Overview of Mission Architecture Options for Jupiter Deep Entry Probes

Presented by
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Pre-decisional – For discussion purposes only
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Overview

- Study Objectives & Initial Drivers & Previous JDEP studies
- Mission Architecture Trades
- Strawman Payload
- Trajectory options
- Mission study matrix
- Baseline case details
- Technology summaries
- Conclusions & Recommendations
### Previous Jupiter Probe Studies and Mission

<table>
<thead>
<tr>
<th>Mission</th>
<th>Year</th>
<th>Number of probes</th>
<th>Probe mass</th>
<th>Orbiter or Spacecraft</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galileo probe (Galileo Mission)</td>
<td>Entry: Dec.7, 1995</td>
<td>1</td>
<td>m = 339 kg (D = 1.25 m)</td>
<td>Galileo S/C</td>
<td>Down to 20bars; Relative Entry V: 47.37 km/s</td>
</tr>
<tr>
<td>JIMO probe study</td>
<td>2003 (Balint, JPL)</td>
<td>1</td>
<td>160-250 kg w/o prop; ~350 w/ propulsion</td>
<td>JIMO</td>
<td>Down to 100bars</td>
</tr>
<tr>
<td>Jupiter Deep Multiprobes study</td>
<td>1997 (Team X, JPL)</td>
<td>3</td>
<td>143 kg Equator 185.3 kg High Inclination</td>
<td>Carrier/Relay Spacecraft (CRSC)</td>
<td>Down to 100bars</td>
</tr>
<tr>
<td>JDMP (see 1997 study)</td>
<td>2002 (Team X Spilker, JPL)</td>
<td>3</td>
<td>160 kg</td>
<td>CRSC</td>
<td>Down to 100bars</td>
</tr>
<tr>
<td>This study</td>
<td>2004/2005</td>
<td>Multiple probes / multi-descent</td>
<td>Dependent on mission architecture</td>
<td>High thrust, ballistic; Equatorial flyby /w 3 probes as a baseline</td>
<td>Down to 100+ bars</td>
</tr>
</tbody>
</table>

The present study will examine Jupiter Deep Entry Probe mission architecture concepts and the capability requirements to address Jupiter’s extreme environment. The findings could help identifying technology development areas and needs.
Study Objectives

- In order to understand the formation of our Solar System, the Decadal Survey gave high ranking to planetary deep entry probes to the Giant Planets (Jupiter, Saturn, Uranus and Neptune).

- Deep Entry Probes to Jupiter could provide **in-situ “ground truth”** measurements to complement remote sensing results by Juno – the next selected NF mission.

- Jupiter, with its highest gravity well and radiation environment would represent a bounding case for all giant planets deep entry probes.

- This study explores and discusses Jupiter Deep Entry Probes concepts:
  - based on high thrust trajectory mission architectures
  - using a single probe or multiple probes with single or multiple descents
  - descending to a 100+ bars pressure depth

- Identifying various
  - mission architectures (science driven & programmatically relevant)
  - technology drivers (including facilities and analysis capabilities)

- In summary: this study examines the current state of the art regarding planetary deep entry probes and recommends strategies, which could enable future deep entry probe missions not only to Jupiter, but to other giant planets as well.
Initial Drivers for a Jupiter Deep Entry Probes Mission

What do we want to know? (Science goals for JDEPs)
- Complete elemental abundance inventory revealed in part by Galileo probe
- Unambiguously determine depth dependence of global wind field below clouds in deep troposphere
- Characterize Jovian cloud system
- Determine deep troposphere thermal structure
- Characterize meteorological, and possible compositional, differences between belts and zones

What can we afford? (proposed+)
- 1 Flagship class mission / Decade
- 3 New Frontiers mission / Decade
- 5 Discovery mission / Decade
- Flagship slots are potentially taken by higher priority science missions:
  - Europa Geophysical Orbiter
  - Titan or Venus In-Situ Explorer
  - Neptune Orbiter / Probes
- Heritage mission cost comparison:
  - Cassini: ~$2.6B-$3.3B (FY05)
  - Galileo: ~$2.5B (FY04)
  - Galileo probe: ~$250M (FY80)
  - FY80 x ~2.7 = ~$700M (FY05)

Note: try targeting New Frontiers class for the JDEPs mission concept (since we are potentially out of Flagship class allocations for the next 3 decades)

Ref: R. Young

Ref: +Source: APIO SSE SRM – 2005
Mission Architecture Trades

**Trade Element (decision driver)**

- **Launch vehicle (lower cost)**
  - Delta IV-H (4050H-19)
  - Atlas V 521
  - High thrust direct
  - Low thrust direct
  - HT Gravity Assist
  - LT GA

- **Trajectory (target mission timeframe)**
  - 2013 Direct
  - 2014 Direct
  - 2012 EGA
  - 2015 EGA
  - 2013 EGA
  - 2014 EGA

- **Launch opportunity (mission timeframe)**
  - Orbiter with Probe(s)
  - Flyby with Probe(s)
  - Polar approach
  - Equatorial approach

- **Approach (comm, TPS)**
  - One
  - Two
  - Three
  - Four or more

- **Number of probes (science)**
  - Half size (dimensions)
  - Galileo class
  - Half size (mass)

- **Descent module(s) (simplicity)**
  - Single descent
  - Two or multiple descents

- **Descent depth (science)**
  - 20 bars
  - 100 bars
  - 200 bars

- **Descent mode (visibility, comm, extr.env)**
  - Parachute only
  - Chute 20bars+freefall 100 bars
  - Chute 20 bars+freefall to 200 bar

- **Telecom Architecture (physics)**
  - Orbiter/Flyby Store and Dump Relay Telecom
  - Direct-to-Earth Telecom

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- **Pre-decisional – For discussion purposes only**
### Strawman Payload for the Jupiter Deep Probes (1 of 2)

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GCMS or equivalent [H]</strong></td>
<td>(noble gases and isotopes, C, S, N, O, D/H, 15N/14N), to ± 10%</td>
<td>Clarify composition of Jupiter with sufficient accuracy to distinguish abundances of heavy elements with respect to each other. O abundance is crucial objective because Galileo probe did not measure it, and it is fundamental to understanding Jupiter's formation and that of the Solar System.</td>
</tr>
<tr>
<td>Atmospheric structure instrument (accelerometers, gyros, pressure and temperature sensors) Recession measurement [H]</td>
<td>Accelerometers: Same accuracy and resolution as Galileo probe ASI Temperature sensors: Absolute accuracy &lt; 0.1%; resolution 0.03 K Pressure sensors: Absolute accuracy &lt; 0.2%; resolution 0.03%</td>
<td>Define static stability to &lt; 0.1 K/km Identify atmospheric waves in all regions of the atmosphere Gyros: 3 degrees of freedom (for descent reconstruction) Recession measurement: mass ablation from instrumented TPS for entry/descent reconstruction</td>
</tr>
<tr>
<td><strong>Ultra-stable oscillator (USO) [H]</strong></td>
<td>Determine vertical profile of winds to within few meters per second</td>
<td>Wind systems on outer planets not well understood. Vertical extent of winds a large unknown.</td>
</tr>
<tr>
<td><strong>Nephelometer [H]</strong></td>
<td>A simple backscatter nephelometer can accomplish the highest priority goal (see box at right). If the nephelometer were to have dual or multiple wave length capability, be capable of measurement of scattering phase function (ala the Galileo probe nephelometer), and have polarization measurement capability, then several other objectives mentioned in box at right could be addressed as well.</td>
<td>Highest priority is determining cloud location as function of pressure level. Of high interest is characterizing cloud particles and aerosols in terms of composition, particle size distribution, and particle shape</td>
</tr>
</tbody>
</table>

**Assigned Priority:** H- high; M- medium

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*Ref: Personal communications with Rich Young, February 2005 & input from the JDEP Technical Exchange Meeting at ARC*


Pre-decisional – For discussion purposes only
Although Galileo measured the helium abundance on Jupiter very well, this is a measurement that would be included on any probe to one of the other outer planets

He/H₂: to < 2% (Galileo probe HAD accuracy < 2%; Galileo NMS accuracy < 20%)

Deposition of solar and IR planetary radiation affects global energy balance, drives winds, provides information on cloud aerosols, and may be a significant factor in understanding evolution of Jupiter.

Measure net solar flux as function of pressure to as deep as probe descends. Accuracy of ± 2% of net solar flux at top of atmosphere. Have sufficient duty cycle to resolve cloud effects.

Measure net planetary longwave flux as function of pressure. Accuracy of ± 2% of total outgoing longwave flux. Have sufficient duty cycle to resolve cloud effects. Include radiometer channels specific to methane bands to better characterize methane distribution.

Although ortho/para hydrogen ratio thought not to be important for Jovian dynamics, it is thought to be important for Neptune and Uranus dynamics, and perhaps dynamics of Saturn. So have included such an instrument in the instrument list.

Measure atmospheric speed of sound, Cs, to < 0.1%. (Cassini-Huygens acoustic sensor measures Cs to 0.03%)

Needs to distinguish actual ortho/para ratio from either local equilibrium value or deep high temperature equilibrium value.

Although Galileo measured the helium abundance on Jupiter very well, this is a measurement that would be included on any probe to one of the other outer planets.

Note: it can be assumed that due to technology advancements over the past 20 years, the instrument mass on the probes of today would be about half of Galileo’s instrument mass allocation.

**Assigned Priority: H- high; M- medium**

*Ref: Personal communications with Rich Young, February 2005*
Trajectories: Methodology & Assumptions

- The study used bounding case scenarios, such as:
  - Highest mass to be delivered by a Delta IV-H LV to Jupiter (it was found early on that this option is not affordable, thus, the mission concept was descoped by working backward from probe sizes to allow for smaller launch vehicles and to reduce mission cost)
  - Deep entry probe(s) to Jupiter - which is the largest planet in our Solar System with the highest gravity well and high radiation

- Various launch opportunities were be assessed, from which a baseline case was identified. The selection was based on delivered mass and launch date in line with potential SSE roadmap opportunities. The delivered mass to Jupiter then was used and partitioned for the probe / probes and the relay / flyby / orbiter S/C
  - The various options are listed on the next viewgraph

- It is agreed that science would be satisfied with access to the Equatorial Zone and to the North/South Equatorial Belts, thus reducing access requirements to +/- 15° (this would greatly simplify the mission architecture elements)

- From there, the entry mass was used to specify the probe’s size and configuration, thermal protection system sizing etc.
Launch Vehicle Trade Options at C3=25.6 km²/s²

Assumptions:
- 2015 launch
- Earth Gravity Assist (EGA)
- Flight time: 5 years
- 3 Galileo class probes, with
  - Each probe ~335kg
- Total probe mass:
  ~1100 kg with adapters
- Allocate ~1180 kg for the flyby S/C
- Total mass: ~2280 kg
- Allows for Atlas V 521 L/V
- Approximate cost savings by descoping to Atlas V (521) from Delta IV-H in FY04 is ~$80M (~$120M vs. ~$200M)

Note:
Using a smaller L/V, an equatorial flyby S/C with 3 probes could potentially fit into the New Frontiers mission class

### Vehicle
<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Max. Injected Mass*</th>
<th>Net Mass Before JOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlas V (521)</td>
<td>2775.0 kg</td>
<td>~2280 kg</td>
</tr>
<tr>
<td>Atlas V (531)</td>
<td>3240.0 kg</td>
<td>~2660 kg</td>
</tr>
<tr>
<td>Atlas V (541)</td>
<td>3670.0 kg</td>
<td>~3020 kg</td>
</tr>
<tr>
<td>Atlas V (551)</td>
<td>3990.0 kg</td>
<td>~3280 kg</td>
</tr>
<tr>
<td>Delta IV (4050H-19)</td>
<td>5735.0 kg</td>
<td>~4740 kg</td>
</tr>
</tbody>
</table>


By Tibor Balint, JPL, June 9-10, 2005

Pre-decisional – For discussion purposes only
Probes Entry Velocities

- Probe entry velocities with respect to Jupiter's atmosphere and rotation were calculated for various probe options as follows:

- From an **equatorial orbit/entry**, in **prograde** direction (like Galileo), (at the Equator)
  - probe \( v_{\text{atm}} \) = \(~47.3 \text{ km/s}~\)

- From a **polar orbit** (at 30°),
  - probe \( v_{\text{atm}} \) = \(~61 \text{ km/s}~\)
  (Note: due to Jupiter’s rotation, velocity varies from \(~60 \text{ km/s at the Equator}~\) to \(~61.3 \text{ km/s at the pole}~\))

- From an **equatorial orbit**, **retrograde** direction (at the equator),
  - probe \( v_{\text{atm}} \) = \(71.5 \text{ km/s}~\)

Note: Equatorial plane prograde approach is recommended (TPS issues)
# Mission Study Matrix for Jupiter Deep Entry Probes

<table>
<thead>
<tr>
<th>Option #</th>
<th>Mission Type</th>
<th>Number of Probes</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option #2</td>
<td>Equatorial Flyby</td>
<td>Multiple (3) Probes</td>
<td>✅ Three probes, one to the Equator, and one each to +15° and –15°</td>
</tr>
<tr>
<td>Option #3</td>
<td>Equatorial Orbiter</td>
<td>Single Probe</td>
<td>✗ Science requires multiple probes to avoid Galileo like problems (5μ h.s.)</td>
</tr>
<tr>
<td>Option #4</td>
<td>Equatorial Orbiter</td>
<td>Multiple (3) Probes</td>
<td>✗ Second best choice after Option 2, but orbiter would increase mission cost, and Juno will address remote sensing</td>
</tr>
<tr>
<td>Option #5</td>
<td>Polar Flyby</td>
<td>Multiple (3) Probes</td>
<td>✗ One to equator and one each to high longitudes; TPS &amp; Telecom issues</td>
</tr>
<tr>
<td>Option #6</td>
<td>Polar Orbiter</td>
<td>Multiple (2) Probes</td>
<td>✗ See Option 6 + Orbiter option would make it too expensive</td>
</tr>
<tr>
<td>Option #7</td>
<td>Equatorial approach</td>
<td>Multiple (3) Probes</td>
<td>✗ Could satisfy the combined science objectives of Juno &amp; Jupiter Deep Entry Probes, but would be way too costly</td>
</tr>
</tbody>
</table>

**Note:** Direct to Earth (DTE) communication was found to be not feasible, due reasons of large distances; large propulsion needs for probe insertion; and high atmospheric absorption
Option # 2: Equatorial Flyby with 3 Probes (baseline)

- **Assumptions:**
  - Similar to the Galileo Probe, probe released 6 months before entry, however,
  - The flyby relay S/C releases 3 probes (nearly) simultaneously,
  - Probe enters at equator (Equatorial Zone) and at +/- 15° (North/South Equatorial Belts)

- **Advantages:**
  - **Satisfies** all **science** requirements by accessing the Equatorial Zone and North/South Belts
  - Easy simultaneous communications; **good visibility** between probe and flyby relay S/C
  - **Small** mass for **relay S/C** allows for higher mass for the probes

- **Disadvantages:**
  - **Telecom** could be more **complex** with 2 to 3 articulated antennas on the flyby S/C pointing to the probes

Ref: by R. Carnright, JPL (with input from R. Haw, T. Spilker and T. Balint)

Recommended baseline configuration

Note: additional options are listed in the backup viewgraphs
**Probe Descent – On Parachute to 20 bars & Free fall to 200 bars**

- **Descent of a half size probe** is only about 6-7 minutes slower over a 1.5 hour descent to 100 bars.
- This does **not** have a significant impact on telecom, pressure vessel or thermal designs.
- **Note:** the **thermal calculations** were performed for a 2.5 hours descent scenario for a full size probe, which is bounding.

**Probe size**

<table>
<thead>
<tr>
<th></th>
<th>Full size</th>
<th>Half size</th>
<th>Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deploy parachute</td>
<td>172 sec</td>
<td>117 sec</td>
<td>-31.98%</td>
</tr>
<tr>
<td>1 bar (0 km)</td>
<td>408 sec</td>
<td>562 sec</td>
<td>37.75%</td>
</tr>
<tr>
<td>20 bars (-125.7 km)</td>
<td>3460 sec</td>
<td>3720 sec</td>
<td>7.51%</td>
</tr>
<tr>
<td>50 bars (-191.8 km)</td>
<td>4229 sec</td>
<td>4558 sec</td>
<td>7.78%</td>
</tr>
<tr>
<td><strong>100 bars (-252.4 km)</strong></td>
<td><strong>5164 sec</strong></td>
<td><strong>5552 sec</strong></td>
<td><strong>7.51%</strong></td>
</tr>
<tr>
<td>200 bars (-328.9 km)</td>
<td>6753 sec</td>
<td>7175 sec</td>
<td>6.25%</td>
</tr>
</tbody>
</table>

Ref: G. Allen, P. Wercinski, NASA Ames, May 2005
Descent Options & Strategies

<table>
<thead>
<tr>
<th>Option</th>
<th>Descent time</th>
<th>Distance to S/C (km)</th>
<th>Probe Comm Angle (Degrees)</th>
<th>Data volume (Mbits)/Data rate (bps) (req.)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parachute only</td>
<td>2.5 hrs max descent time (driven by visibility with flyby S/C)</td>
<td>~285000 km (<em>slight diff. btw. Equatorial Probe and +/-15° Probes</em>)</td>
<td>30° for Eq. Probe &gt;30° for Probes to the Equatorial Belts (+/-15°)</td>
<td>2.3 Mbits total / 252 bps average (through 2 telemetry strings w/o addition for error mitigation)</td>
<td>Would only reach 89 bars! (If required, we could resize the parachute, thus change its ballistic coefficient and adjust its descent time.)</td>
</tr>
<tr>
<td>Para to 20 bars, free fall to 100 bars</td>
<td>5164 sec (1.43hours)</td>
<td>212100 km - 212800 km</td>
<td><strong>2.5° (Eq. Probe)</strong> 20° (+/-15° Probe)</td>
<td>1.55 Mbits total / 301 bps average</td>
<td>Good visibility between probes and S/C at 100 bars</td>
</tr>
<tr>
<td>Para to 20 bars, free fall to 200 bars</td>
<td>6753 sec (1.87hours)</td>
<td>238000 km - 241000 km</td>
<td>13.3° (Eq.Probe) 13.3° (+/-15° Pr.)</td>
<td>1.7 Mbits total / 251 bps average</td>
<td>The trajectory, pressure vessel, and temperature calculations seem to allow it. Telecom not.</td>
</tr>
</tbody>
</table>

- **Probes release** at 6 months prior to Jupiter entry would not add significantly more complexity to Guidance Navigation and Control.
- **GN&C** for multi-probes is considered **heritage technology** in this study
- **Parachute** in this study is assumed **heritage technology** at TRL9
- Data rate and volume is through **two telemetry strings**, but does not include error check overhead
- In comparison, descent to **22 bars with Galileo probe** took ~58 min
Telecom Approach for the Jupiter Deep Entry Probes

Frequency: **L-band** (~1.35GHz)

**Lower frequency:**
- attenuation by ammonia & water vapor

**Higher frequency:**
- natural synchrotron radiation noise
  (Note: attenuation needs to be further studied in details)

Transmit Antenna D = **0.35 m**
Power = **46 W**

With 2x46W and the same antennas the data rate increases to ~1500 bps, 4 times the required rate (used to mitigate atmospheric attenuation)
(relative to a bounding 241000 km separation distance)

**Data rate (with error checks):**
- ~750 bps

Data to transfer (decreases with depth)

**Total data (w/o error checks):**
- 1.55 Mbits @ 100 bars; 1.43hrs
- 1.70 Mbits @ 200 bars; 1.87hrs
(with error check ~3.1-3.4 Mbits)

Articulated Receive Antenna(s)
D = **2.3 m / probe**

Deploy chute: 172 sec
~152000 km; α: 19°-29°

Freefall

Drop parachute / freefall
- 20 bars: 3460 sec (~1hrs)
~187000 km; α: 7°-22°

- 50 bars: 4229 sec (1.17hrs)
~198000 km; α: 2.5°-20°

- 100 bars: 5164 sec (1.43hrs)
~212700 km; α: 2.5°-20°

- 200 bars: 6753 sec (1.88hrs)
~241000 km; α: 13°-23°

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Data volume:
- 1.25Mbits
- 204 bps
- 157 kbits
- 160 bps
- 150 kbits
- 92 bps
- 146 kbits

Total data (w/o error checks) (through 2 telemetry strings):
- 1.55 Mbits @ 100 bars; 1.43hrs
- 1.70 Mbits @ 200 bars; 1.87hrs

Error check overhead (increases with depth)

With 2x46W and the same antennas the data rate increases to ~1500 bps, 4 times the required rate (used to mitigate atmospheric attenuation)
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Technologies: Thermal Protection System Materials

- In over 40 years, NASA entry probes have only employed a few ablative TPS materials. Half of these materials are (or are about to be) no longer available.

- Jupiter has a hydrogen (85%) & helium (~15%) atmosphere

- During entry the probe encounters multiple environmental factors, such as atmospheric pressure, convective heating, and radiative heating

- Severe radiative heating requires shallow flight paths, posigrade, near-equatorial entries to reduce heating rates and heat loads to achieve useful payload mass fractions

- TPS represents a significant mass fraction (45.4% on Galileo probe)

- For Jupiter probe entry carbonaceous TPS is used (e.g., carbon phenolic on Galileo probe, which could be replaced with new carbon-carbon TPS)

Ref: B. Laub, ARC, SSE Technology Planning meeting, August 26, 2004
• To apply atmospheric reconstruction techniques to entry probe accelerometer data, the aerodynamics (drag coefficient) and the mass of the probe need to be known.

• If there is significant loss of the probes Thermal Protection System (TPS), through ablation, spalding, etc., then the aerodynamics and the mass of the probe are not constant through descent.

• The Galileo probe lost nearly half of its TPS during entry. Thus, if significant (>10%) TPS loss is expected the TPS should be instrumented in such a way that both changes to the probes aerodynamics and mass can be determined as a function of descent.

Ref: A. Colaprete, ARC
• To enable Giant Planetary Deep Entry Probes architectures, technology issues must be addressed
  – Thermal Protection Systems materials
  – Facilities (Arcjet; Laser ablation; Giant Planets Facility – GPF)
  – Analysis and codes (Jupiter Atmospheric Entry (JAE) code to calculate ablation of TPS)
Technologies: Pressure Vessel Design Considerations

- Cross cutting between the Extreme Environments of Jupiter and Venus (i.e., pressure 100 bars vs. 90 bars; temperature over 460°C vs. similar)

- Several materials are evaluated for pressure vessel shell for Venus Lander and Jupiter Deep Entry Probes missions; Titanium (monolithic shell), Inconel 718 (monolithic and honeycomb sandwich construction), and Titanium Metal matrix

- Advanced thermal technologies such as phase change material thermal storage, light weight high temperature thermal insulation, and advanced concepts for thermal configuration of the thermal enclosure are evaluated

- The environmental conditions and physical configuration considered are as follows:
  - Jupiter environment ~500°C and ~100 bars at ~250 km depth
  - The pressure vessel shell evaluated is of 56-60 cm diameter (similar to Galileo)

- Assumed
  - a conservative and bounding 2.5 hours descent time
  - electronic and science equipment inside the thermal enclosure should not exceed 125°C

- The preliminary structural and thermal trade-off and analyses show the following mass for one of the materials
  - Titanium metal matrix will have a mass of about 50 kg

Ref: M. Pauken, G. Birur, N. Emis, JPL
Technologies: Pressure Vessel Design Concept

Thermal model represents simplified probe (shown as a cut away view)

1.5 cm inner structural shell
5 cm outer insulation
2.2 kg PCM material

Electronics 1
(148 W, 17.4 kg)

Electronics 2
(Transmitter)
(92 W, 17.4 kg)

(Assumed 2x Galileo’s power dissipation)
Structural shell inner diameter = 0.43 m,
Outside diameter = 0.56 m

Note: Analysis proved the concept
to 100 bars and 500°C for 2.5 hours;
Thus, a pressure vessel with insulation
and Phase Change Material (PCM)
could enable the probe mission for this
pressure/temperature environment.
Note: the volume and mass gains from the new smaller instruments are likely negated; and with the additional needs to size up the telecom system, the probe would likely not be smaller than the Galileo probe. Thus in the study the baseline is a Galileo size probe with a mass of about 335kg and aeroshell diameter of 1.25m
## Summary of Technologies for Deep Entry Probes

<table>
<thead>
<tr>
<th>Technologies (partial list)</th>
<th>Availability</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch vehicle</td>
<td></td>
<td>Mission class would drive LV selection</td>
</tr>
<tr>
<td>Flyby S/C</td>
<td></td>
<td>For the simplest &amp; most cost effective architecture</td>
</tr>
<tr>
<td>- GN&amp;C</td>
<td></td>
<td>Heritage based, standard</td>
</tr>
<tr>
<td>- Telecom (S/C-Earth)</td>
<td></td>
<td>Heritage, standard store and dump; assumed DSN array (not required)</td>
</tr>
<tr>
<td>- Power &amp; propulsion</td>
<td></td>
<td>Flyby S/C was assumed given, standard propulsion and power</td>
</tr>
<tr>
<td>- Avionics</td>
<td></td>
<td>Standard, heritage</td>
</tr>
<tr>
<td>Jupiter Deep Entry Probes</td>
<td></td>
<td>Some Galileo heritage</td>
</tr>
<tr>
<td>- TPS</td>
<td></td>
<td>Needs significant technology investment in: <strong>TPS materials development; testing; facilities; design/analysis tools</strong></td>
</tr>
<tr>
<td>- Instruments</td>
<td></td>
<td>Some heritage from Galileo, but smaller mass/volume/power; improvements in data processing; sampling from 20-100 bars</td>
</tr>
<tr>
<td>- Extreme environments</td>
<td></td>
<td>Needs development in <strong>pressure vessel</strong> and thermal design (high temperature and high pressure; cross cutting with Venus environment); <strong>Radiation</strong>: estimated that at 3Rj=~200kRad; a 100mil Al shielding would reduce radiation by ~40 fold; 20mil by ~10fold</td>
</tr>
<tr>
<td>- Parachute</td>
<td></td>
<td>Galileo heritage</td>
</tr>
<tr>
<td>- Autonomy &amp; GN&amp;C</td>
<td></td>
<td>Assumed standard and heritage</td>
</tr>
<tr>
<td>- Power</td>
<td></td>
<td>Significant improvements in battery technologies since Galileo</td>
</tr>
<tr>
<td>- Telecom (probe-S/C)</td>
<td></td>
<td>Significant <strong>atmospheric absorption</strong>; detailed design is required</td>
</tr>
</tbody>
</table>
Conclusions and Recommendations

- Seven mission architectures were assessed for Jupiter Deep Entry Probes.
- Equatorial flyby with 3 probes was selected as a baseline architecture, with descent to 100 bars. Science requirements asked for targeting the Equatorial Zone and North/South Belts, covering +/-15° from the Equator (driven by mission class).
- Galileo size probes are assumed (driven by extreme environments p,T).
- Most technologies are available, however, key enabling technologies require significant technology investments. These are:
  - Thermal Protection Systems (materials, facilities, analysis codes)
  - Pressure vessel designs and materials (including thermal management)
  - Telecom between probe and S/C (significant atmospheric absorption)
- TPS development requires urgent attention. The development time can take up to 6-7 years with the startup of GPF, and development of new materials.
- Probes and technologies developed for Jupiter could enable probe missions to other Giant Planets destinations (Neptune, Saturn, Uranus).
- It is recommended to perform a larger scope point design study on Jupiter Deep Entry Probes in order to further refine the trade space and mission options.
- Such a study should involve multiple NASA centers and the science community.
Thanks for your attention
Any questions?
Backup Slides
TPS:

Studies and analyses presented at the NASA Roadmapping meeting at NASA ARC, August 2004
• Cheatwood, N., Corliss, J., “Planetary Probes, Descent System Technologies”, NASA Langley
• Abraham, D., “Communications Considerations for Outer Planets Probes”, JPL
• Hartman, J., “Test Facilities”, NASA ARC
• (?) Cutts, J., “Technology Assessment Process”
• Kolawa, E., “Extreme Environment Technologies”
• Laub, B., “Planetary Exploration: Missions and Material Needs”, NASA ARC
• Spilker, T., “Technology Needs for Tomorrow’s Entry Vehicle Missions”, JPL

White Paper:

Instruments:
Young, R., “Jupiter Probe Instruments”, Personal Communications, January 24, 2005

Additional information is available from the 1st and 2nd International Planetary Probe Workshop presentation materials
References – mission and concept studies

• Jupiter probe from JIMO, single equatorial probe:

• Jupiter Multi-probes, polar flyby relay, 3 probes, N-Eq-S

• Jupiter multi-probes, polar orbiter, 3 probes, N-Eq-S

Other

• Haw, R., Personal communications, Jan-April 2005
• Carnright, R., Personal communications, Jan-April 2005
• Spilker, T., Personal communications, Jan-April 2005
• Young, R., Personal communications, Jan-April 2005
### Galileo Probe Mass Summary (JDEP would be similar)

<table>
<thead>
<tr>
<th>Item / Subsystem</th>
<th>Mass (kg)</th>
<th>Mass Subtotals (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deceleration Module</td>
<td></td>
<td>213.4</td>
</tr>
<tr>
<td>Forebody heat shield</td>
<td>152.1</td>
<td></td>
</tr>
<tr>
<td>Afterbody heat shield</td>
<td>16.8</td>
<td></td>
</tr>
<tr>
<td>Structure</td>
<td>25.5</td>
<td></td>
</tr>
<tr>
<td>Parachute</td>
<td>8.2</td>
<td></td>
</tr>
<tr>
<td>Separation hardware</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>Harness</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>Thermal control</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>Descent module</td>
<td></td>
<td>117.6</td>
</tr>
<tr>
<td>Communications subsystem</td>
<td>13.0</td>
<td></td>
</tr>
<tr>
<td>C&amp;DH subsystem</td>
<td>18.4</td>
<td></td>
</tr>
<tr>
<td>Power subsystem</td>
<td>13.5</td>
<td></td>
</tr>
<tr>
<td>Structure</td>
<td>30.4</td>
<td></td>
</tr>
<tr>
<td>Harness</td>
<td>9.1</td>
<td></td>
</tr>
<tr>
<td>Thermal control</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>Science instruments</td>
<td>28.0</td>
<td></td>
</tr>
<tr>
<td>Separation hardware</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td><strong>Probe Total</strong></td>
<td></td>
<td><strong>331.0</strong></td>
</tr>
<tr>
<td>Probe / Orbiter adapter</td>
<td>6.8</td>
<td></td>
</tr>
<tr>
<td>Relay radio hardware</td>
<td>23.2</td>
<td></td>
</tr>
<tr>
<td>Receiver (2)</td>
<td>20.1</td>
<td></td>
</tr>
<tr>
<td>Antenna</td>
<td>3.1</td>
<td></td>
</tr>
</tbody>
</table>


Pre-decisional – For discussion purposes only

**Science Instruments:**
- **(ASI)**: Atmosphere structure instrument
- **(NEP)**: Nephelometer
- **(HAD)**: Helium abundance detector
- **(NFR)**: Net flux radiometer
- **(NMS)**: Neutral mass spectrometer
- **(LRD/EPI)**: Lighting and radio emission detector/ energetic particle detector
Galileo Probe Science Instrument Accommodation

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Mass</th>
<th>Power</th>
<th>Bit rate</th>
<th>Volume</th>
<th>Special Acc. Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere structure instrument (ASI)</td>
<td>4.0 kg</td>
<td>6.3 W</td>
<td>18 bps</td>
<td>3100 cm³</td>
<td>Pressure inlet port; temperature sensor outside boundary layer; 12,408 bits storage</td>
</tr>
<tr>
<td>Nephelometer (NEP)</td>
<td>4.8 kg</td>
<td>13.5 W</td>
<td>10 bps</td>
<td>3000 cm³</td>
<td>Free-stream flow through sample volume; 800 bits data storage; pyro for sensor deployment</td>
</tr>
<tr>
<td>Helium abundance detector (HAD)</td>
<td>1.4 kg</td>
<td>1.1 W</td>
<td>4 bps</td>
<td>2400 cm³</td>
<td>Sample inlet port</td>
</tr>
<tr>
<td>Net flux radiometer</td>
<td>3.0 kg</td>
<td>10.0 W</td>
<td>16 bps</td>
<td>3500 cm³</td>
<td>Unobstructed view 60° cone +/-45° with respect to horizontal</td>
</tr>
<tr>
<td>Neutral mass spectrometer (NMS)</td>
<td>12.3 kg</td>
<td>29.3 W</td>
<td>32 bps</td>
<td>9400 cm³</td>
<td>Sample inlet port at stagnation point</td>
</tr>
<tr>
<td>Lighting and radio emission detector/energetic particle detector (LRD/EPI)</td>
<td>2.5 kg</td>
<td>2.3 W</td>
<td>8 bps</td>
<td>3000 cm³</td>
<td>Unobstructed 4P Sr FOV; RF transparent section of aft cover, 78° full cone view at 41° to spin axis</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>28 kg</td>
<td>62.5 W</td>
<td>128 bps+</td>
<td>24,400 cm³</td>
<td></td>
</tr>
</tbody>
</table>

+ including playback of entry data and miscellaneous allocation: 40 bps


Note: Instrument suite sizes pressure vessel mass / volume / thermal
## Galileo Probe Science Instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Atmosphere Structure Instrument</strong></td>
<td>Provides information about temperature, density, pressure, and molecular weight of atmospheric gases. These quantities were determined from the measured deceleration of the Probe during the atmospheric entry phase. During the parachute-descent phase, the temperature and pressure were measured directly by sensors extending from the body of the spacecraft.</td>
</tr>
<tr>
<td><strong>Neutral Mass Spectrometer</strong></td>
<td>Analyzes the composition of gases by measuring their molecular weights.</td>
</tr>
<tr>
<td><strong>Nephelometer</strong></td>
<td>Locates and measures cloud particles in the immediate vicinity of the Galileo Probe. This instrument uses measurements of scattered light from a laser beam directed at an arm extending from the Probe to detect and study cloud particles.</td>
</tr>
<tr>
<td><strong>Lightning and Radio Emissions Detector</strong></td>
<td>Searches and records radio bursts and optical flashes generated by lightning in Jupiter's atmosphere. These measurements are made using an optical sensor and radio receiver on the Probe.</td>
</tr>
<tr>
<td><strong>Helium Abundance Detector</strong></td>
<td>Determines the important ratio of hydrogen to helium in Jupiter's atmosphere. This instrument accurately measures the refractive index of Jovian air to precisely determine the helium abundance.</td>
</tr>
<tr>
<td><strong>Net Flux Radiometer</strong></td>
<td>Senses the differences between the flux of light and heat radiated downward and upward at various levels in Jupiter's atmosphere. Such measurements can provide information on the location of cloud layers and power sources for atmospheric winds. This instrument employs an array of rotating detectors capable of sensing small variations in visible and infrared radiation fluxes.</td>
</tr>
<tr>
<td><strong>Energetic Particles Instrument</strong></td>
<td>Used before entry to measure fluxes of electrons, protons, alpha particles, and heavy ions as the Probe passes through the innermost regions of Jupiter's magnetosphere and its ionosphere.</td>
</tr>
<tr>
<td><strong>Relay Radio Science Experiments</strong></td>
<td>Variations in the Probe's radio signals to the Orbiter will be used to determine wind speeds and atmospheric absorptions.</td>
</tr>
<tr>
<td><strong>Doppler Wind Experiment</strong></td>
<td>Uses variations in the frequency of the radio signal from the Probe to derive variation of wind speed with altitude in Jupiter's atmosphere.</td>
</tr>
</tbody>
</table>

*Ref: Personal communications with Rich Young, February 2005*
By Tibor Balint, JPL, June 9-10, 2005

**Probe Off Zenith Angles & Ranges During Descent**

**Good phasing for the probes:**
- Descent to 100 bar takes 1.43 hours (5164 sec)
- Atm. absorption is high
- The flyby S/C is the farthest
- The 2.5° angle for the Equatorial probe is very good
- Probes at +/-15° from Equator must cope with higher absorption at their 20° off zenith angle

<table>
<thead>
<tr>
<th>Probe 1 &amp; 2 (+/-15°)</th>
<th>Probe 3 (Equatorial)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Full size probe</strong></td>
<td><strong>Time (sec)</strong></td>
</tr>
<tr>
<td>Deploy chute</td>
<td>172</td>
</tr>
<tr>
<td>20 bars</td>
<td>3460</td>
</tr>
<tr>
<td>100 bars</td>
<td>5164</td>
</tr>
<tr>
<td>200 bars</td>
<td>6753</td>
</tr>
</tbody>
</table>

Note: due to symmetry, the results for Probe 1 and 3 are the same.
From polar orbit, the difference in probe velocity based on latitude access is negligible.
Because of its higher approach velocity and greater mass, the propellant mass expended during JOI of option A is ~50 kg more than used in option B, but this is still less than the difference between the two Mouet.

Option C uses ~60 kg less propellant than option A (higher velocity, less mass).

Note: L/V & trajectory bound maximum deliverable mass to Jupiter

- Earth Gravity Assist (EGA)
- 2015 Launch
- 5 years flight time
- ~4740 kg is available for probe(s) + relay/flyby/orbiter
## Data Rates from Instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Data rate (b/s) to 20 bar, per telemetry string</th>
<th>Data rate (b/s) 20-50 bar, per telemetry string</th>
<th>Data rate (b/s) 50-100 bar, per telemetry string</th>
<th>Data rate (b/s) 100-200 bar, per telemetry string</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric Structure Instrument (ASI)</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>18</td>
</tr>
<tr>
<td>Helium Abundance Detector (HAD)</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Neutral Mass Spectrometer (NMS)</td>
<td>64</td>
<td>32</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Nepholometer (NEP)</td>
<td>24</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ultra-Stable Oscillator (USO)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Net Flux Radiometer (NFR)</td>
<td>24</td>
<td>12</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>PLAYBACK OF ENTRY DATA and MISCELLANEOUS</td>
<td>40</td>
<td>24</td>
<td>24</td>
<td>12</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td><strong>180</strong></td>
<td><strong>102</strong></td>
<td><strong>80</strong></td>
<td><strong>46</strong></td>
</tr>
</tbody>
</table>

**BIT RATE = 2 x TOTAL for each telemetry string**

<table>
<thead>
<tr>
<th></th>
<th>Total science bits to 20 bars in 1.4 hrs</th>
<th>Total science bits 20-50 bars in 0.3 hrs</th>
<th>Total science bits 50-100 bars in 0.4 hrs</th>
<th>Total science bits 100-200 bars in 1.4 hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Actual descent from Gary/Paul</strong></td>
<td><strong>3460</strong></td>
<td><strong>769</strong></td>
<td><strong>935</strong></td>
<td><strong>1589</strong></td>
</tr>
<tr>
<td>Actual data, updated based on descent</td>
<td><strong>1.25E+06</strong></td>
<td><strong>1.57E+05</strong></td>
<td><strong>1.50E+05</strong></td>
<td><strong>1.46E+05</strong></td>
</tr>
<tr>
<td>Updated: down to 100 bar</td>
<td></td>
<td><strong>1.55E+06</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Updated: down to 200 bar</td>
<td></td>
<td><strong>1.70E+06</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Data rate (average)**

- over 2.5 hours descent: **252**
- updated values down 100 bar: **301**
- updated values down to 200 bar: **251**

*Ref: R. Young, ARC*
What do we know about Jupiter?

- **Ground-based observations**
  - Began with Galileo Galilei – nearly 400 years of history
  - Radio to near-UV
- **Earth-orbit observatories**
  - **Flybys**
    - Pioneers 10 & 11
    - Voyagers 1 & 2
    - Cassini
  - **Orbital**
    - Galileo
  - **Entry Probe**
    - Galileo
- **Near-Jupiter space environment**
  - Low insolation: low temperature
  - Strong magnetic field
    - Intense radiation belts
    - Powerful synchrotron radiation emissions
  - Equatorial dust rings, ~1.4-2.3 Rj
  - Deep gravity well: high speeds
- **Turbulent, zonally-organized atmosphere**
  - Some features stable on 100-year time scales

Model of Jupiter’s Atmosphere

• Composition
  – \( \text{H}_2 \sim 85\% \), He \( \sim 14\% \), \( \text{CH}_4 \sim 0.2\% \)
  – \( \text{H}_2\text{O}, \text{NH}_3, \text{H}_2\text{S}, \) organics, noble gases
  – \( \text{PH}_3? \), CO?
  – Probably many others, especially at depth

• Clouds
  – \( \text{NH}_3 \), 0.25-1 bars
  – \( \text{NH}_4\text{SH}, (\text{NH}_3 + \text{H}_2\text{S}), 2-3 \) bars
  – \( \text{H}_2\text{O}, 5-10 \) bars
  – Other clouds? Silicates?

• Winds and bulk circulation
  – Galileo Probe saw an increase in flow speed with decreasing sunlight
  – Flow speed fairly steady below 5 bars
  – Maximum just under 200 m/s

• Temperatures
  – Minimum \( \sim 110 \) K at the 0.1 bar tropopause
  – Increases with depth below the tropopause:
    – 165 K at 1 bar,
    – \( >670\text{K} (>400\text{°C}) \) at 100 bars;
    – \( >1000\text{K} \) at 1000 bars;


Primary Science Objectives
- Determine Jupiter’s bulk composition
- Characterize Jupiter’s deep atmospheric structure
- Characterize Jupiter’s deep atmospheric winds (dynamics)

Secondary Science Objectives
- Characterize Jupiter’s tropospheric clouds
- Determine the relative importance to large-scale atmospheric flow of Jupiter’s internal energy source and solar energy

References:
- 2001 SSE Decadal Survey Giant Planets Panel
Science Objectives for Jupiter Deep Entry Probes (cont.)

- Down to **100 bar pressure level** (Galileo probe reached to ~23 bar only)
  (a second option of 200 bar was also assessed)

- Sample the vertical profiles of atmospheric composition and behavior, and Jupiter’s deep atmospheric structure, in-situ
  - Ammonia
  - Temp, press
  - Cloud particle composition size & bulk particle density
  - Hydrogen sulfide
  - Ortho-to-para H₂
  - Water vapor
  - Wind speed

- (Secondary objectives: characterize tropospheric clouds; determine the importance of large scale atmospheric flow of Jupiter’s internal energy source and solar energy)

- Avoid non-representative “5-micron hot spot”

  - **Shall be defined through discussions with the science community, such as OPAG and SSES**
  (Note: throughout this study, Rich Young contacted as a contact point to the science community)
Jupiter Deep Multiprobes Mission Design Example

Scenario:
Spacecraft launch Dec, 2012
Deep Space maneuver Dec, 2013
Earth Gravity Assist Oct, 2014
Release probes March, 2018
Jupiter arrival Sep, 2018
Science mission occurs over ~9 hours

Trajectory:
C3 of 27.7 km/s² (w/30 day window)
ΔV-EGA to Jupiter
5.8 years trip time
LV: Delta IV – 4040
1190 kg capability at this C3

• The JDMP study represents a starting point for the present study
• Additional architectures will be assessed, with extended science and mission goals

Ref: Spilker, T., “Multiple Deep Jupiter Atmospheric Entry Probes”, JPL, Decadal Survey Support Studies, Report Published on April 5, 2002

Pre-decisional – For discussion purposes only