Mission Statement

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

MINERVA (M)

Mars Orbiting (S)  Earth Based (E)

Payload (P)       Bus (B)

Program (Z)
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch date</td>
<td>18 Aug 2007</td>
</tr>
<tr>
<td>Launch window</td>
<td>± 1 sec, every 1 sidereal day from 3–18 Aug 2007</td>
</tr>
<tr>
<td>Launch site</td>
<td>Cape Canaveral Air Station</td>
</tr>
<tr>
<td>Launch vehicle</td>
<td>Delta III</td>
</tr>
<tr>
<td>Vehicle provider</td>
<td>Boeing</td>
</tr>
<tr>
<td>Total mass</td>
<td>1974 kg</td>
</tr>
<tr>
<td>Shared payload</td>
<td>Possible, but not necessary</td>
</tr>
<tr>
<td>Configuration</td>
<td>Four stacked spacecraft</td>
</tr>
</tbody>
</table>

Image by MIT OpenCourseWare.
## Transit Overview

<table>
<thead>
<tr>
<th>Event</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch</td>
<td>18 Aug 2007</td>
</tr>
<tr>
<td>Departure burn</td>
<td>T+ 0d 3:23</td>
</tr>
<tr>
<td>Separation</td>
<td>T+ 0d 3:29</td>
</tr>
<tr>
<td>Deploy arrays</td>
<td>T+ 0d 6:01</td>
</tr>
<tr>
<td>Initial checkout</td>
<td>T+ 0d 6:05</td>
</tr>
<tr>
<td>Alignment burn</td>
<td>T+ 2d 16:39</td>
</tr>
<tr>
<td>Correction burn</td>
<td>T+ 122d 16:00</td>
</tr>
<tr>
<td>Insertion burn</td>
<td>T+ 285d 14:29</td>
</tr>
<tr>
<td>Circularization</td>
<td>T+ 290d 8:22</td>
</tr>
<tr>
<td>Deploy antenna</td>
<td>T+ 290d 8:24</td>
</tr>
<tr>
<td>Test/calibration</td>
<td>T+ 296d 12:00</td>
</tr>
<tr>
<td>IOC</td>
<td>10 Jul 2008</td>
</tr>
</tbody>
</table>
Day in the Life: Positioning

Two-way Doppler tracking over 10-hour DSN pass

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

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

180 measurements per day:
- Two-way ranging
- Two-way Doppler tracking
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 $\Delta V$
- Allows constellation replenishment
Detailed Design
Design Iteration Process

- Integrated Concurrent Engineering (ICE)

- # S/C
- Altitude
- Inclination
- # Orbit planes
- Earth parking orbit
- Availability
- Revisit time
- Max eclipse time
- Total ΔV
- P/L mass
- Cost
- Power
- Lifetime performance
- RDT&E cost
- 1st unit cost
- Launch cost
- System cost
- Cost per function

Design Vector

Orbits
- Max cone angle
- S/C mass
- Exhaust velocity
- Total mass

Payload

Bus

Launch

Systems
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

<table>
<thead>
<tr>
<th></th>
<th>Earth</th>
<th>Interplanetary</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔV (km/s)</td>
<td></td>
<td>ΔV (km/s)</td>
<td></td>
</tr>
<tr>
<td>Time (d h)</td>
<td></td>
<td>Time (d h)</td>
<td></td>
</tr>
</tbody>
</table>

- Chemical
  - ΔV: 3.80 km/s
  - Time: 2d 17h
  - ΔV: 0.17 km/s
  - Time: 282d 23h
  - ΔV: 1.60 km/s
  - Time: 3d 17h

- Electric
  - ΔV: 7.38 km/s
  - Time: 421d 14h
  - ΔV: 5.66 km/s
  - Time: 323d 3h
  - ΔV: 2.63 km/s
  - Time: 150d 1h

Using 185km parking orbit
Transit Method Trade Study

<table>
<thead>
<tr>
<th></th>
<th>Earth</th>
<th>Interplanetary</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chemical Propulsion</strong></td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>Electric Propulsion</strong></td>
<td><img src="image4" alt="Diagram" /></td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
</tr>
</tbody>
</table>
Transit Method Selection

- Considerations
  - Chemical propulsion provides fast transfer for smaller $\Delta V$
  - 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 MI NERVA 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

<table>
<thead>
<tr>
<th>Launch</th>
<th>Departure ΔV</th>
<th>Capture ΔV</th>
<th>Time of Flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>3.726 km/s</td>
<td>1.742 km/s</td>
<td>278d 15h 35m</td>
</tr>
<tr>
<td>2007</td>
<td>3.799 km/s</td>
<td>1.601 km/s</td>
<td>290d 8h 22m</td>
</tr>
<tr>
<td>2009</td>
<td>3.712 km/s</td>
<td>1.753 km/s</td>
<td>278d 21h 54m</td>
</tr>
</tbody>
</table>
Delta III Launch Sequence

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

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>T+ 3:23:20</td>
<td>Departure burn (second stage)</td>
</tr>
<tr>
<td></td>
<td>$\Delta V = 3.799 \text{ km/s}$</td>
</tr>
<tr>
<td></td>
<td>Duration = 5.59 min</td>
</tr>
<tr>
<td>T+ 3:29:30</td>
<td>Start release sequence</td>
</tr>
<tr>
<td></td>
<td>Interval = 50.15 min</td>
</tr>
<tr>
<td>T+ 6:01:00</td>
<td>Despin maneuver</td>
</tr>
<tr>
<td>T+ 6:01:50</td>
<td>Deploy solar arrays</td>
</tr>
<tr>
<td>T+ 6:05:00</td>
<td>Initial checkout</td>
</tr>
<tr>
<td>T+ 2d 16:39</td>
<td>Depart Earth SOI</td>
</tr>
</tbody>
</table>
Fairing Jettison

Satellite Separation

Solar Array Deployment
   Solar Arrays gimbaled about North-South axis

Cross-Link Deployment
   Deploys on hinged boom
Transit - Rendezvous

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
</tr>
</thead>
</table>
| T+ 2d 16:39 | Alignment burn (four ACS thrusters) \[\Delta V \approx 0.020 \text{ km/s} \]
  | Duration = 48.2 sec                                           |
| T+ 2d 16:45 | Functional testing                                            |
| T+ 122d 16:00 | Correction burn (four ACS thrusters) \[\Delta V \approx 0.005 \text{ km/s} \]
  | 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

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
<th>ΔV</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>T+ 285d 14:29</td>
<td>Injection burn (main kick motor)</td>
<td>0.167 km/s</td>
<td>2.1 sec</td>
</tr>
<tr>
<td>T+ 290d 08:22</td>
<td>Circularization burn (main kick motor)</td>
<td>1.602 km/s</td>
<td>19.1 sec</td>
</tr>
<tr>
<td>T+ 290d 08:23</td>
<td>Despin maneuver</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T+ 290d 08:24</td>
<td>Deploy large antenna</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T+ 290d 10:54</td>
<td>All satellites in place</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T+ 291d 12:00</td>
<td>Correction maneuvers (as necessary)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T+ 296d 12:00</td>
<td>Test and calibration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T+ 326d 01:40</td>
<td>IOC: 9 July 2008</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 $\pm 15^\circ$ 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 $\approx 30^\circ$
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 ± 15° latitude band
- Reduced coverage up to ± 65°
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 $(\pm 15^0 \text{ Lat})$
  - Avg. revisit time $< 20 \text{ min}$
  - Max. revisit time $< 30 \text{ min}$
  - Contact duration $\approx 50 \text{ min}$
  - Availability $> 70%$
  - 3 satellites in view of Earth
  - Reduced coverage up to $(\pm 60^0 \text{ Lat})$
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** MI NERVA shall provide communication capability between MSEs and EGS for at least 10 continuous hours per day.

- **M002** MI NERVA shall provide MSE position accuracy of 100 m (horizontal resolution) or less.

- **M003** MI NERVA 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 MI NERVA shall have a BER of no greater than $10^{-9}$.

- **E009** Uplink from EGS to MI NERVA 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 MI NERVA 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 MI NERVA 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

Earth-MI NERVA Link

Cross-link

MI NERVA-MSE Link
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

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

Image removed due to copyright restrictions.
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

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 MI NERVA-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 MI NERVA-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
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-MI NERVA 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 MI NERVA-MSE link**
  - Good performance for omnidirectional antennas on Mars surface
  - Reduces necessary antenna mass on board MSE
Antenna Types Trade Analysis

- **MI NERVA - Earth link: Parabolic antenna**
  - Mars Earth distance: 50 - 400 million km
  - ⇒ high gain required

- **MI NERVA - Mars link: Helix antenna**
  - UHF 0.4 GHz to support existing assets
  - High beamwidth to improve coverage
    - (77 deg at 2000 km altitude)

- **MI NERVA cross-links: Parabolic antenna**
  - Necessity to use antenna for Earth link during Mars approach and as a backup
# Payload Hardware

## Antennas and Transponders

<table>
<thead>
<tr>
<th>MINERVA-Earth Link: Ka-(X)-band</th>
<th>MINERVA-Mars Link: UHF</th>
<th>MINERVA Cross-Link: X-(Ka)-band</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.05 m parabolic, 130 W, 26.6 kg</td>
<td>Ø 25 cm x 31 cm helix, 21 W, 2.9 kg</td>
<td>2 x 50 cm parabolic, 5 W, 5.6 kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 Omni-directional, 5 W, 0.3 kg</td>
</tr>
<tr>
<td>Total Mass: 35.4 kg</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Other Hardware

<table>
<thead>
<tr>
<th>Computer: RAD 6000, 5 kg</th>
<th>Navigation Equipment: Ultra Stable Oscillator, 0.2 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Used on Mars Pathfinder, Globalstar, ISS</td>
<td>Other equipment: Switches, etc. 2 kg</td>
</tr>
<tr>
<td>Total Mass: 7.2 kg</td>
<td></td>
</tr>
</tbody>
</table>

Total Payload Mass: 42.5 kg
Payload Mass Breakdown

Total Mass: 42.5 kg

- Cross-links: 5.9 kg
- Earth link: 20 kg
- Mars link: 2.9 kg
- Amplifiers: 6.6 kg
- Computers: 5 kg
- Other: 2.2 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

Pros
- No requirement on user
- Single coverage for 2-D
- Double coverage for 3-D

Cons
- Infrared not proven
- Computational load

Active
- One-way (GPS-like)
- Range
- Doppler

Pros
- Unlimited #users
- Proven methods

Cons
- Time offset
- Frequency offset

Two-way
- Range
- Doppler

Pros
- Quick 2-D positioning with single satellite
- Double coverage for 2-D
- Triple coverage for 3-D

Cons
- Limited #users
- Transponders on user
Position Determination Method

MINERVA satellite

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

Mars rotation:
\[ L = R_M \omega_M \Delta T \cos(\text{latitude}) \]

Satellite A at \( t_1 \):
\[ L \approx 70 \text{ km} / 5 \text{ min} \]

Satellite A at \( t_2 = t_1 + k \Delta T \) (\( \Delta T = 5 \text{ min} \))

\[ \Delta x \approx 63 \text{ km} / 5 \text{ min} \]

Ambiguity resolution:
\[ \Delta x \approx 2L \sin(i) \]

\[ L \approx 70 \text{ km} / 5 \text{ min} \]
## Sources of Error

<table>
<thead>
<tr>
<th>Internal Sources</th>
<th>Properties</th>
<th>Magnitude</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ranging error</strong></td>
<td>Code chip rate</td>
<td>10 m</td>
<td>Not limiting factor</td>
</tr>
<tr>
<td><strong>Doppler error</strong></td>
<td>Integration time</td>
<td>&lt; 1 cm/s</td>
<td>Not limiting factor</td>
</tr>
<tr>
<td></td>
<td>Sat. oscillator stability</td>
<td>&lt; 1 mm/s</td>
<td></td>
</tr>
<tr>
<td><strong>MSE altitude</strong></td>
<td>Mars topography</td>
<td>~ 200 m</td>
<td>Corrected with time</td>
</tr>
<tr>
<td><strong>MSE velocity</strong></td>
<td>Assumed very slow</td>
<td>&lt; 1 cm/s</td>
<td>4 – 90 km error</td>
</tr>
<tr>
<td></td>
<td>Measured with IMUs</td>
<td></td>
<td>Per km/hr</td>
</tr>
<tr>
<td><strong>MINERVA orbits</strong></td>
<td>Quick positioning: orbit prediction</td>
<td>100 m – 10 km</td>
<td>Absolute upper bound on accuracy</td>
</tr>
<tr>
<td></td>
<td>Post-processing: orbit determination</td>
<td>20 m</td>
<td></td>
</tr>
</tbody>
</table>
Time to Get 100 m Accuracy

- Probability to reach 100 m accuracy ($1\sigma$) within certain time:

0° latitude

![Bar chart showing probability to reach accuracy within a certain time at 0° latitude.](chart.png)
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

<table>
<thead>
<tr>
<th>Level of Autonomy</th>
<th>MSE Position Determination</th>
<th>Communications</th>
<th>GN&amp;C</th>
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</thead>
<tbody>
<tr>
<td>High</td>
<td>• Calculated on-board</td>
<td>• Automatic communications routing</td>
<td>• High precision orbit propagator</td>
</tr>
<tr>
<td></td>
<td>• Continuously tracks MSEs</td>
<td></td>
<td>• Accurate position calculated on-board</td>
</tr>
<tr>
<td>Partial</td>
<td>• Calculated on-board with Earth input</td>
<td>• Preplanned communications routing • Simple search</td>
<td>• Medium precision orbit propagator</td>
</tr>
<tr>
<td>Low</td>
<td>• Calculated on Earth</td>
<td></td>
<td>• Earth provides accurate positions</td>
</tr>
</tbody>
</table>
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

![Graph showing Flight Software Size](attachment:image.png)
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 Graph]

- The graph illustrates the comparison betweenTotal Software Cost andOperations Cost per Year across High, Partial, and Low autonomy levels.
Autonomy vs. Operations Cost

- High autonomy is cheaper in the long run

Total Software and Operations Cost for Different Autonomy Levels

- High Autonomy
- Partial Autonomy
- Low Autonomy

FY00 $M (not including inflation)

Years after IOC

0 1 2 3 4 5
Detailed Design: Bus Analysis
Bus Requirements

- **M008** MI NERVA 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 $\Delta V$ (total).

- **B008** Propulsion subsystem shall provide sufficient $\Delta V$ 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 $\Delta V$ 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

<table>
<thead>
<tr>
<th>System Component</th>
<th>Number</th>
<th>Mass</th>
<th>Total Mass</th>
<th>Total Power</th>
<th>Critical Dim</th>
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</thead>
<tbody>
<tr>
<td><strong>Payload</strong></td>
<td>1</td>
<td>37</td>
<td>37</td>
<td>190</td>
<td>Ant Diam = 2m</td>
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<tr>
<td><strong>ADCS</strong></td>
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<td>30.7</td>
<td>39.0</td>
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<td>Sun sensor</td>
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<td>1.2</td>
<td>7.0</td>
<td>0.8</td>
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<td>Horizon Sensor</td>
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<td>0.7</td>
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<td>5.0</td>
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<td>Gyroscope</td>
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<td>Accelerometer</td>
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<td>Reaction Wheel</td>
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<td>3.8</td>
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<tr>
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<td>-</td>
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<td>273.8</td>
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<td>Propellant</td>
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<td>177.4</td>
<td>211.8</td>
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<td>Main Engine</td>
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<td>4.5</td>
<td>15.0</td>
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<td>ACS Engine</td>
<td>12</td>
<td>0.5</td>
<td>6.0</td>
<td>-</td>
<td>Diameter = 0.6m</td>
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<td>2</td>
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<td>Blow down System</td>
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<td>20.0</td>
<td>20.0</td>
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<td>Feed System</td>
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<td>5.0</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>Structure</td>
<td>-</td>
<td>4.4</td>
<td>5.3</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>Thermal</strong></td>
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<td></td>
<td>7.0</td>
<td>11.6</td>
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<tr>
<td>Heater</td>
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<td>2.3</td>
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<tr>
<td>Radiator</td>
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<td>2.3</td>
<td>2.3</td>
<td>-</td>
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<td>Insulator</td>
<td>-</td>
<td>2.3</td>
<td>2.3</td>
<td>-</td>
<td></td>
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<tr>
<td><strong>Power</strong></td>
<td></td>
<td></td>
<td>50.1</td>
<td>418.0</td>
<td>Area = 4.00 m²</td>
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<tr>
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<td>2</td>
<td>11.0</td>
<td>22.0</td>
<td>418.0</td>
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<td>-</td>
<td>8.3</td>
<td>8.3</td>
<td>-</td>
<td></td>
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<tr>
<td>Batteries</td>
<td>6</td>
<td>1.2</td>
<td>7.4</td>
<td>393 W-hrs</td>
<td></td>
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<td>Wiring</td>
<td>-</td>
<td>1.0</td>
<td>1.0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Structure</td>
<td>-</td>
<td>11.3</td>
<td>11.3</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>Launch Structure</strong></td>
<td>-</td>
<td>10.5</td>
<td>10.5</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

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
  \(~ 4 \, \text{m}^3\)

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

MINERVA
Communication
Positioning

- Radiation/atmosphere
- Meteorites

Environment

Requirements

Mars

- MSEs
- Science data

En route
On station

Other Satellites

Earth

- Ground station
- DSN
- Launch vehicle

Ground station
DSN
Launch vehicle

Operations: Functional Analysis

1. System Development
2. System Production
3. Integration/Test
4. Launch and Deployment
5. Normal Operations
6. Conduct Training
7. Contingency Ops
8. Replenishment/Replacement
9. Retirement
Operations: Functional Analysis

- **Earth Uplink**
  - Data collection/processing at EGS
  - Segments are time/destination tagged
- **Mars Uplink**
  - MI NERVA initiates communication per instructions
- **Positioning Loop**
  - MI NERVA 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

System Reliability over Lifetime

- 4 Sats Operational
- At least 3 Sats Operational

Mission Timeline [years]

Time (years)

Probability of Success

Reliability [0 - 1]
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 km²/s².
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

Design vector

Payload cost

Bus

Spacecraft RDT&E

Spacecraft TFU

Systems

Ground S/W

Launch

Margins
Factors
Learning Curve

Total System Development Costs

Payload

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

<table>
<thead>
<tr>
<th>Option</th>
<th># of S/C</th>
<th>Prop System</th>
<th>Launch Vehicle</th>
<th>Cost ($M)</th>
<th>Margin* (.15)</th>
<th>Total ($M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 1</td>
<td>4</td>
<td>EP</td>
<td>Delta III</td>
<td>279.1</td>
<td>33.3</td>
<td><strong>312.3</strong></td>
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<tr>
<td><strong>Option 2</strong></td>
<td>4</td>
<td>Chem</td>
<td>Delta III</td>
<td>266.4</td>
<td>31.5</td>
<td>297.9</td>
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<tr>
<td>Option 3</td>
<td>3*</td>
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<td><strong>290.9</strong></td>
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<tr>
<td>Option 4</td>
<td>3*</td>
<td>Chem</td>
<td>Delta II</td>
<td>244.0</td>
<td>28.2</td>
<td><strong>272.2</strong></td>
</tr>
</tbody>
</table>

* 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

- **Spacecraft (59%)**
  - $170.3 M

- **Ground Station (12%)**
  - $39.8 M

- **Launch (19%)**
  - $56.3 M

- **Margin (11%)**
  - $31.5 M
Life Cycle Costs

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

Operations (5 years)
- $129.0 M

Operations (transit)
- $20.2 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

<table>
<thead>
<tr>
<th>CY</th>
<th>01</th>
<th>02</th>
<th>03</th>
<th>04</th>
<th>05</th>
<th>06</th>
<th>07</th>
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<td>Flight Software</td>
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<tr>
<td>Mars Transfer</td>
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<tr>
<td>On-orbit checkout</td>
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</table>

Margin

121
# Funding Profile

**Total Program Cost:** $297.9 M*

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

<table>
<thead>
<tr>
<th>Program Yr</th>
<th>1</th>
<th>2</th>
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<td>51.1</td>
<td>26.1</td>
<td>4.8</td>
</tr>
</tbody>
</table>

![Funding Profile Graph](image-url)

*Profile*

$0 \rightarrow $20 \rightarrow $40 \rightarrow $60 \rightarrow $80

Program Year 1 to 8

*Cumulative*

$0 \rightarrow $100 \rightarrow $200 \rightarrow $300

Program Year 1 to 8

*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**

<table>
<thead>
<tr>
<th>Step</th>
<th>Date/Time</th>
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<tbody>
<tr>
<td>Departure burn</td>
<td>18 Aug 07, 09:56</td>
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<tr>
<td>Separation</td>
<td>18 Aug 07, 13:25</td>
</tr>
<tr>
<td>Deploy arrays</td>
<td>18 Aug 07, 13:31</td>
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<tr>
<td>Initial checkout</td>
<td>18 Aug 07, 14:00</td>
</tr>
<tr>
<td>Exit Earth SOI</td>
<td>21 Aug 07, 02:35</td>
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<tr>
<td>Arrive Mars SOI</td>
<td>29 May 08, 10:56</td>
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<tr>
<td>Circularization</td>
<td>03 Jun 08, 18:18</td>
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<tr>
<td>Deploy antenna</td>
<td>03 Jun 08, 18:20</td>
</tr>
<tr>
<td>Test/calibration</td>
<td>09 Jun 08, 22:20</td>
</tr>
<tr>
<td>IOC</td>
<td>10 Jul 08, 00:00</td>
</tr>
</tbody>
</table>
Percentage of Time in View
Single Satellite Failure

- Constellation provides >50% coverage in the ± 15° latitude band
- Reduced coverage up to ± 65°
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 - MI NERVA link:**
  - Uplink: 28.8 dB, downlink: 3.09 dB

- **MI NERVA - Mars link:**
  - Uplink: 5.29 dB, downlink: 4.73 dB

- **MI NERVA cross-link:**
  - Uplink and Downlink: 17.4 dB

- **MI NERVA cross-link with Ka-band for DTE link:**
  - Uplink: 16.65 dB, downlink: 2.97 dB

- **MI NERVA 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 \(\approx 165\) 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) ≠ loss of the satellite
Frequency Used For Future Mars Missions (from Chad Edwards speech)
High gain antenna failure

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

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

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

Accuracy as a function of time

Accuracy [1/σ RSS]

Time [hr]

- 0° latitude
- 5° latitude
- 10° latitude
- 15° latitude
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:

![Graph showing Time to obtain 100 m accuracy (1σ) vs Latitude (°) for different inclinations.](image)
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 ($1 \sigma$) 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

![Bar chart showing probability to reach accuracy in a certain time.

- 25° inclination
- 27° inclination improvement

Time to reach 100 m accuracy:
- 30 min
- 60 min
- 90 min
- 120 min
- 150 min
- 180 min
Time to Get 100 m Accuracy: Comparison with $25^\circ$ inclination

- Probability to reach 100 m accuracy ($1 \sigma$ RSS) within certain time:

15° latitude
## Software Cost

Software cost estimated by SLOC

<table>
<thead>
<tr>
<th>Cost per SLOC</th>
<th>Flight Software</th>
<th>Ground Software</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ada</td>
<td>$ 435</td>
<td>$ 220</td>
</tr>
<tr>
<td>C</td>
<td>$ 726</td>
<td>$ 220</td>
</tr>
</tbody>
</table>
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

- Earth Antenna
- Attachment Ring (Upper)
- Course Sun Sensor (4 PLS.)
- Thruster (10 PLS.)
- Solar Array (2 PLS.)
- Fine Sun Sensor
- Mars Horizon Sensor (2 PLS.)
- Mars Antenna
- Omni-Directional Antenna (2 PLS.)
- Attachment Ring (Lower)
- Cross-Link Antenna (2 PLS.)

EXTERNAL COMPONENTS
Internal Satellite Components

INTERNAL COMPONENTS

- Power Electronics (2 units)
- Transponder (6 PCS.)
- Solar Array Gimbal Drive (2 PCS.)
- Earth Antenna Gimbal Drive
- Central Computer
- Payload Computer/Electronics (2 PCS.)
- Propellant Tank (2 PCS.)
- Oxidizer Tank (2 PCS.)
- Main Engine
Backup Slides: Launch Analysis
Launch Vehicle Performance

**LEO Performance**

Altitude (km) vs. Mass (kg)

**Escape Performance**

C3 Energy (km^2/s^2) vs. Mass (kg)
Backup Slides: Operations Analysis
Earth Uplink

- Collect data/commands from PI for Mars Units at EGS
- Collect data/commands from PI for MINERVA at EGS
- Generate EGS data/commands/updates/ephemeris at EGS

EGS data processing: interleaving, time tagging, destination

Transmit to DSN (assumed access)

DSN transmit to MINERVA

MINERVA checks transmission

MINERVA de-interleaves signal

Segments for retransmit sent to buffer

Segment is stored until time tag directs

Acquire contact with Mars Unit

Transmit to Mars Unit

Receive confirmation from Mars Unit

MINERVA associates list of users (comm and positioning)

MINERVA updates position from ephemeris

Maneuver if necessary

Signal terminates at MINERVA crosslink satellite

Receive confirmation from crosslink satellite
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

MINERVA updates position from on-orbit propagation analysis → MINERVA sends initialization signal to user → MINERVA receives user reply → MINERVA calculates positioning solution → MINERVA sends solution (for an allotted time) → MINERVA ends positioning loop
Anomaly Resolution

MINERVA subsystem checkout not OK

or

MINERVA subsystem sends anomaly flag

go to Safe Mode 1

run autonomous analysis

or

go to Safe Mode 1 if necessary

fix anomaly (correct, reroute)

or

go to Safe Mode 2 if necessary

or

go to Safe Mode 3 if necessary

send Safe Mode notification to EGS

receive EGS Safe Mode response

implement EGS instructions

or

or

or
Failure Tree: Setup

MINERVA Setup

- launch failure
  - separation failure
    - detachment failure
      - deployment failure
        - transit failure
          - capture failure
            - deployment failure
              - successful launch - correct altitude
              - successful separation - pyros
              - 1 to 3 successfully detach
                - successful detachment - mechanics - power
                - successful deployment - solar arrays
                - successful transit - propulsion
                - 1 to 3 capture successfully
                  - successful deployment - computers - thrusters - correct altitude - enter correct orbit - enter correct spacing
                  - successful deployment - antennas
**Failure Tree: Normal Lifetime Ops**

- **Lifetime Ops**
  - no failure
  - externally-caused failure
    - radiation
    - meteorites
  - internally-caused failure
    - operators
      - improper command
      - fault/data oversight
    - software
      - improper code
      - inability to compensate for input/unknown
    - hardware
      - wiring failure
      - battery failure
      - power supply failure
      - engine failure
      - propellant containment failure
      - main computer failure
      - data hard storage failure
      - data soft storage failure
      - thermal cooling failure
      - attitude sensor failure
      - control actuator failure
      - antenna failure
      - transponder failure
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