Final Report Briefing

of the

Joint SDIO/NASA Study of SDIO Technology Applications to NASA Solar System Exploration

presented to

Dr. Michael Griffin (SDIO)
Dr. Wesley Huntress (NASA)

Capt. Randy J. Lavigne, SDIO Study Manager
Dr. Richard W. Vorder Bruegge, NASA Study Scientist
Foci of Study

Per Terms of Reference

1) What Solar System Exploration Objectives are Attainable Using SDIO (BP) Technology with Minimal Modifications?

2) What Are the Recent Technology Advances Which Could be Beneficially Incorporated into NASA Missions?
Selection of Near-Earth Objects as Mission Objective

Assumptions
1) Minimum Modification to Spacecraft Design (Low ΔV)
2) Perform Good Science
3) Limit the Budgetary Requirements
4) Launch Window 1993-1995 and Achieve Mission Objective within Short Time (Less than 2 Years) After Launch

Therefore, Based on 1-4
1-4 Consistent with Discovery Mission to Near-Earth Object
1) Low ΔV Limits Targets to Moon and/or Near-Earth Objects
2) Reconnaissance of Near-Earth Objects is Good Science
3) Low Cost
4) Near-Earth Object Opportunities Available in 1993-1995 Timeframe with Arrival Times of Less than Two Years
Findings

Based on 90-Day Study:

(1) Near Earth Asteroid (NEA) Multi-Flyby Mission is of High Scientific Value and Appears Feasible with Proposed SDIO BP Technology Suite.

(2) Identified Several Technologies (Navigation, Computation, Propulsion) Which Could Make Important Contributions to Planned NASA Missions (e.g., MESUR, Discovery) by Lowering Mass and Enhancing Capabilities.
Study Process

- Kick-Off Meeting, Crystal City, January 29, 1991
- Information Packages Distributed, February, 1991
- Science Team Meeting, Falls Church, March 6, 1991
- Technology Team Meeting, Livermore, April 13, 1991
- Final Briefing, Pentagon, April 30, 1991
Briefing Outline

- Science Team Findings
- Technology Team Findings
- Recommendations
Science Team Findings
Near-Earth Asteroid Science Objectives

- Near-Earth Asteroids (NEAs) are a Diverse Group Whose Various Members Probably are Related to Main Belt Asteroids, Comets, and Meteorites.

- Exploration of the NEAs May be Expected to Enhance Our Understanding of the Solar System in the Following:

  1. Some NEAs Probably Preserve Clues to the Makeup and Characteristics of Planetesimals Believed to have been the Building Blocks of the Terrestrial Planets.

  2. Other NEAs Probably are Extinct Comet Nuclei; Such Objects Provide Opportunities to Investigate the Evolutionary Fate of Comets Injected into Short Period Orbits.

  3. NEAs May Provide a Key to Understanding the Relationship of Meteorites to Their Parent Bodies.

  4. As an Important Part of the Earth’s Environment the NEAs Probably have Influenced Significantly the Geological and Biological Evolution of Our Planet.

  5. Because of Their Proximity, NEAs Provide Optimum Targets for Future Sample Return and Space Resource Utilization Missions.

  6. Owing to Their Small Size and Feeble Gravity, the NEA’s May Reveal Surface Characteristics, Processes, and Histories Significantly Different from Those Studied on Larger, More Massive Objects.
Science Team Findings
Near-Earth Asteroid Flyby Science Objectives

- Characterization of Multiple Targets to Address Issue of Asteroid Diversity
- When Flyby is Near Earth, Can Correlate with Ground-Based Observation
- Mapping and Volume/Shape Determination from a Limited Perspective (Using UV-Vis Camera and LIDAR)
- Determination of Spin State
- Multispectral Imagery from a Limited Perspective to Infer Mineralogical Composition (Approximately 6 Meter Resolution)
- Investigation of Regolith with Thermal Images of Dark Side
Science Team Findings
Near-Earth Asteroid Rendezvous Science Objectives

- Global Mapping and Shape/Volume Determination (within a Few Percent Using UV-Vis Camera and LIDAR)
- Precise Determination of Spin State
- High Resolution Characterization of Surface Geology
- Global Multispectral Imagery to Infer Mineralogical Composition (Approximately 6 Meter Resolution)
- Investigation of Regolith with Thermal Images of Dark Side

Limitation:
Precise Mass Determination Difficult Despite LIDAR Presence Due to Active ACS
Science Team Findings
Lunar Flyby/Loose Orbit Science Objectives

- High Resolution Imaging of Lunar Polar Regions and Far Side (UV-Vis Camera)
  - Geological Interpretation Greatly Enhanced Over Present Data Base
  - Possible Use in Landing Site Selection for Mission From Planet Earth
- Multispectral Imagery of Lunar Polar Regions and Far Side to Infer Mineralogical Composition
# Mission Overview

<table>
<thead>
<tr>
<th>Modification Requirements</th>
<th>Mission</th>
<th>ΔV Requirements (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>Multi-Flybys 1-3</td>
<td>400 --&gt; 750</td>
</tr>
<tr>
<td>Moderate</td>
<td>Multi-Flybys 4-6</td>
<td>1200 --&gt; 1400</td>
</tr>
<tr>
<td>Maximum</td>
<td>Rendezvous</td>
<td>1800</td>
</tr>
</tbody>
</table>

Based on Present Knowledge of Baseline Planned ΔV Capability
## Encounter Parameters: Multi-Flybys 1-3

<table>
<thead>
<tr>
<th>Encounter</th>
<th>Sun Distance (AU)</th>
<th>Earth Distance (AU)</th>
<th>Phase Angle (Degrees)</th>
<th>Flyby Speed (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographos August 25, 1994</td>
<td>1.03</td>
<td>0.034</td>
<td>140</td>
<td>11.8</td>
</tr>
<tr>
<td>Giacobini-Zinner November 28, 1998</td>
<td>1.04</td>
<td>0.86</td>
<td>104</td>
<td>20.9</td>
</tr>
<tr>
<td>Loose Lunar Orbit</td>
<td>1.00</td>
<td>0.003</td>
<td>0 – 180</td>
<td>—</td>
</tr>
</tbody>
</table>
Spacecraft Issues: Multi-Flybys 1-3

- Launch Vehicle: Pegasus ($C_3<0$)
- Launch Anytime Before May 1994
- Solar Distances Near One AU (Power, Thermal O.K.)
- Fuel Loading Adequate for Flight Profiles
- Near-Earth Operations for Asteroid Flybys (Permits Simultaneous Radar Observations and Support)
- If Store Data On Board For Playback Near Earth, Use Low Gain Antenna (Full Beamwidth ~100°)
- Required Spacecraft Modifications:
  - Assure Structural Integrity for High Acceleration Kick-Stage
  - Increased Data Storage
  - Add DSN Transponder and Associated Equipment (X-Band)
  - Add Medium Gain Antenna (Full Beamwidth ~12°) for Data Return > 0.1 AU from Earth (Comet Flyby)
## Encounter Parameters: Multi-Flybys 4-6

<table>
<thead>
<tr>
<th>Encounter</th>
<th>Sun Distance (AU)</th>
<th>Earth Distance (AU)</th>
<th>Phase Angle (Degrees)</th>
<th>Flyby Speed (Km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographos</td>
<td>1.03</td>
<td>0.034</td>
<td>140</td>
<td>11.8</td>
</tr>
<tr>
<td>August 25, 1994</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bacchus</td>
<td>1.00</td>
<td>0.072</td>
<td>153</td>
<td>11.3</td>
</tr>
<tr>
<td>March 27, 1996</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1980 PA</td>
<td>1.07</td>
<td>0.081</td>
<td>112</td>
<td>5.9</td>
</tr>
<tr>
<td>November 11, 1996</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dionysius</td>
<td>1.03</td>
<td>0.14</td>
<td>72</td>
<td>11.9</td>
</tr>
<tr>
<td>June 24, 1997</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1983 RD</td>
<td>1.10</td>
<td>0.79</td>
<td>81</td>
<td>8.4</td>
</tr>
<tr>
<td>October 24, 1998</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Giacobini-Zinner</td>
<td>1.04</td>
<td>0.86</td>
<td>104</td>
<td>20.9</td>
</tr>
<tr>
<td>November 28, 1998</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Spacecraft Issues: Multi-Flybys 4-6

- Launch Vehicle: Pegasus ($C_3<0$)
- Launch Anytime Before May 1994
- Solar Distances Near One AU (Power, Thermal O.K.)
- Near-Earth Operations for Early Asteroid Flybys
- If Store Data On Board For Playback Near Earth, Use Low Gain Antenna (Full Beamwidth ~100°)
- Required Spacecraft Modifications:
  - Assure Structural Integrity for High Acceleration Kick-Stage
  - Increased Fuel Loading (Higher $\Delta V$)
  - Increased Data Storage
  - Add DSN Transponder and Associated Equipment (X-Band)
  - Add Medium Gain Antenna (Full Beamwidth ~12°) for Data Return > 0.1 AU from Earth (Comet or Late Asteroid Flyby)

- Assume Known Asteroid Orbit
- Total ΔV Requirement < 6.0 km/s
- Post-Launch ΔV Requirement < 1.8 km/s
- Flight Time < 800 days

<table>
<thead>
<tr>
<th>Target</th>
<th>Launch Date</th>
<th>Total ΔV (km/s)</th>
<th>Post-Launch ΔV (km/s)</th>
<th>ΔV (km/s)</th>
<th>Flight Time (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1982 DB</td>
<td>January 1993</td>
<td>4.66</td>
<td>0.56</td>
<td>4.10</td>
<td>607</td>
</tr>
<tr>
<td>Orpheus</td>
<td>March 1994</td>
<td>5.43</td>
<td>1.43</td>
<td>4.00</td>
<td>453</td>
</tr>
<tr>
<td>1982 XB</td>
<td>December 1995</td>
<td>5.84</td>
<td>1.39</td>
<td>4.45</td>
<td>768</td>
</tr>
</tbody>
</table>

- Orpheus Represents Best Case
  - 1982 DB Too Early – Can't Meet Schedule
  - 1982 XB Too Late – Arrival in 1998
Spacecraft Issues: Orpheus Rendezvous

- Launch Vehicle: Taurus
- Two Week Launch Window in March, 1994, for $C_3 < 23 \text{ km}^2/\text{s}^2$
- Solar Distance Ranges from 0.8 to 1.6 AU
- Earth Distance During Rendezvous Ranges from 1.5 to 2.6 AU (Data Return)
- Potential DSN Conflict with Galileo
- Required Spacecraft Modifications:
  - Assure Structural Integrity for High Acceleration Kick-Stage
  - Increase Fuel Loading (Higher $\Delta V$)
  - Modify Solar Array (Increase Area or Add Pointing Capability)
  - Modify Thermal Control
  - Increased Data Storage
  - Add DSN Transponder and Associated Equipment (X-Band)
  - Add High-Gain Antenna (Full Beamwidth $\sim 3^\circ$)
Technology Team Findings

- Technology Areas of Interest
- Specific Components/Subsystems
- Potential Mission Applications
Technology Team Findings
Technology Areas of Interest to NASA

• Propulsion
  - Lightweight Engines
• Command and Data Handling
  - Very High Density Computer Element Packaging
• Guidance, Navigation, and Control Package
  - WFOV Star Tracker
  - Inertial Maneuvering Unit
• Communications
• Power Systems
  - Batteries
• Sensor Mechanical Cooler
• Instruments/Sensors
  - Optics/CCDs
  - LIDAR
Technology Team Findings
Specific Technologies of Interest to NASA

- WFOV Star Tracker for Real-time Attitude Determination Including Computation Support System (Software, Processing)
  - Low mass (~ 300 g)
  - Combine Innovative Star Tracker and Powerful Information Processor to Produce System Capable to Some Degree of Autonomously Solving Complex Navigational Problems
  - In Context of Discovery Missions, This Capability Could Potentially Reduce Operations Cost in a Rendezvous Mission Since Intense Tracking for Orbit Maintenance Would Not be Required

- Sensor Mechanical Coolers
  - Very Light-weight, Efficient, Long-life Coolers of Great Interest
  - Particular Interest for Mass/Power Constrained Missions (Deep Space - Planetary/Lunar Applications)
  - No Particular Advantage for NASA Low-Earth Orbit Operations
Technology Team Findings
Specific Technologies of Interest to NASA (con’t)

- Miniature, Pumped Hydrazine Propulsion System
  - Pump and Short Design Life Permit Low Dry Mass and Very Large Mass Ratio
  - Short Design Life Precludes Use on Most NASA Missions
  - Potential Application to Probes, Penetrators, and Landers

- High Resolution Optics and LIDAR System
  - Broad Band Sensor with UV, Vis, and IR Capabilities
  - Passive Imaging and Active Capability
  - Imaging and Ranging with One Instrument
  - “…Lasting Benchmark for Compact, Low Mass Instrument Design, Fabrication and Packaging.” (JPL)
  - Potential Application to Descent Vehicles with Simultaneous Imaging and Ranging
• Batteries
  - Lithium-Iodide (LiI) and Nickel-Metal-Hydride (NiMH), High Energy Density
  - Extended Temperature Range (-10 to 45°C)
  - Extended Shelf-Life (5 Years or More)
Technology Team Findings
NASA Programs Which Could Utilize These Technologies

"...the Type of Space Science Mission Most Likely to Benefit from SDIO Subsystem Technology is Probably a Survey-Type Planetary Mission Involving Multiple Identical Spacecraft." (Ames)

MESUR
Potential SDIO Technologies which Could be Utilized:

- Star Tracker
- Visible Sensors and Optics
- Propulsion
- Microcomputers
- Batteries
Technology Team Findings
NASA Programs Which Could Utilize These Technologies

Lunar Network
Components Comparable to Those in MESUR

Mars Rover/Sample Return
Lightweight Components Decrease Launch Vehicle/Propulsion Requirements

Discovery
• Low Cost, Focused Science Missions May Benefit from Any Low Mass, Low Power Components that are ‘Off-the-Shelf’ (e.g., Lunar Gravity Field, Mars/Venus Aeronomy)
• Potential for Multiple Asteroid Missions Enhances Desirability of Autonomous Spacecraft Navigation (Star Tracker)
Recommendations

- Flyby Missions 1-3 are Recommended Based on Initial Study
- Future Work is Recommended After a Mission is Selected to Address the Following Issues:
  - Launch Date
  - Spacecraft Modifications
  - Instrument Calibrations
  - DSN Support
  - Data Reduction
  - Data Analysis
  - Process for Technology Transition (?)
- NASA Centers Recommend Continuing the Exchange of Information on SDIO-Developed Technologies.
  - Ames Proposes Joint Study of SDIO-Developed Technologies for MESUR as a Follow-on to This Study
  - JPL is Pursuing Joint Studies with LLNL on Advanced Electronic Packaging and NiMH Battery Issues Associated with Power
BACKUP CHARTS
Science Team Findings
Earth Asteroid Flyby/Rendezvous and Lunar Flyby/Loose Orbit Science Objectives

- Candidate Wavelengths for Multispectral Imagery Include:
  - 0.40 and 0.56 micron to Measure the UV-Vis Continuum Slope
  - 0.75 micron to Observe a Major Inflection in the Continuum
  - 0.95 and 1.05 micron to Measure Mafic Mineral Abundance
  - 2.00 microns to Measure Mafic Mineral Abundance
  - 2.50 microns to Measure the Continuum
  - 2.90 microns to Measure Water and Water Ice Abundance
  - 3.20 microns to Measure Hydrocarbon Abundance
  - 4.00 microns to Measure the Continuum
Approximate Data Rates

- Assumptions
  - DSN Antenna: 34-meter HEF (If Use 70m, Data Rates Increase 4-5 Times)
  - Spacecraft Radiated Power: 5 Watts (~60 Watts Input)
  - X-Band

<table>
<thead>
<tr>
<th>Distance (AU)</th>
<th>Full Beamwidth (Spacecraft Antenna)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100°</td>
</tr>
<tr>
<td></td>
<td>12°</td>
</tr>
<tr>
<td></td>
<td>~0.2 m Antenna</td>
</tr>
<tr>
<td></td>
<td>3°</td>
</tr>
<tr>
<td></td>
<td>~0.8 m Antenna</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flybys</th>
<th>0.034</th>
<th>0.14</th>
<th>0.86</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5000</td>
<td>250</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>320,000</td>
<td>20,000</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>500</td>
<td>—</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rendezvous</th>
<th>1.6</th>
<th>2.6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>150</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>2400</td>
<td>1000</td>
</tr>
</tbody>
</table>
NEAR-EARTH ASTEROID RENDEZVOUS – 1994 LAUNCH TO 3361 ORPHEUS

MISSION SUMMARY

\[ \frac{C_3}{s^2} = 17.8 \text{ km}^2/\text{s}^2 \]

\[ \text{DLA} = 10.7 \text{ deg} \]

\[ \Delta V_{\text{TOTAL}} = 5.433 \text{ km/s} \]

\[ \text{TRIP TIME} = 453 \text{ days} \]
1994 LAUNCH ORPHEUS (3361) RENDEZVOUS

SPACECRAFT–SUN RANGE (AU) vs. TIME FROM LAUNCH (days)

TIME FROM LAUNCH (days)

SPACECRAFT–SUN RANGE vs. TIME FROM LAUNCH
1994 LAUNCH ORPHEUS (3361) RENDEZVOUS

TIME FROM LAUNCH (days)

SPACECRAFT—EARTH RANGE vs. TIME FROM LAUNCH
1994 LAUNCH ORPHEUS (3361) RENDEZVOUS

TIME FROM LAUNCH (days)

SUN–S/C–EARTH ANGLE vs. TIME FROM LAUNCH