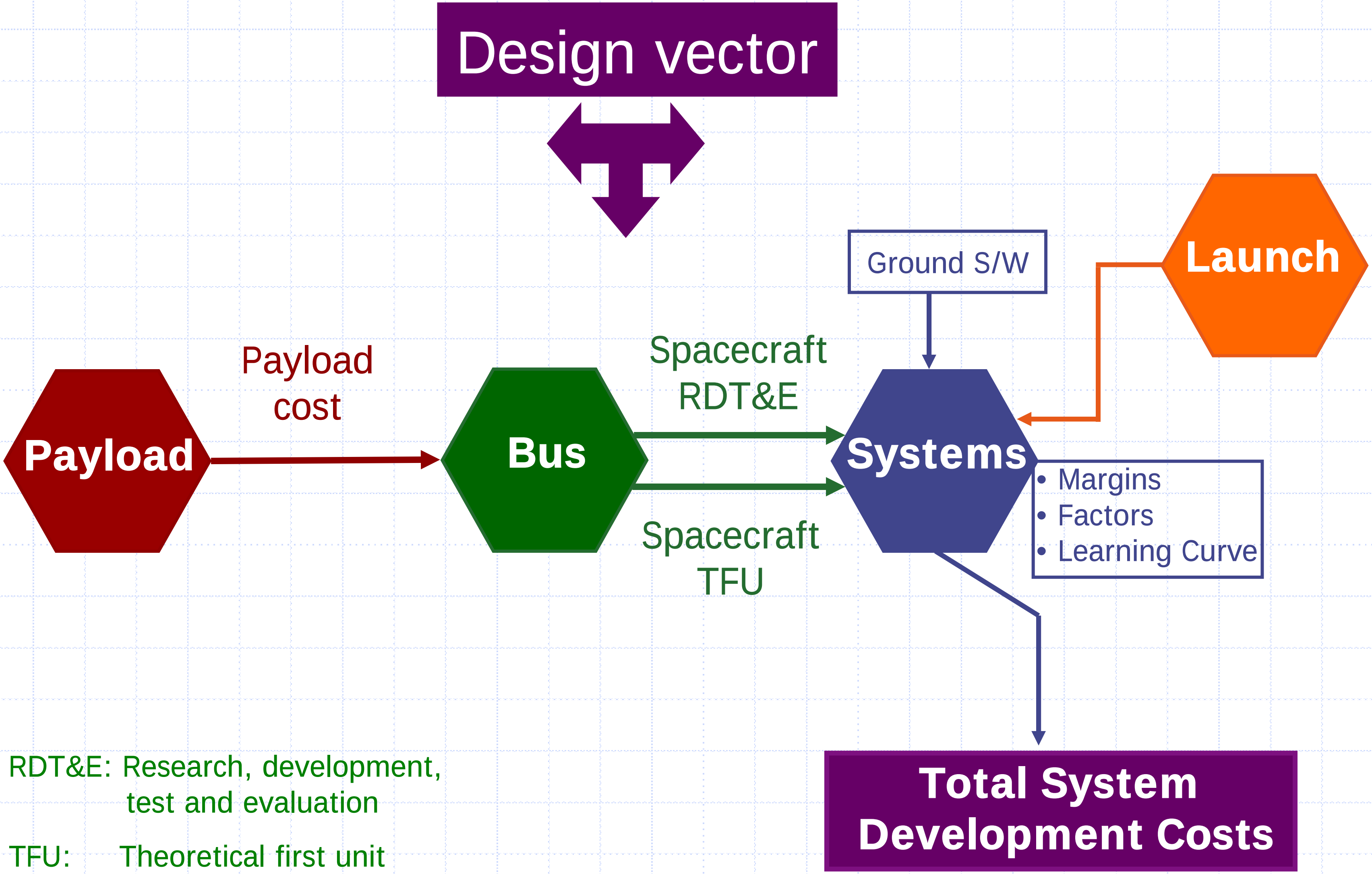
- Z003 At IOC the expenditures in FY2000 dollars shall be less than $300 million.

Cost Methodology

- Concurrent engineering sessions calculated total program cost for each design iteration
- Spacecraft development (10% profit, 15% margin)
  - Design-based cost estimating relationships (CERs)*
  - Limitation: Accuracy of CER methodology
- Ground station development (10% profit, 15% margin)
  - Ground software x 1.5 (equipment, management, etc.)
  - Assumption: JPL to provide space, equipment to minimize costs
- Launch
  - Delta III launch vehicle
  - Assumption: Reduction in Delta III costs with EELV-related efficiencies and market pressures
- Transit and on-orbit operations are not included

*Applied cost factor of 1.25 (addresses uncertainty in methodology)

Cost and Concurrent Engineering



RDT&E: Research, development, test and evaluation

TFU: Theoretical first unit

Major Cost Trades

- Level of spacecraft autonomy
  - Problem: Spacecraft autonomy drives software costs
  - Trade space
    - Highly autonomous spacecraft functions
    - Minimal spacecraft autonomy (on-board position fix or earth position fix)
  - Decision: Minimal autonomy (on-board position fix)
- Spacecraft propulsion
  - Problem: Determine most cost-effective propulsion system
  - Trade space: Electrical versus chemical propulsion
  - Decision: Chemical propulsion is more cost effective given launch vehicle ability to inject into Mars transfer

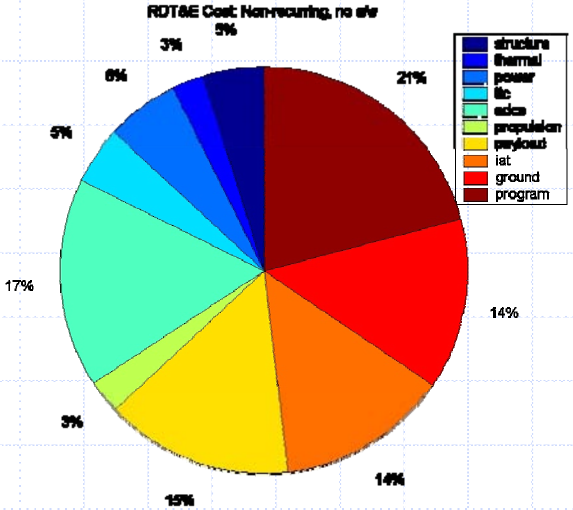
Design Freeze Down-Select

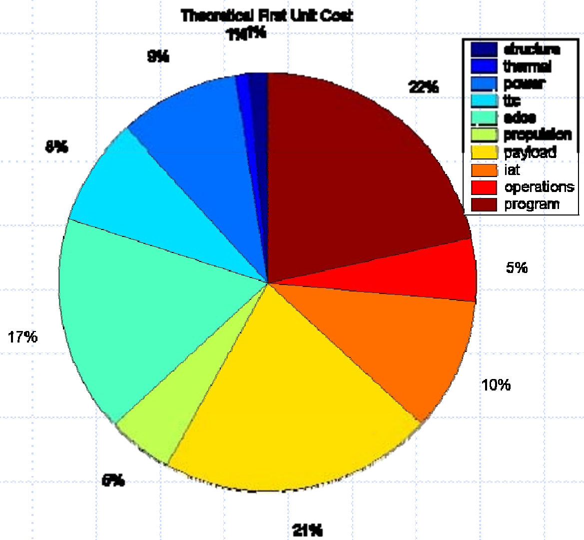
	# of S/C	Prop System	Launch Vehicle	Cost ($M)	Margin* (.15)	Total ($M)
Option 1	4	EP	Delta III	279.1	33.3	**312.3**
Option 2	**4**	**Chem**	**Delta III**	**266.4**	**31.5**	**297.9**
Option 3	3*	EP	Delta III	261.2	29.8	**290.9**
Option 4	3*	Chem	Delta II	244.0	28.2	**272.2**

* Does not meet all performance requirements (coverage, Gb/sol)
* On spacecraft and ground station development costs. No margin on launch costs.

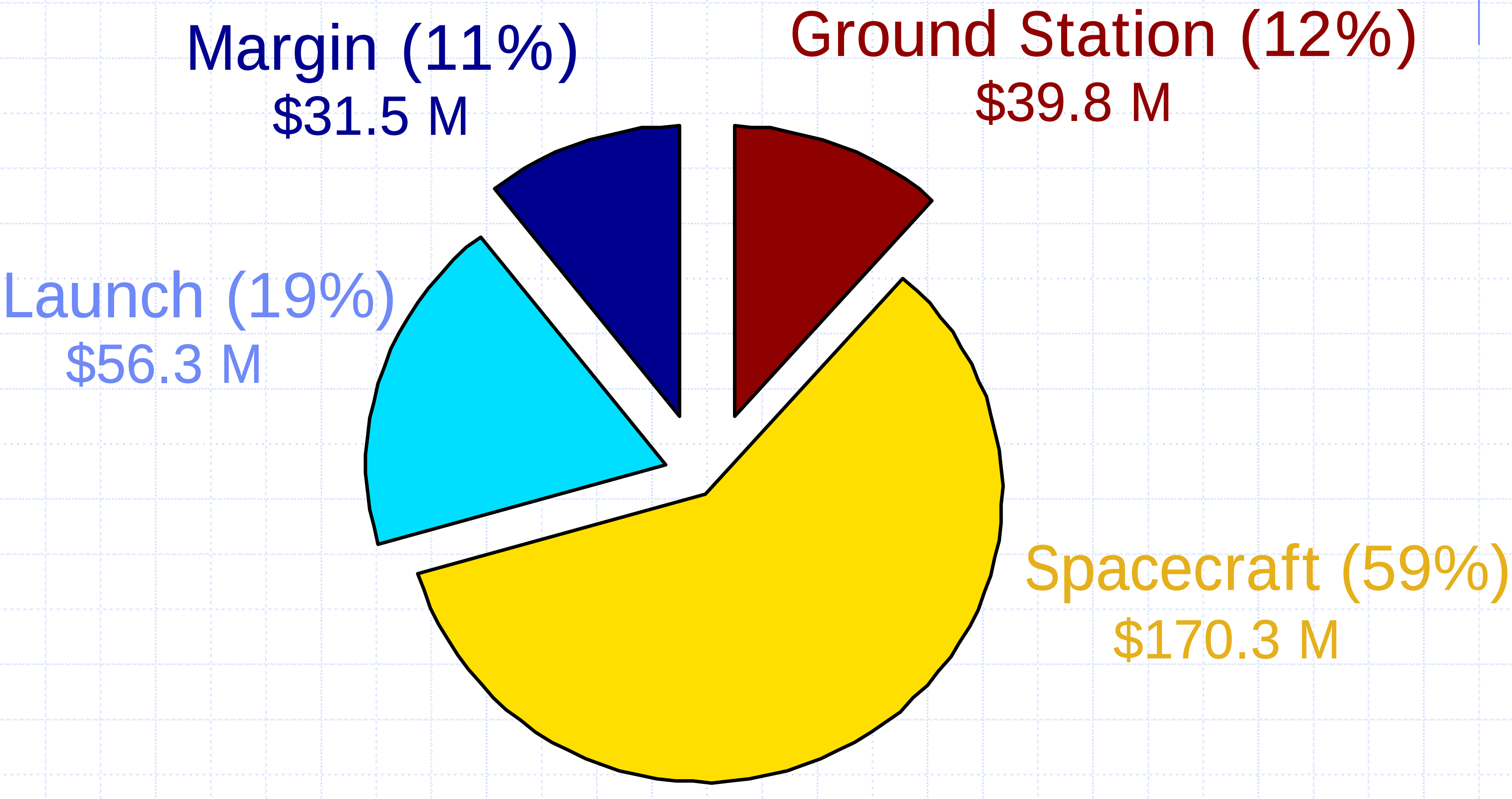
Spacecraft Cost Model

- CERs from SMAD
  - Assumes deep space and Earth orbiting systems
  - Accuracy to within 25-50%
- Calculate RDT&E, TFU cost separately
- TFU cost scales with number of spacecraft according to learning curve



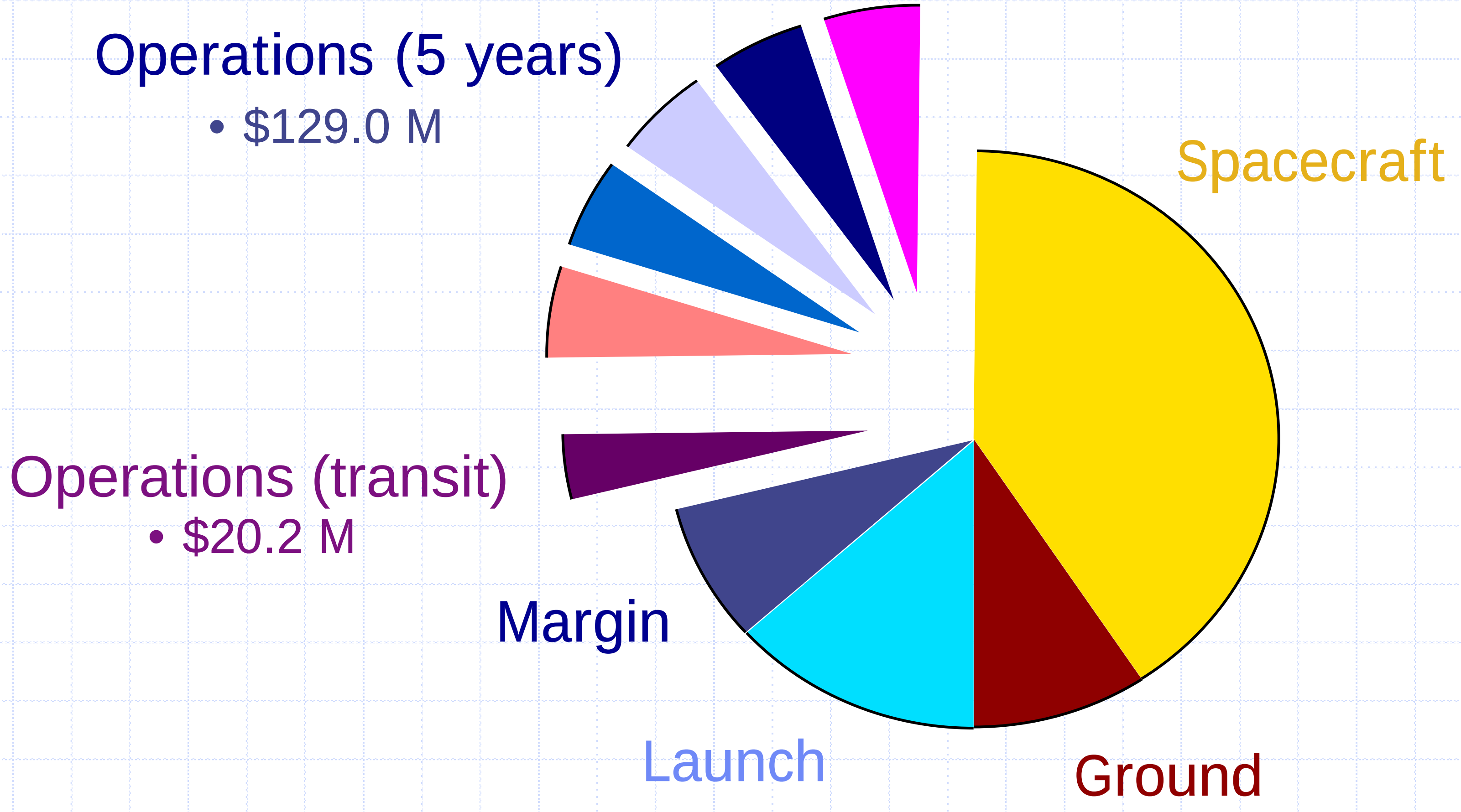


Major Elements of Cost



Life Cycle Costs

- Total Life Cycle Cost (5 year mission): **$447.1 M**



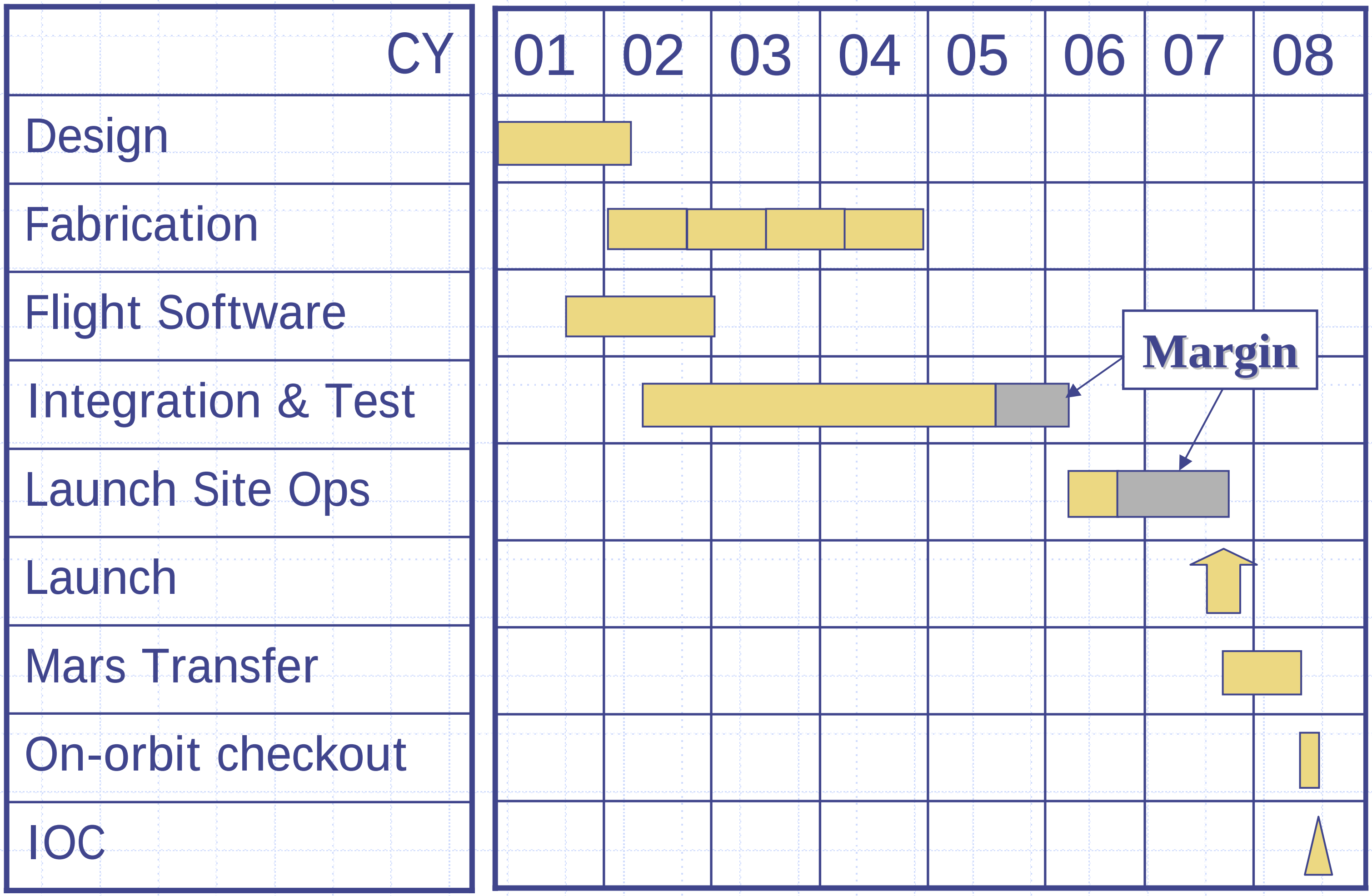
System Level Issues

System-Level Risk Management Strategy

- Cost Risk (Medium)
  - Source: CER methodology; software & launch costs
  - Strategy: Apply cost factor (1.25) and hold margin (15%)
- Technical Risk (Low – Medium)
  - Source: Mission integration, software development, cross-links
  - Strategy: Maximize use of proven hardware and software
- Schedule Risk (Low)
  - Source: Complexity of deep space program
  - Strategy: Hold margin before 2007 launch window

Maintain low risk through cost and schedule management and reliance on existing technology

Program Schedule



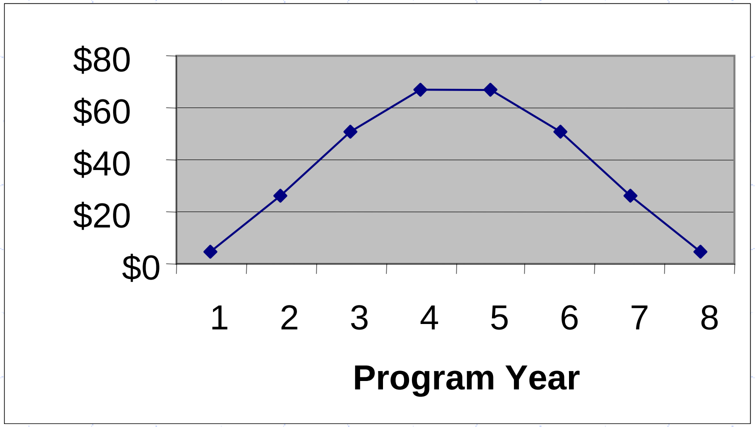
Funding Profile

Total Program Cost: $297.9 M*

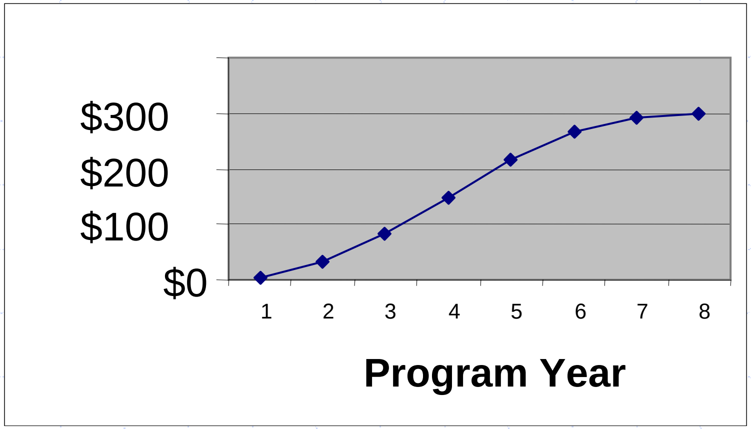
(CY00 $M)

Program Yr	1	2	3	4	5	6	7	8
Calendar Yr	2001	2002	2003	2004	2005	2006	2007	2008
Funding	4.8	26.1	51.1	67.0	67.0	51.1	26.1	4.8

Profile



Cumulative



*Includes 15% margin (Note: CER methodology limits validity of cost estimate)

MINERVA Science Capabilities

- Improve Mars gravity field model
  - Indirect gravitational study of Phobos and Deimos
- Atmospheric composition of Mars
  - Absorption and scattering properties of Martian atmosphere
- Radio science
  - Study solar corona and interplanetary medium

Post-IOC System Expandability

- Upload software with improved autonomy
- Provide positioning and communication service to other spacecraft
- Relay between MSEs without Earth interaction
- Automate ground operations
- Add more spacecraft to constellation
  - Improve coverage, availability, and reliability
  - Include upgraded capabilities (e.g. remote sensing)
- Replenish constellation as spacecraft fail

Lessons Learned

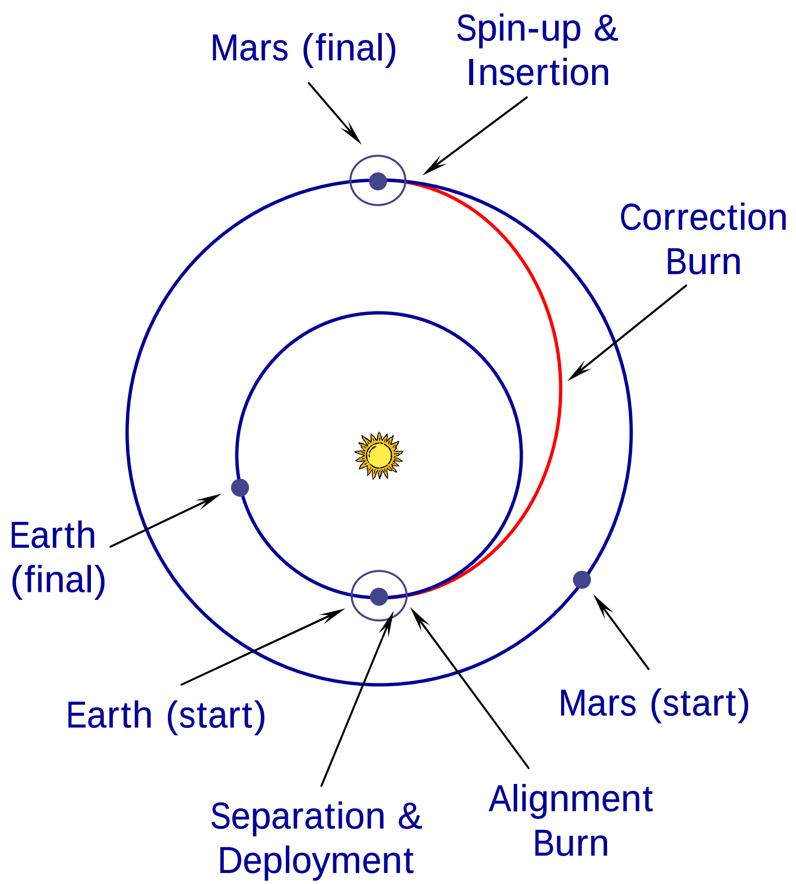
- Methods for discovery of errors and disconnects
  - Usefulness of frequent integration meetings and status briefings
  - Evaluation of concurrent engineering session results
- Transitions
  - Team structure changed after TARR, delaying some tasks
  - Post-PDR transition much more rapid, effective
- Concurrent engineering
  - Useful for rapid characterization of design options via real-time inter-team communication
  - Must be supplemented with detailed design analysis between sessions
  - ICEMaker is useful interfacing tool
  - More automation would speed process

Backup Slides

Backup Slides: Orbit Analysis

Transit Overview

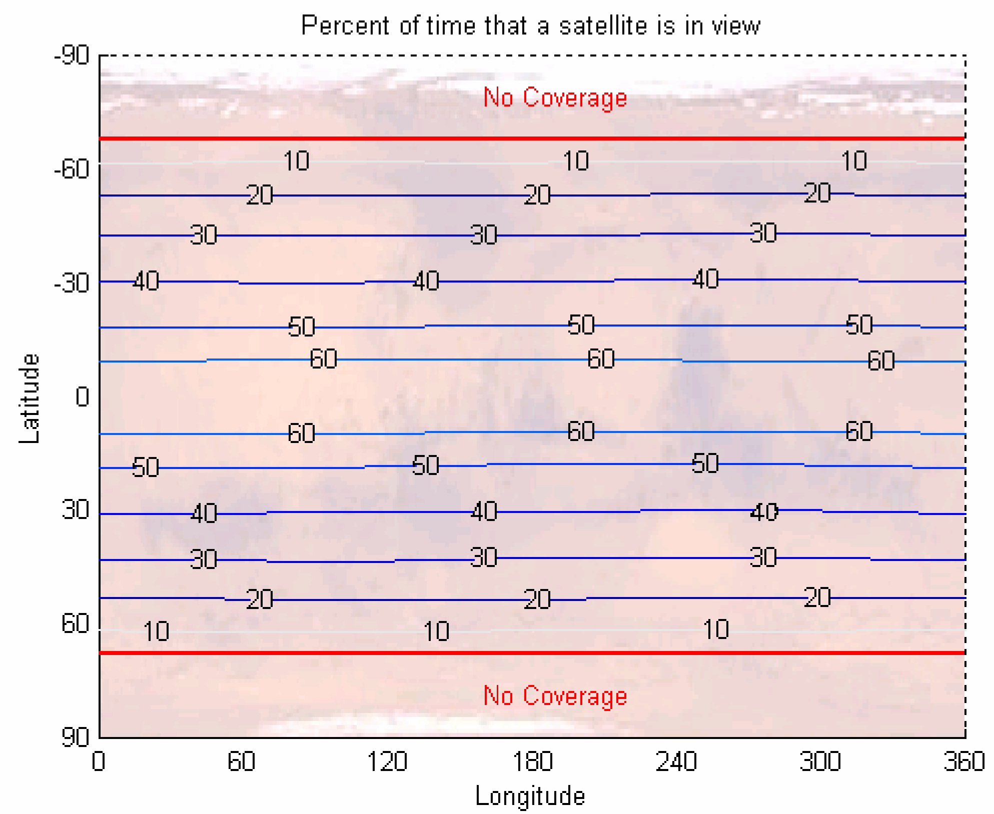
Departure burn	18 Aug 07, 09:56
Separation	18 Aug 07, 13:25
Deploy arrays	18 Aug 07, 13:31
Initial checkout	18 Aug 07, 14:00
Exit Earth SOI	21 Aug 07, 02:35
Arrive Mars SOI	29 May 08, 10:56
Circularization	03 Jun 08, 18:18
Deploy antenna	03 Jun 08, 18:20
Test/calibration	09 Jun 08, 22:20
IOC	10 Jul 08, 00:00



Percentage of Time in View

Single Satellite Failure

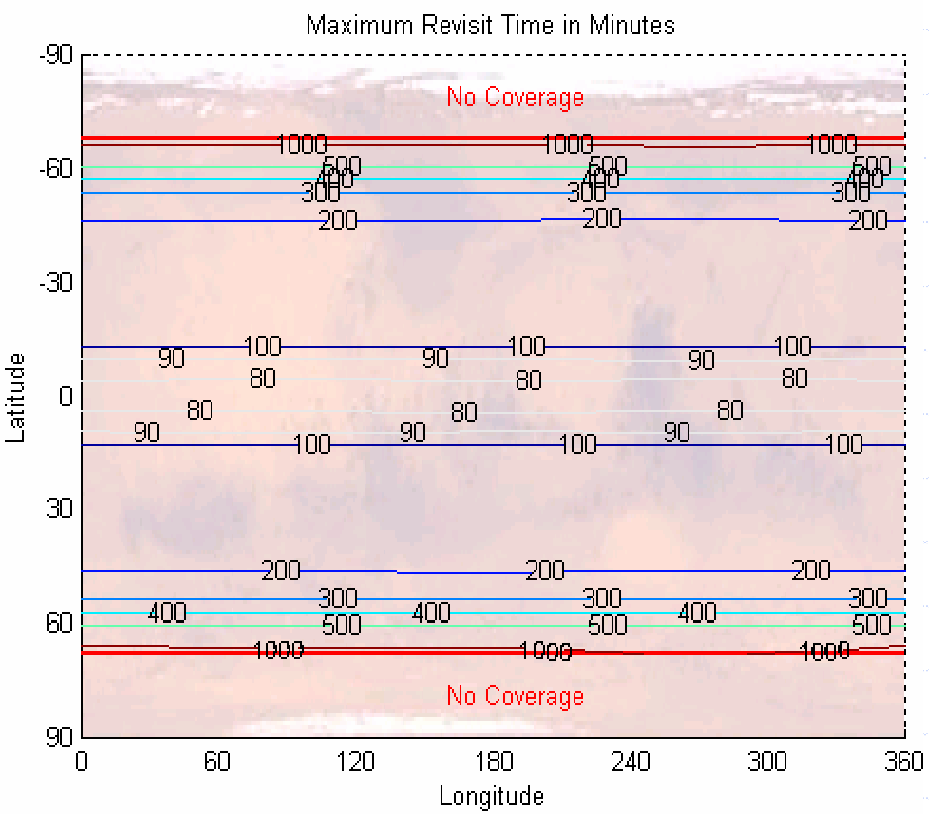
- Constellation provides >50% coverage in the $\pm 15^0$ latitude band
- Reduced coverage up to $\pm 65^0$

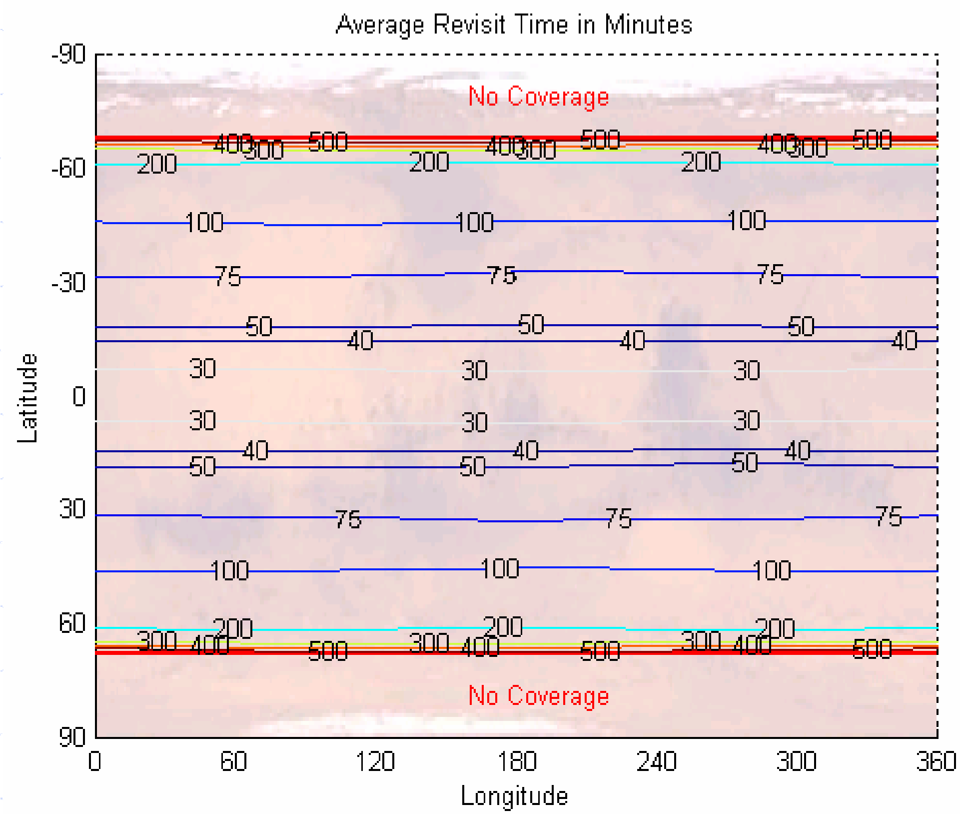


Revisit Time

Single Satellite Failure

- The maximum time between satellite passes is <100 min
- The average time is <45 min

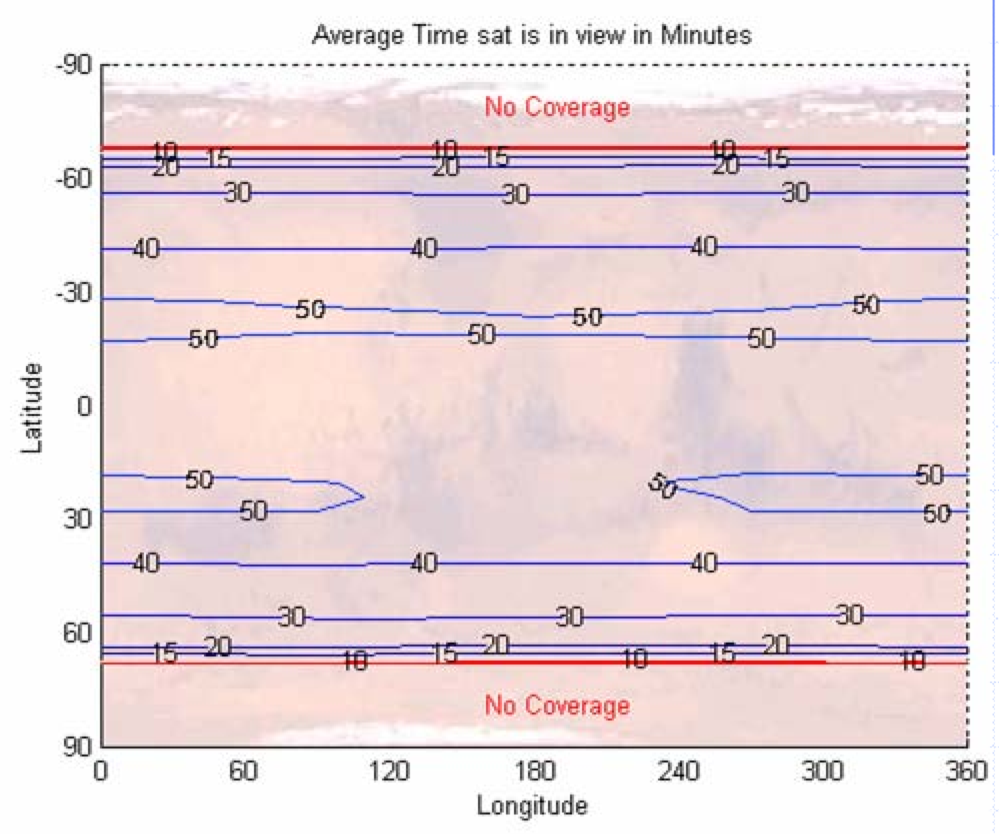




Contact Duration

Single Satellite Failure

- On average, a satellite will remain in view for 50 minutes.



Backup Slides: Payload Analysis

Link Margins

- Earth - MINERVA link:
  - Uplink: 28.8 dB, downlink: 3.09 dB
- MINERVA - Mars link:
  - Uplink: 5.29 dB, downlink: 4.73 dB
- MINERVA cross-link:
  - Uplink and Downlink: 17.4 dB
- MINERVA cross-link with Ka-band for DTE link:
  - Uplink: 16.65 dB, downlink: 2.97 dB
- MINERVA cross-link with omni-directional antenna for case of the loss of attitude control:
  - Uplink and Downlink: 12.4 dB

Communications Analysis: Worst Case

- Two MSEs on the dark side of Mars.
- Each of the MSEs is at the edge of the cone of MINERVA-Mars link.
- Each MSE has no more than 10W RF power.
- Largest distance between Earth and Mars is equal to 401,300,000 km.
- Maximum distance between MINERVA satellites is equal to 7,633 km.

Payload Electronics Hardware

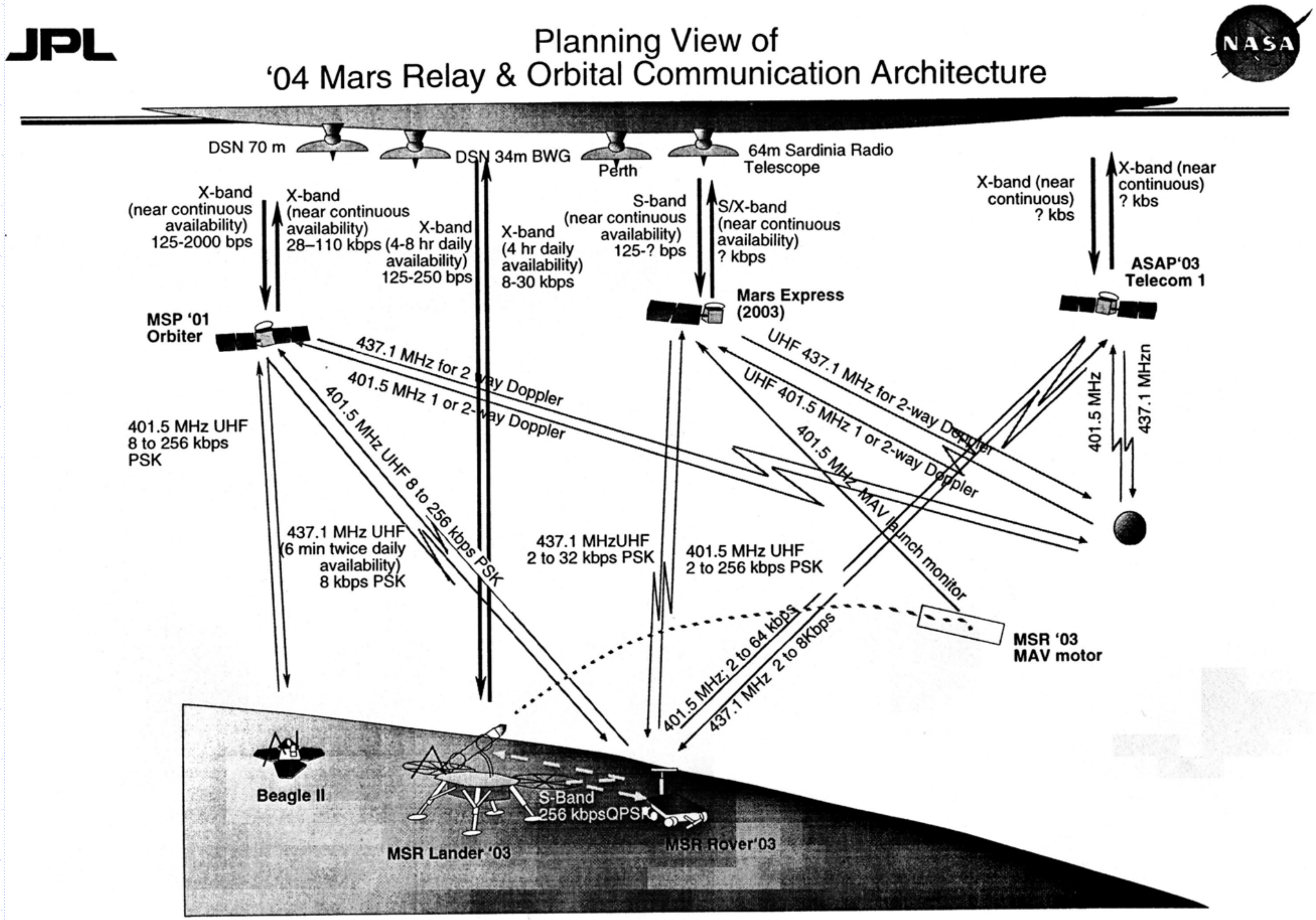
- 3 amplifiers (total output power ≈165 W)
- 2 Ka-band and X-band supporting transponders
- 2 computers
- 1 UHF transceiver
- One ultra-stable oscillator

One failure of a critical component
(amplifier, transponder, computer)

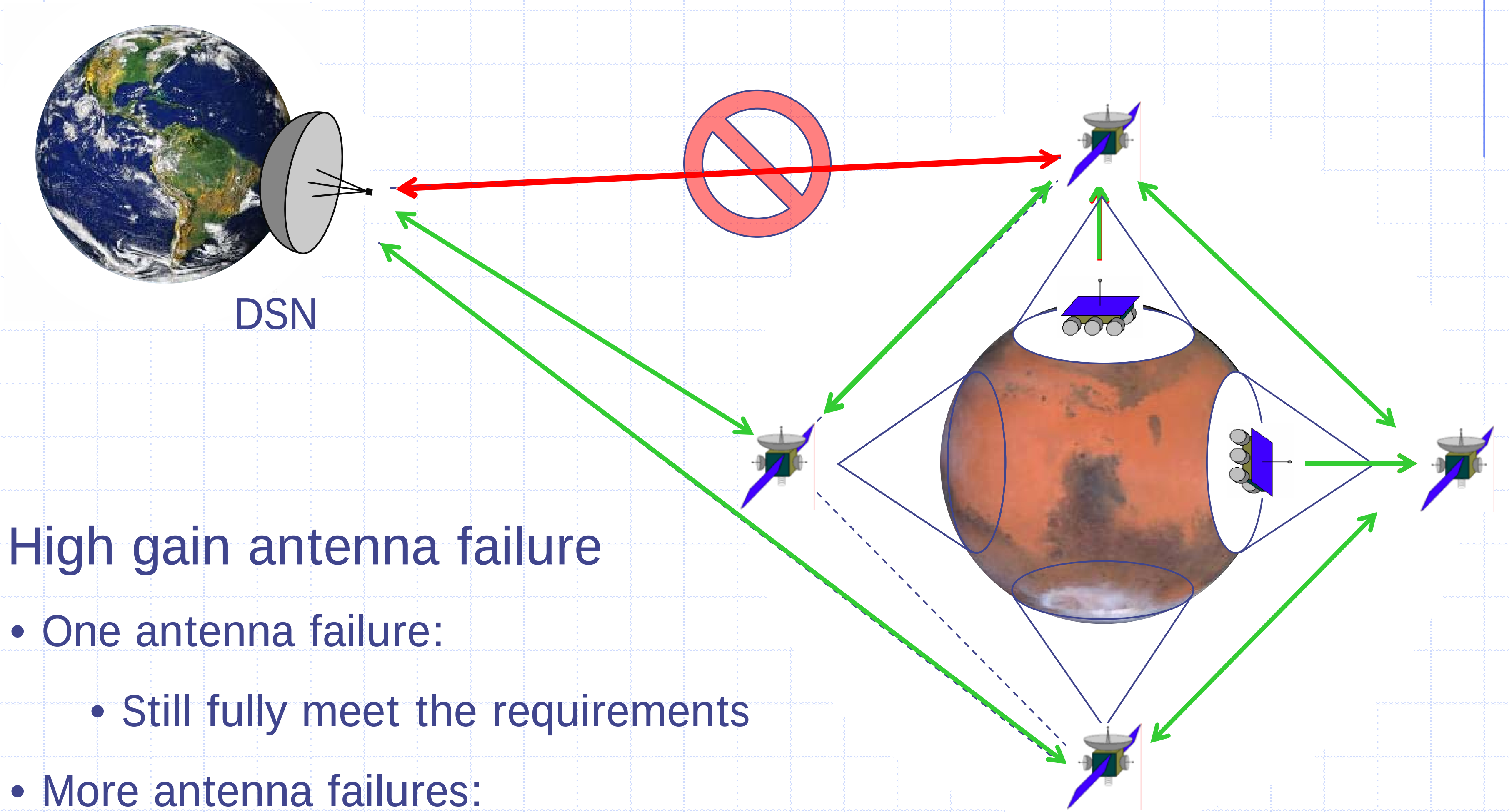
$\neq$

loss of the satellite

Frequency Used For Future Mars Missions (from Chad Edwards speech)



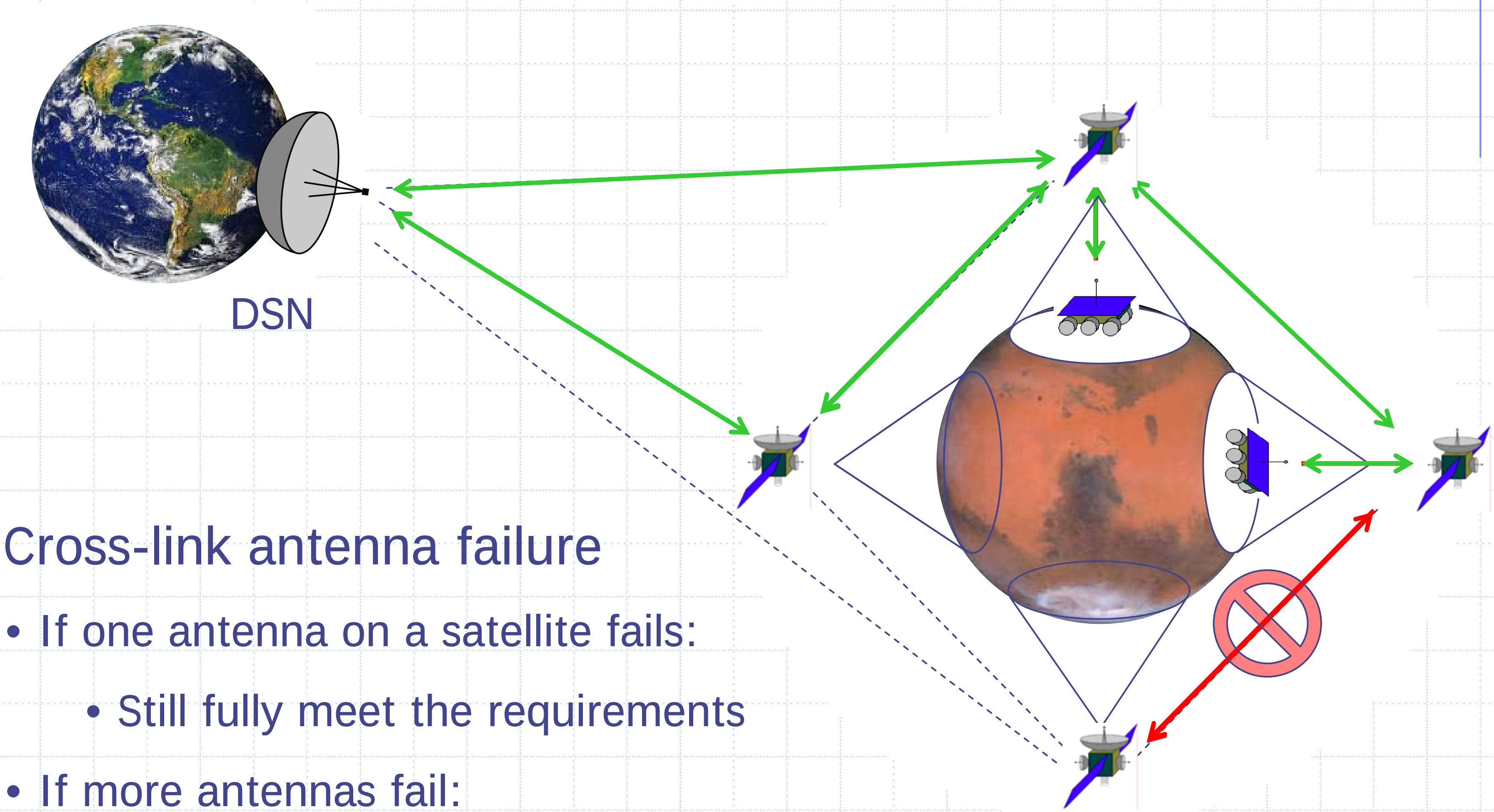
Failure Mode Analysis



High gain antenna failure

- One antenna failure:
  - Still fully meet the requirements
- More antenna failures:
  - Graceful degradation of performance

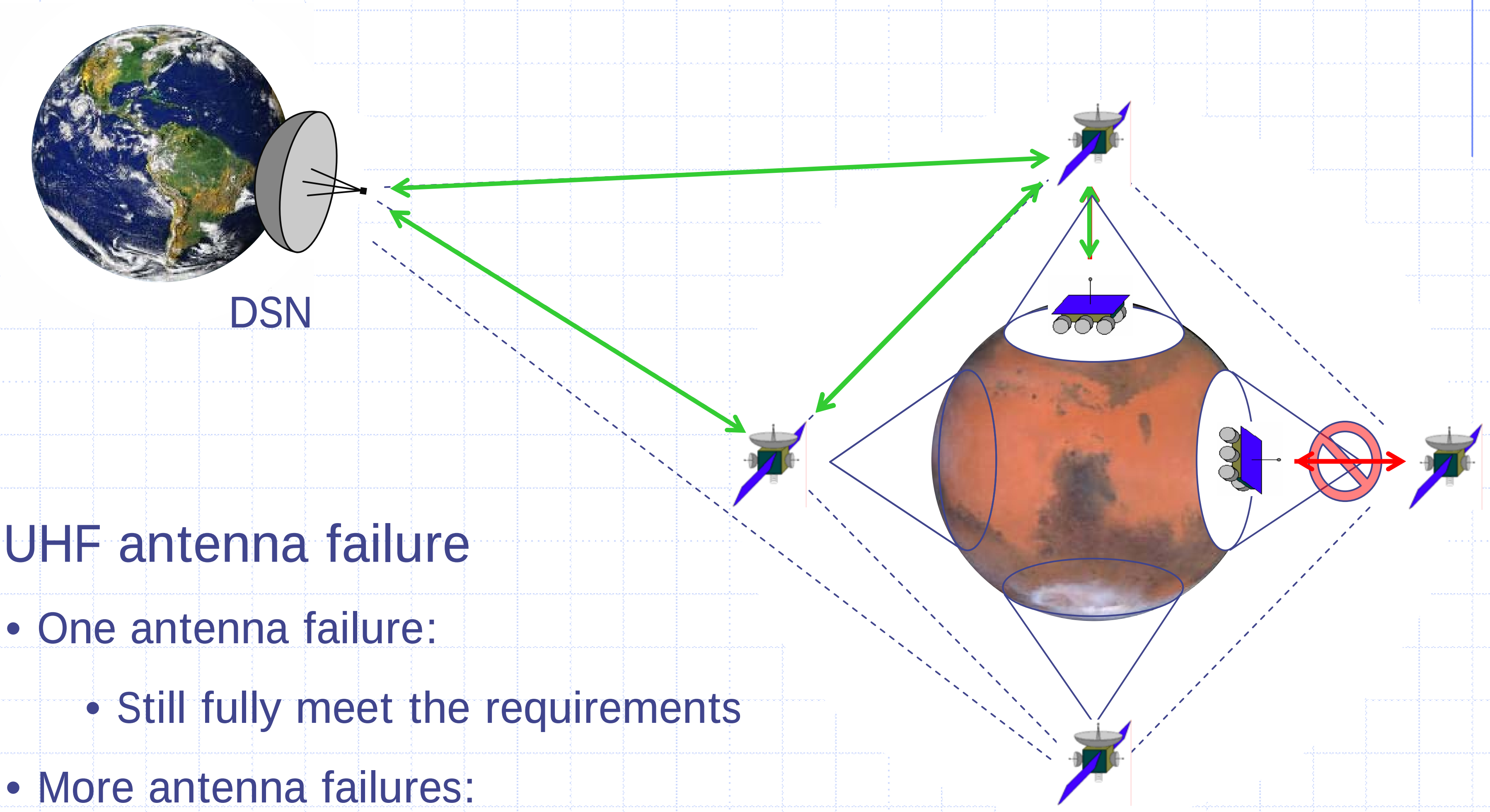
Failure Mode Analysis



Cross-link antenna failure

- If one antenna on a satellite fails:
  - Still fully meet the requirements
- If more antennas fail:
  - Graceful degradation of performance

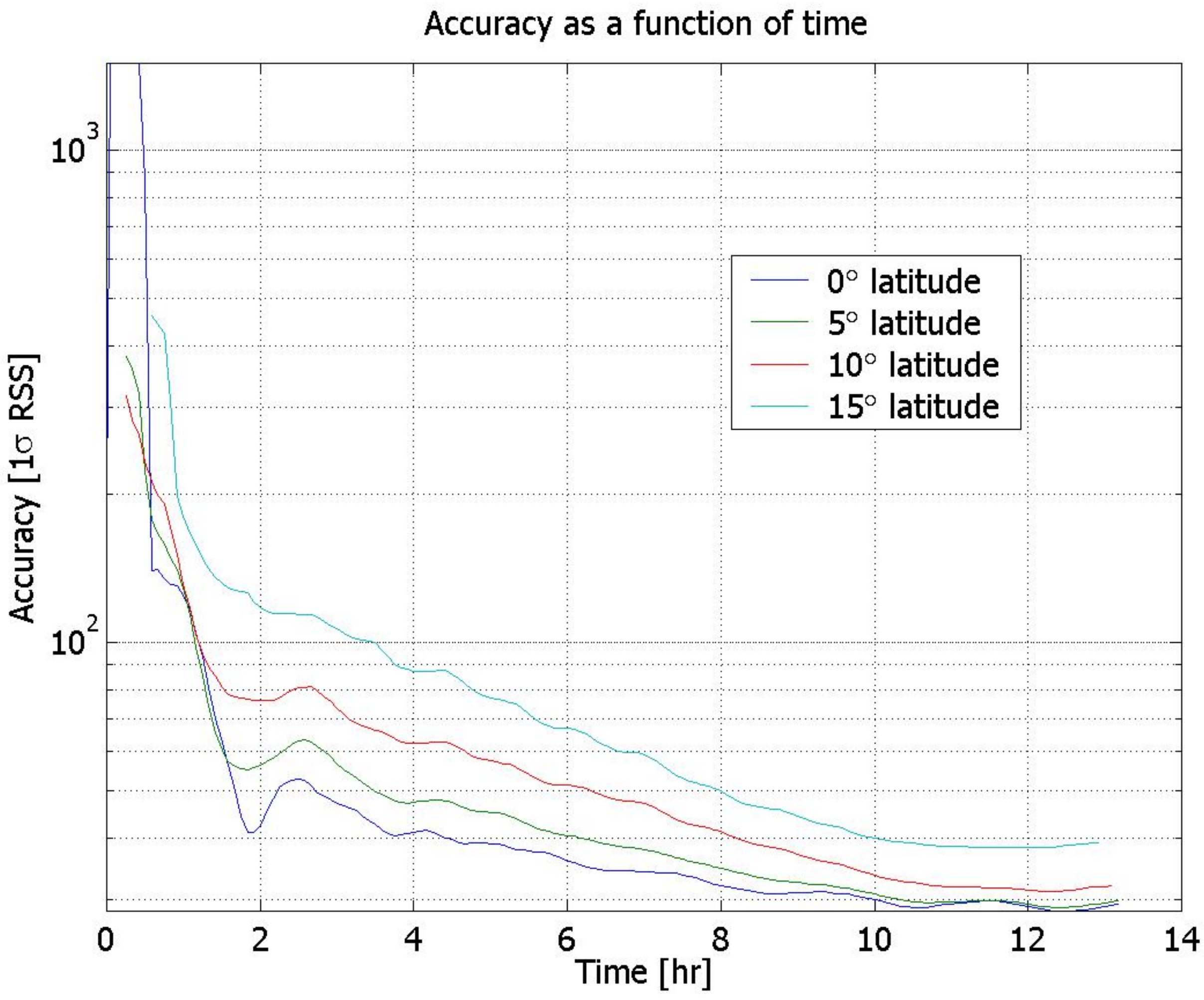
Failure Mode Analysis



UHF antenna failure

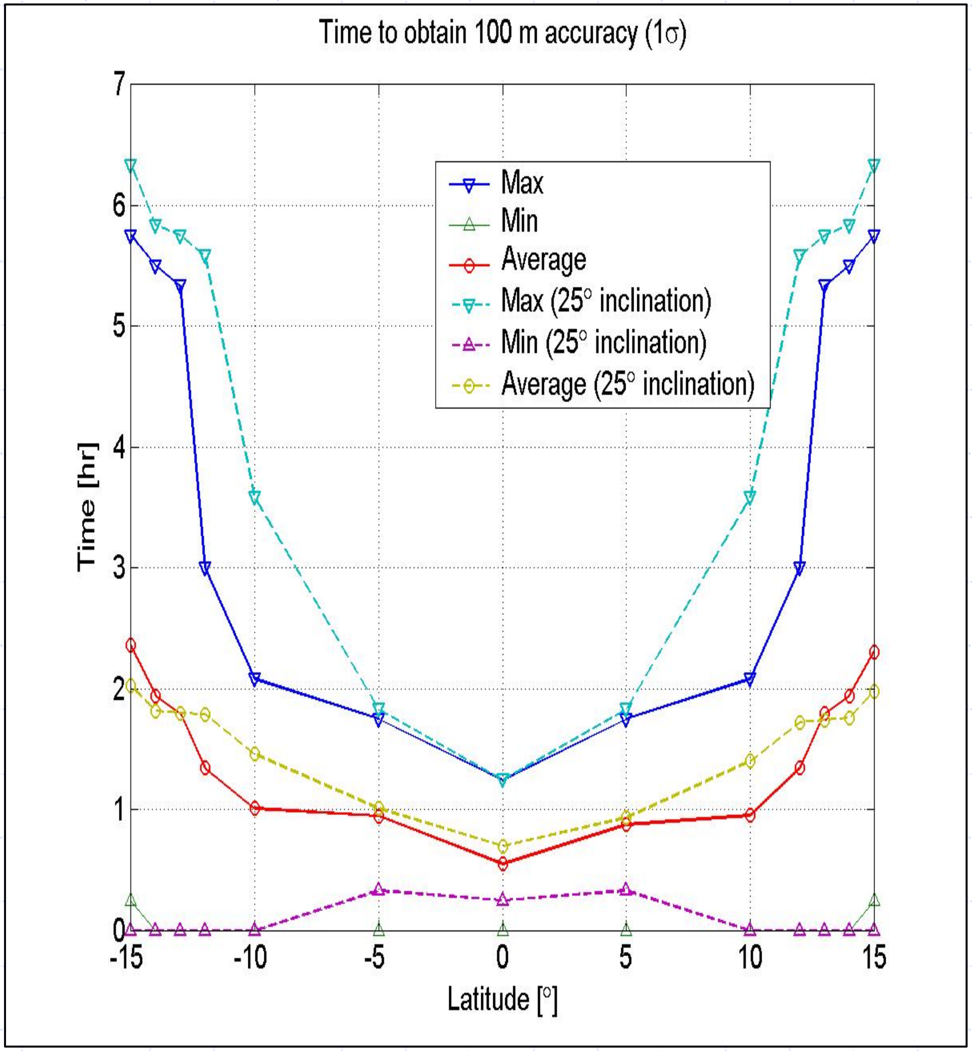
- One antenna failure:
  - Still fully meet the requirements
- More antenna failures:
  - Graceful degradation of performance

Accuracy Over Time



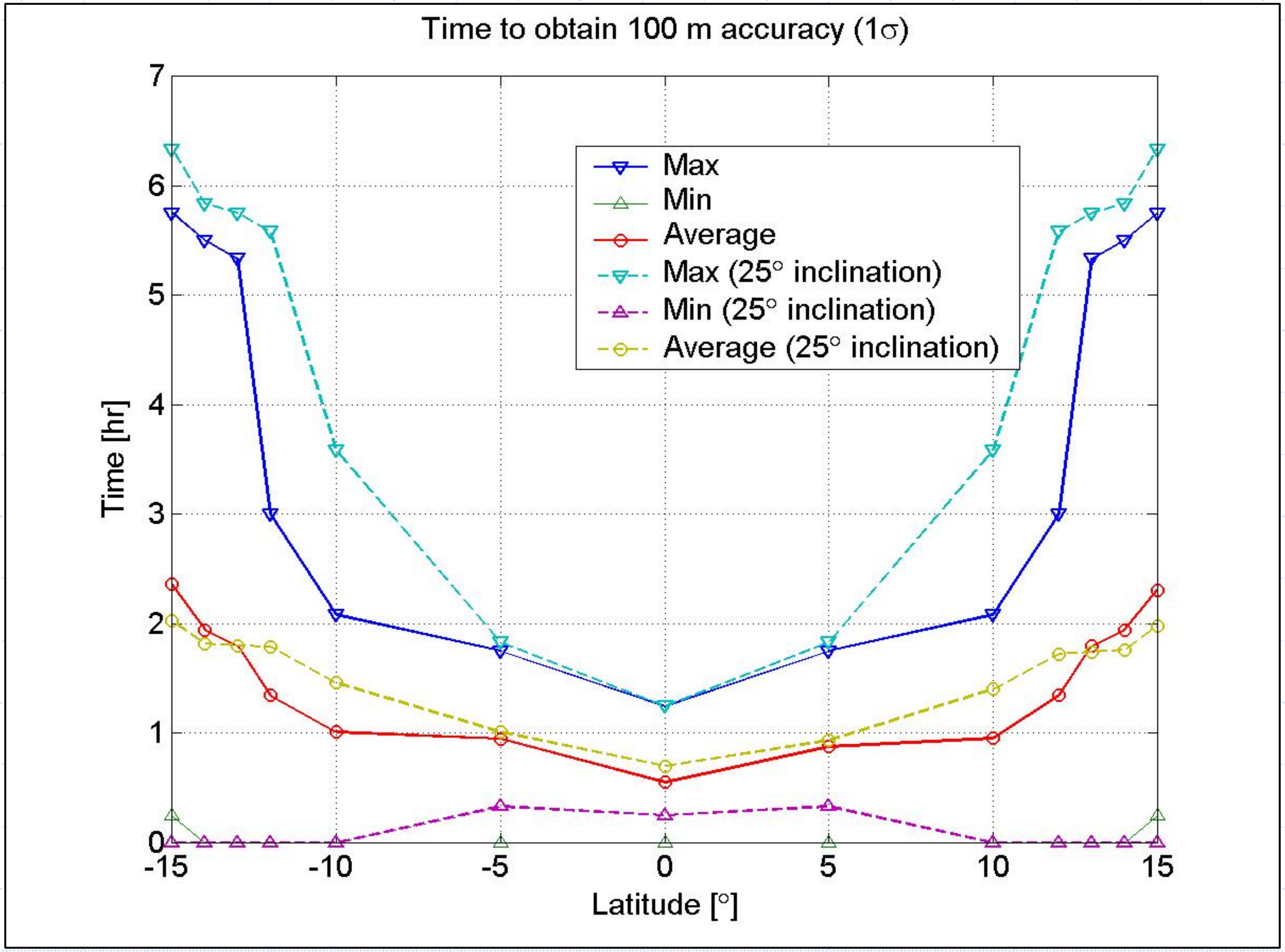
Positioning Performance

- First estimate accuracy depends on geometry w.r.t. satellite ground track
- Time to reach accuracy is a function of
  - Orbital inclination
  - MSE latitude
- Best performance around the equator (coverage)



Positioning Performance

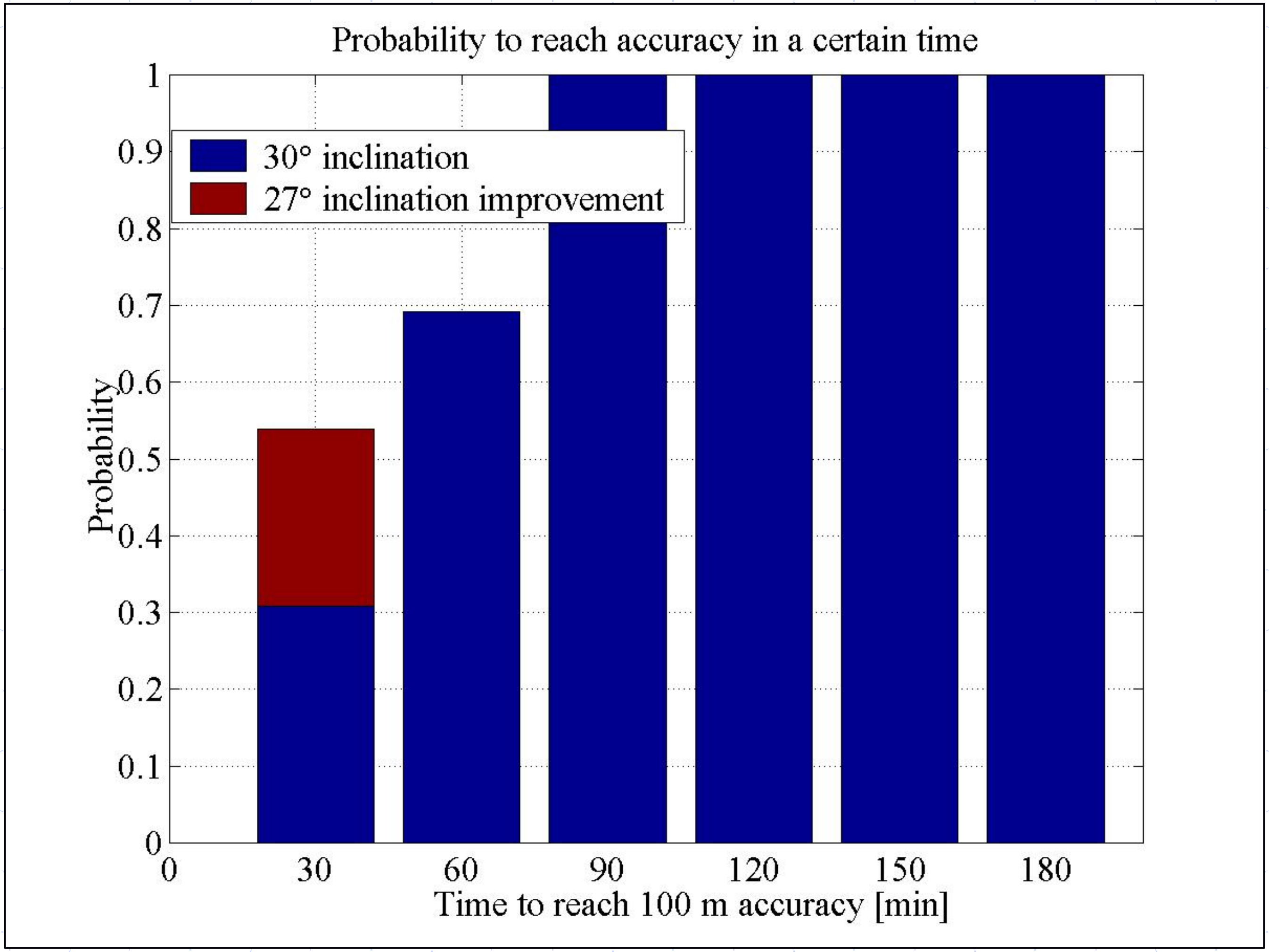
- Comparison with 30 degrees inclination:



Time to Get 100 m Accuracy: Comparison with 30° inclination

- Probability to reach 100 m accuracy (1 σ) within certain time:

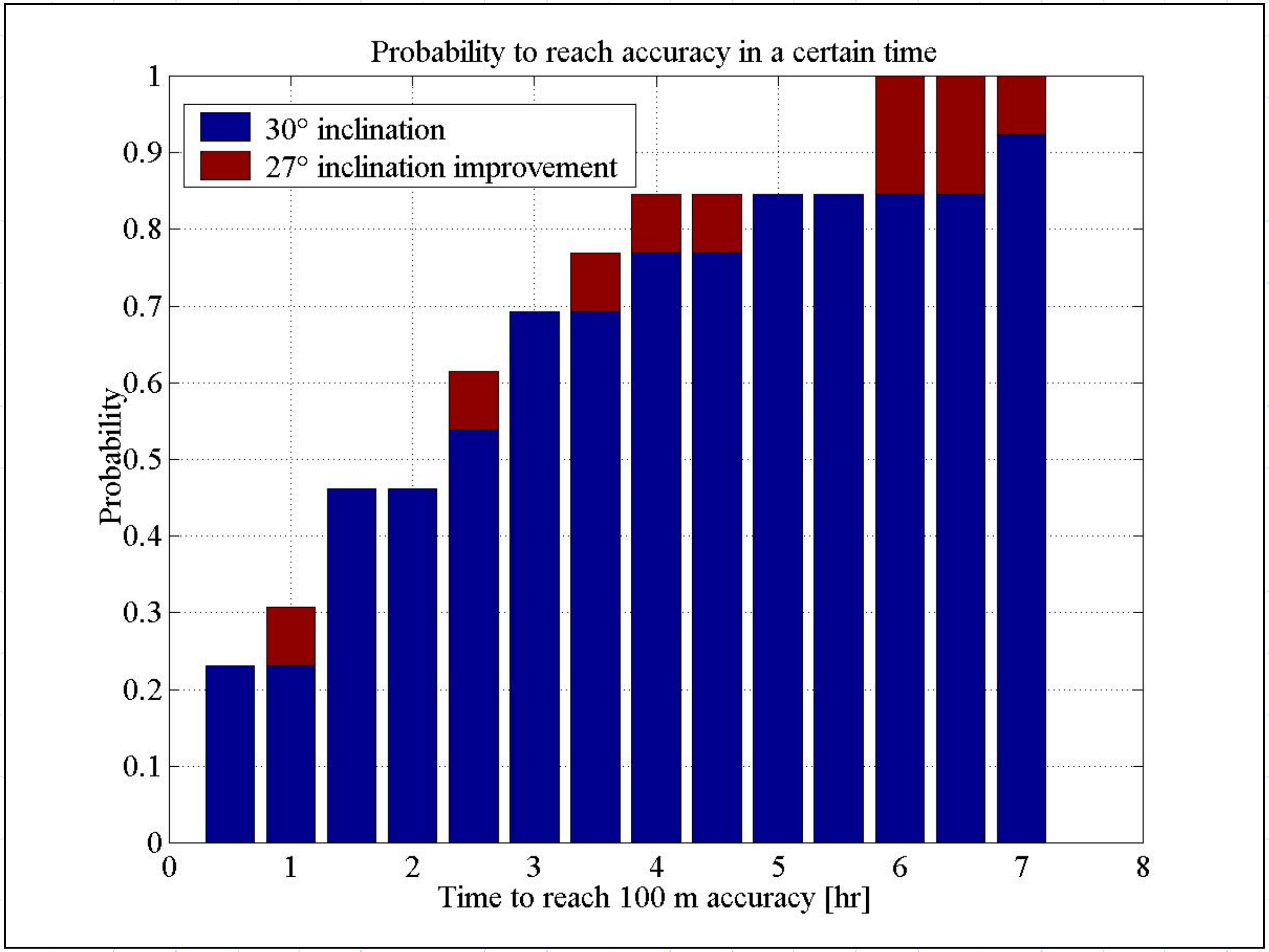
0° latitude



Time to Get 100 m Accuracy: Comparison with 30° inclination

- Probability to reach 100 m accuracy (1 σ) within certain time:

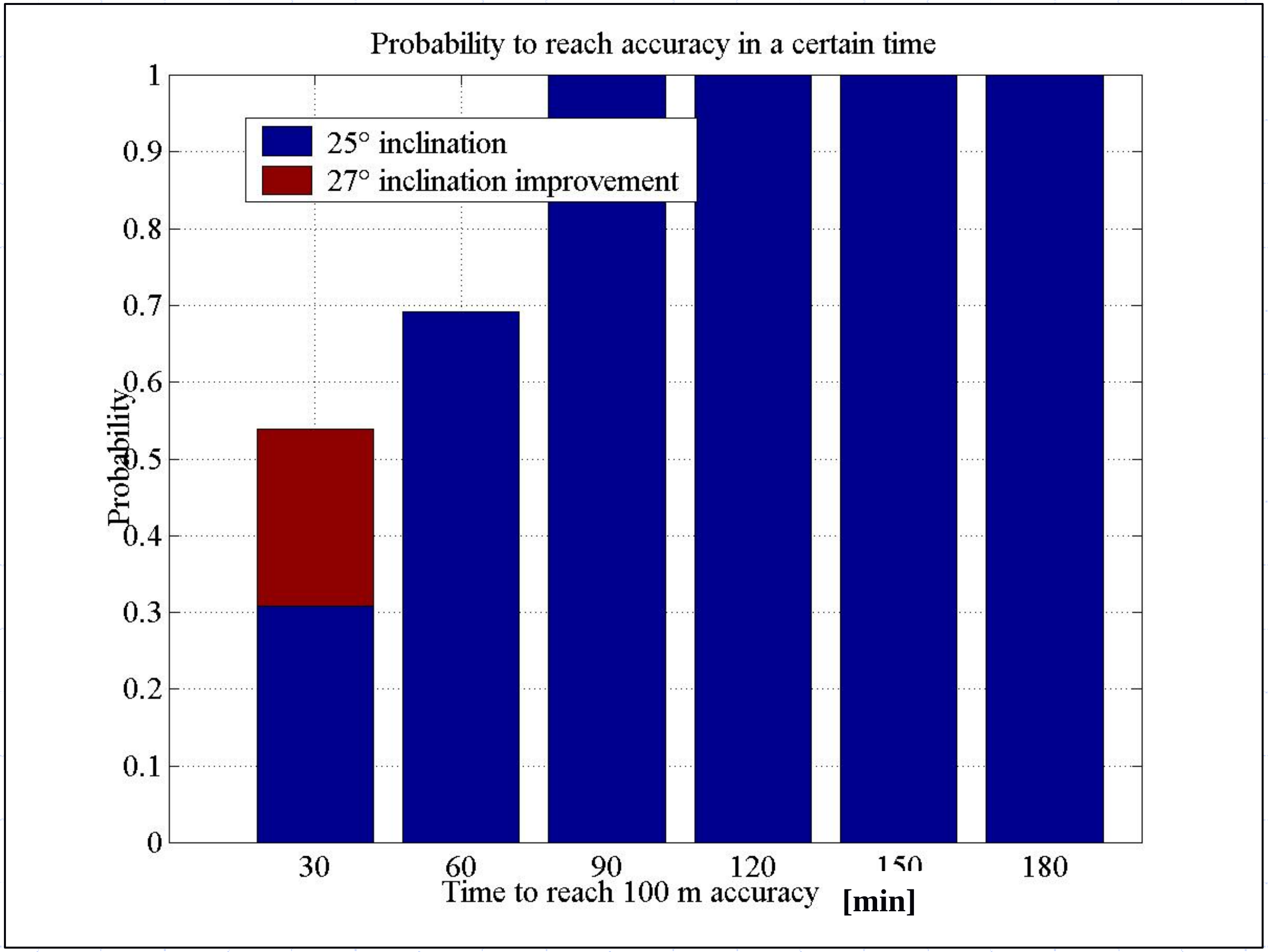
15° latitude



Time to Get 100 m Accuracy: Comparison with 25° inclination

- Probability to reach 100 m accuracy (1 σ) within certain time:

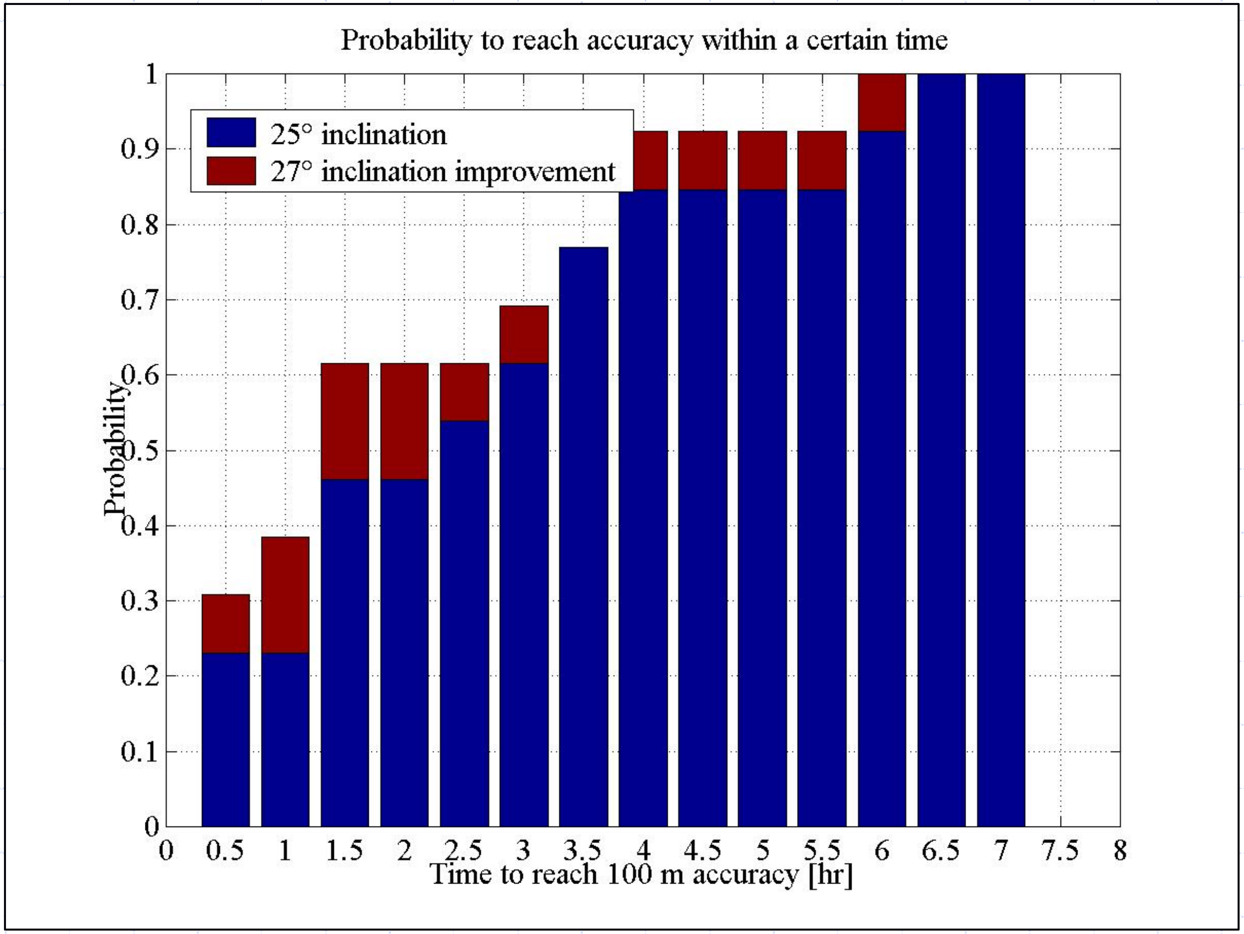
0° latitude



Time to Get 100 m Accuracy: Comparison with 25° inclination

- Probability to reach 100 m accuracy (1 σ RSS) within certain time:

15° latitude



Software Cost

- Software cost estimated by SLOC

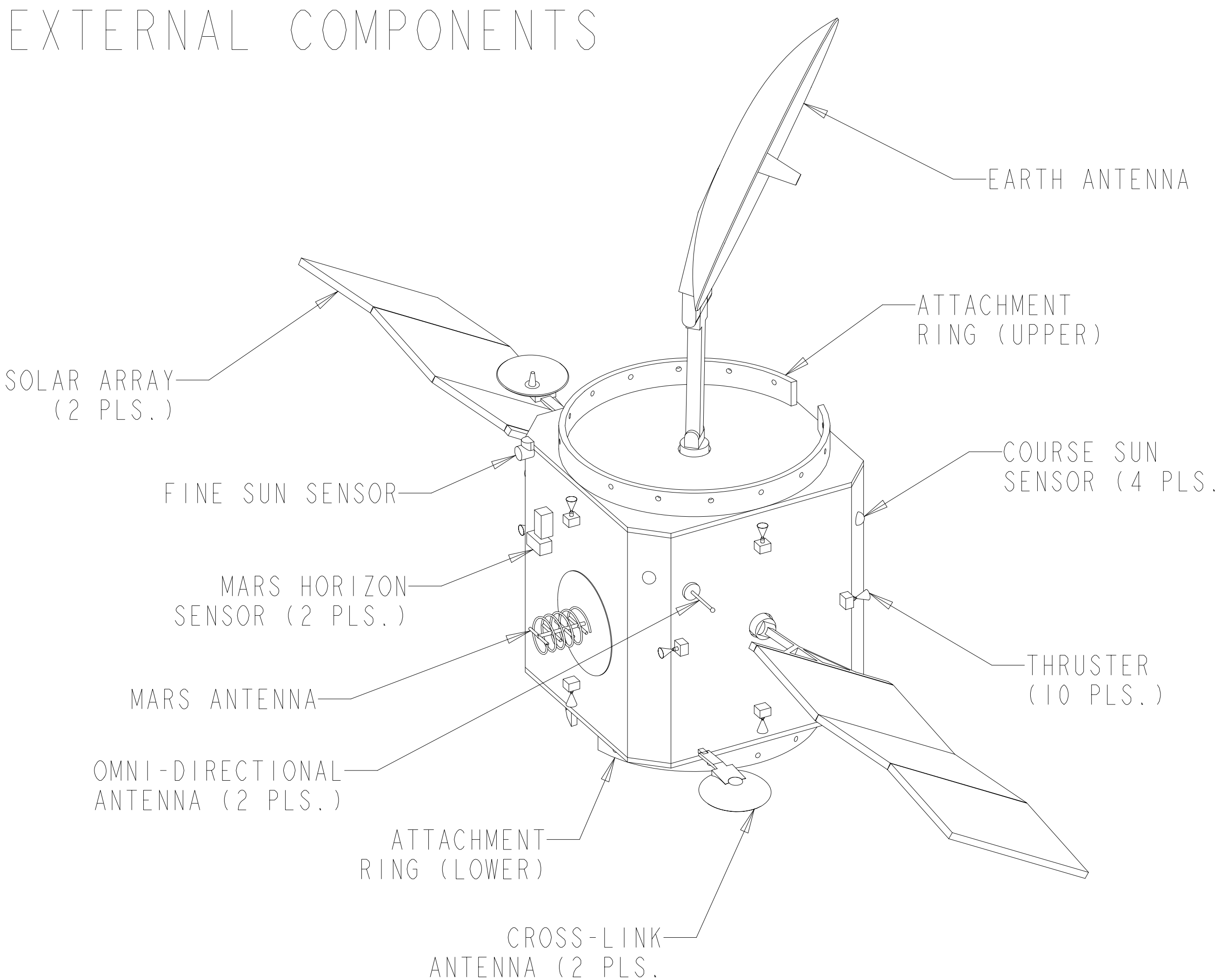
Cost per SLOC	Flight Software	Ground Software
Ada	$ 435	$ 220
C	$ 726	$ 220

Computer Hardware - RAD 6000

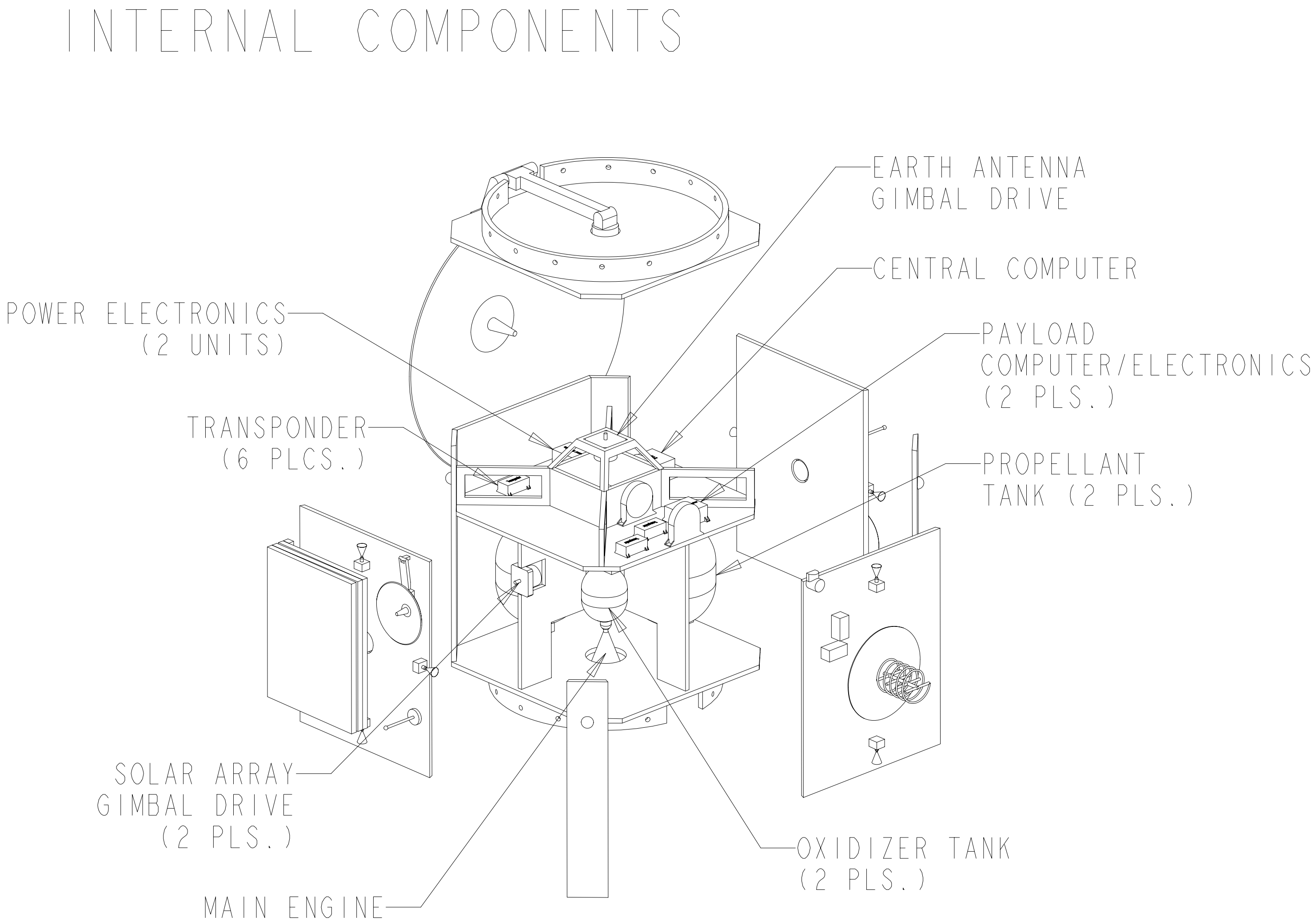
- Radiation hardened version of IBM Risc 6000 Single Chip CPU (32 bit)
  - Chip dimensions: 8” x 9” x 2” inches
  - Mass: ~5 kg
  - Memory: 128 MB of DRAM + 16 GB of EEPROM
  - MIL-STD-1553 interface
- Processing speeds
  - 20 MHz (22 MIPS) using 9 W
  - 10 MHz it (11 MIPS) using 5.5 W
  - 2.5 MHz (2.7 MIPS) it uses 2.5 watts.
- Two processors (2 for 1 redundancy)

Backup Slides:
Bus Analysis

External Satellite Components

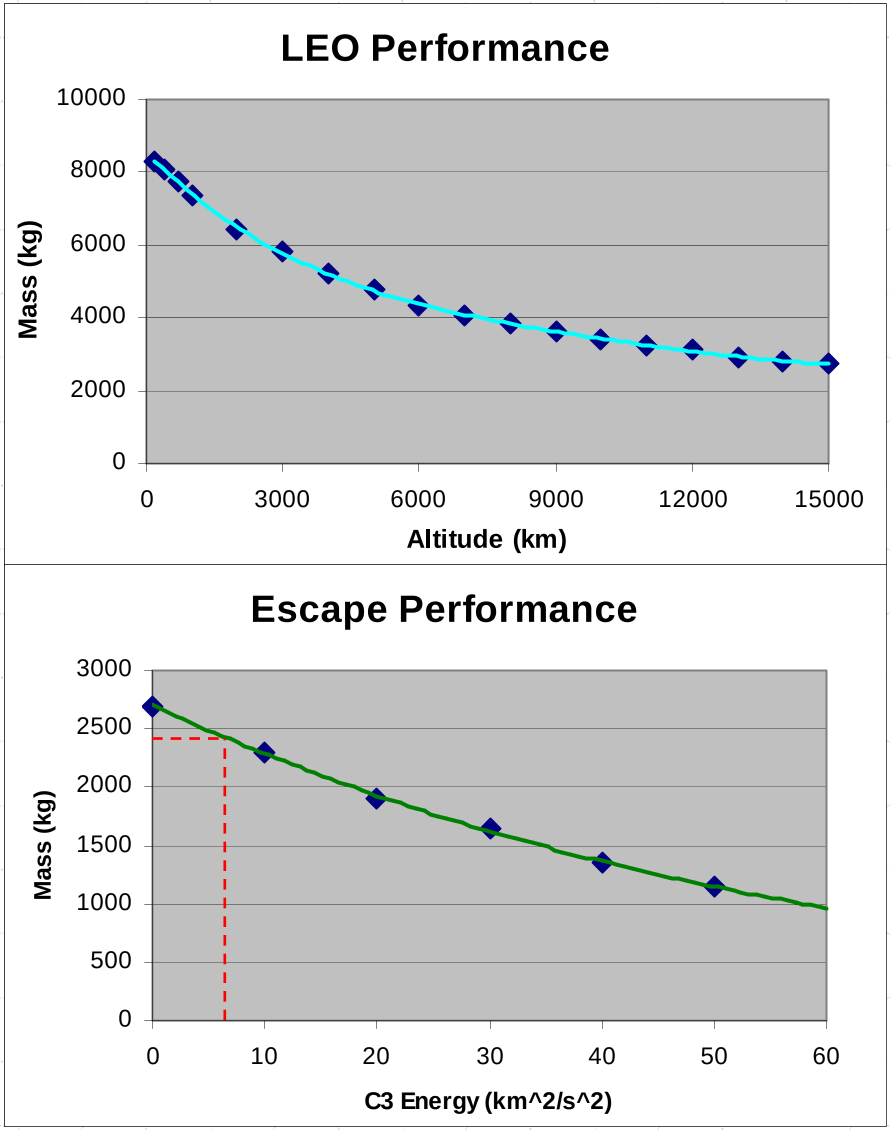


Internal Satellite Components



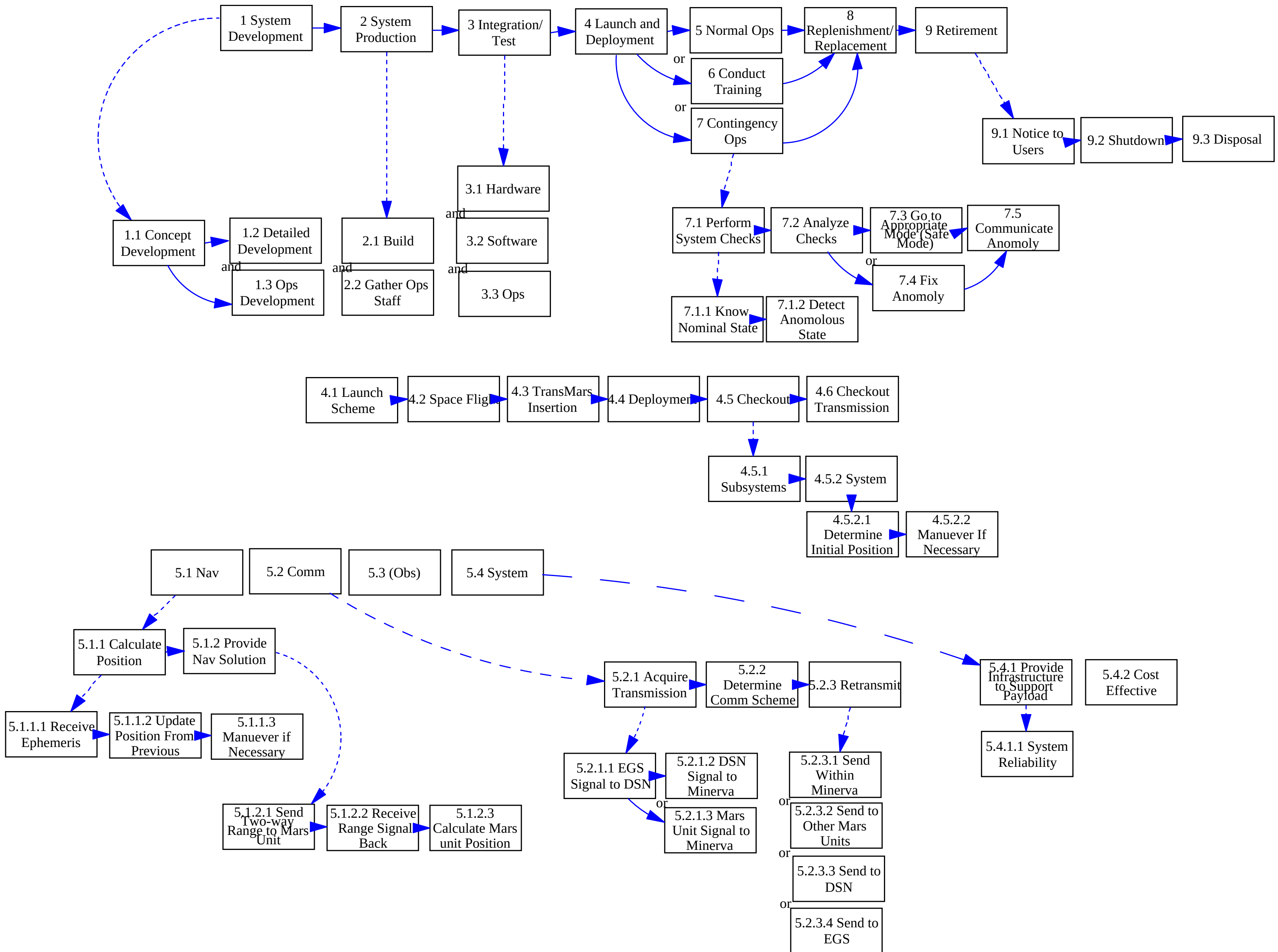
Backup Slides:
Launch Analysis

Launch Vehicle Performance

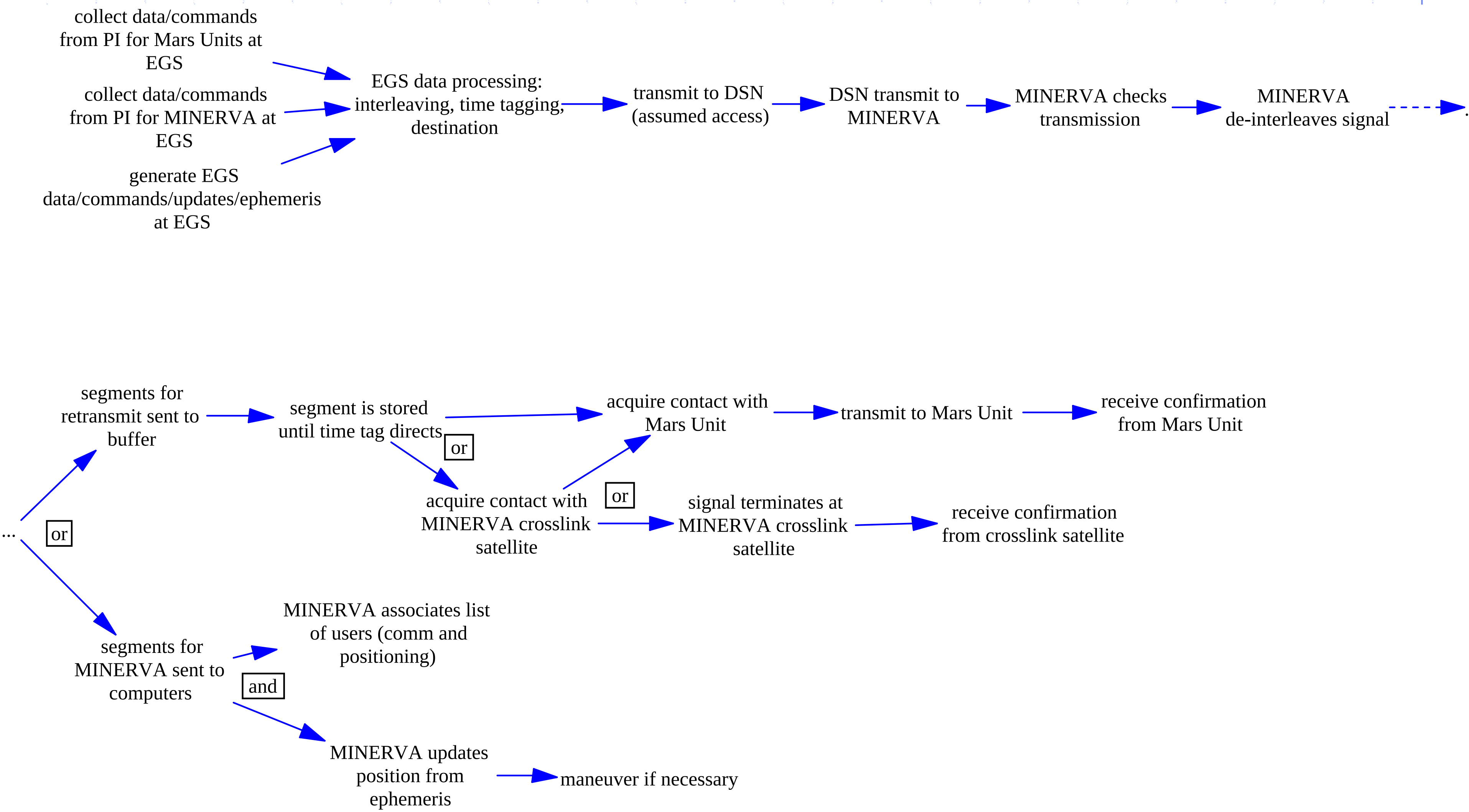


Backup Slides: Operations Analysis

Functional Flow



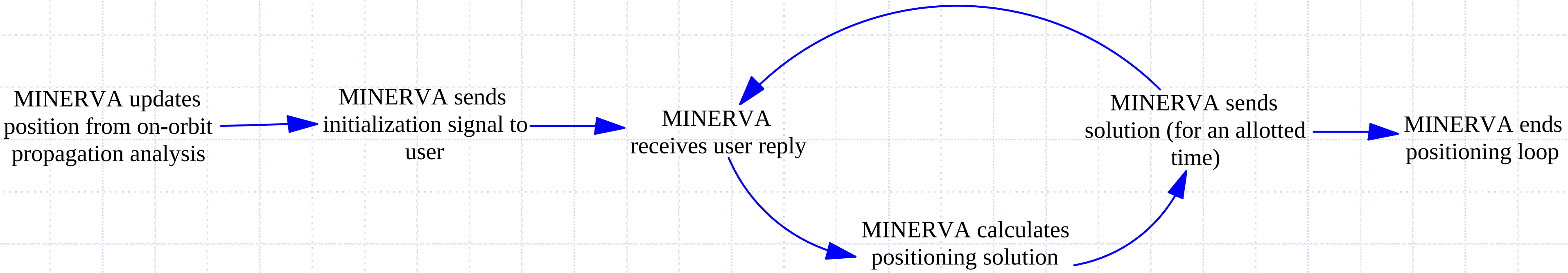
Earth Uplink



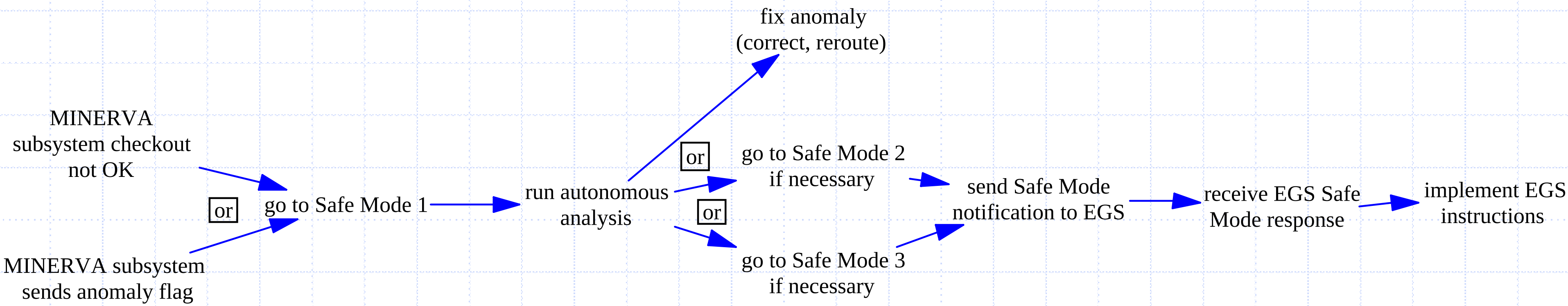
Mars Uplink


MINERVA sends comm initialization signal to user
MINERVA receives user signal
data stored in buffer
MINERVA sends confirmation
MINERVA interleaves data with next transmission to DSN
MINERVA receives confirmation from EGS (through DSN)
MINERVA clears buffer

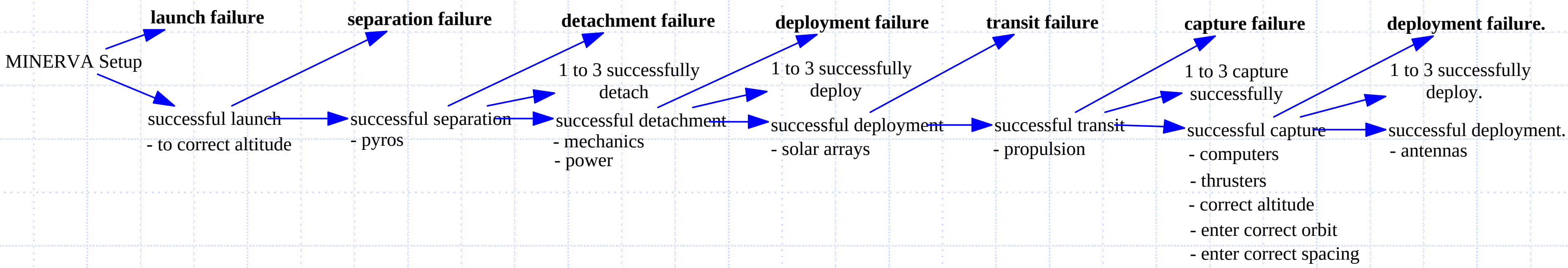
Positioning Loop



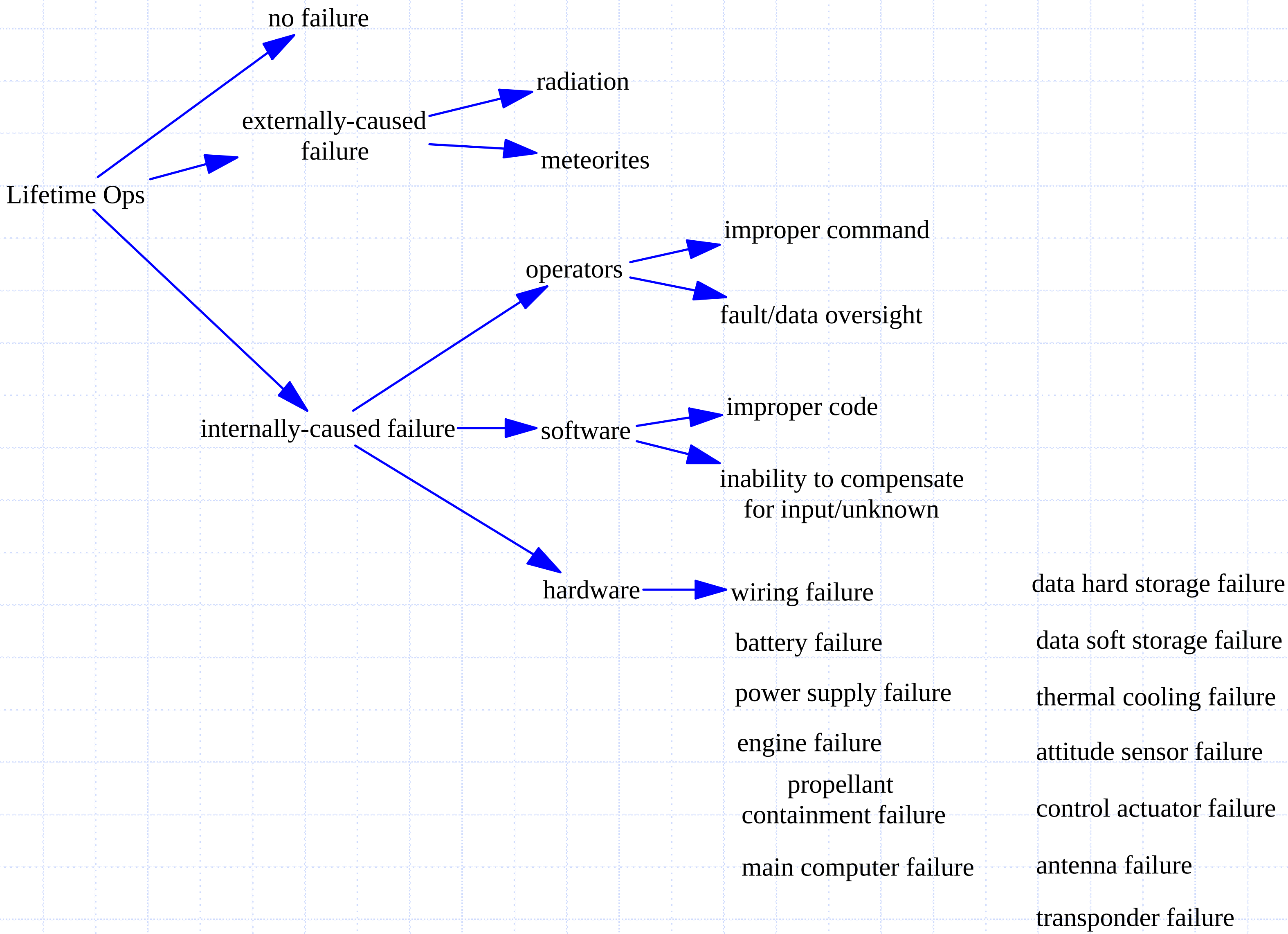
Anomaly Resolution



Failure Tree: Setup



Failure Tree: Normal Lifetime Ops



Reliability (and Failure Rates)

- Launch: 0.997 (or 0.90)
- Separation: 0.99
- Detachment: 0.99
- Transit: (0.005 failures/year)
- Capture: 0.99
- Deployment: 0.99
- ADCS: (0.001 failures/year)
- Payload: (0.00201 failures/year)
- Power: (*** failures/year)
- Propulsion: (0.005 failures/year)
- Thermal: (0.002 failures/year)
- Computers: (0.005 failures/year)

Backup Slides:
Cost Analysis

Cost Trade: Level of Autonomy

- Problem: Spacecraft autonomy drives software costs
- Trade space:
  - Highly autonomous s/c functions
    - Flight software: $24.8M
    - Ground software: $50M
  - Minimal s/c autonomy (on-board position fix)
    - Flight software: $17.6M
    - Ground software: $20.5M
  - Minimal s/c autonomy (Earth position fix)
    - Flight software: $16.4M
    - Ground software: $19.1M
- Decision: Select minimal autonomy (Earth position fix) due to program cost constraints

Notes on Concurrent Engineering

- Design sessions enabled thorough exploration of trade space via real-time inter-team communication
  - Earth parking orbit
  - Constellation altitude
  - # s/c
  - Orbit inclination
- ICEMaker is useful interfacing tool
- More automation would speed process
  - Models in Excel
  - Matlab/Excel integration