Overview of Mission Architecture Options for Jupiter Deep Entry Probes

Presented by

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Graphics by T.Balint

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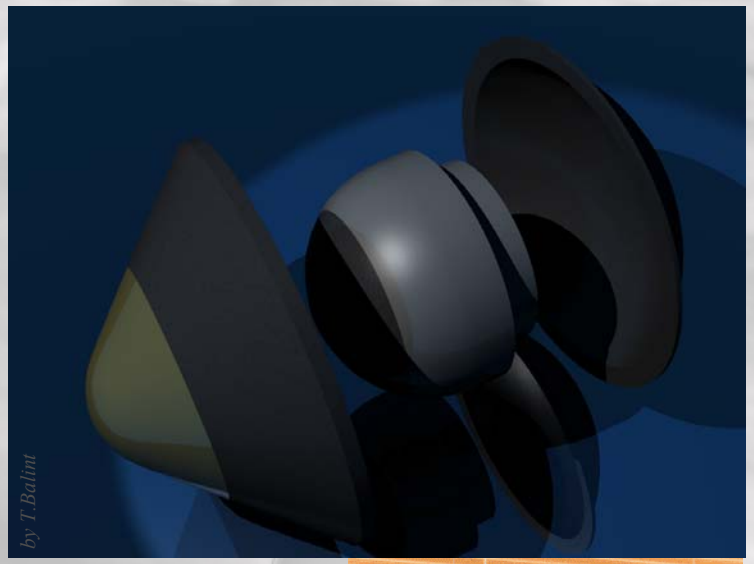
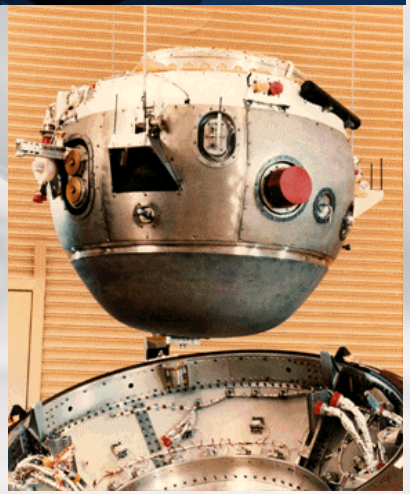
Overview

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





Galileo Probe

Previous Jupiter Probe Studies and Mission

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

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 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

Ref: R. Young

- 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)

Ref: +Source: APIO SSE SRM – 2005

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)

Mission Architecture Trades

Trade Element *(decision driver)*						
Launch vehicle *(lower cost)*	Delta IV-H (4050H-19)	**Atlas V 521**				
Trajectory *(target mission timeframe)*	High thrust direct	**HT Gravity Assist**	Low thrust direct	LT GA		
Launch opportunity *(mission timeframe)*	2013 Direct	2014 Direct	2012 EGA	**2015 EGA**	2013 EGA	2014 EGA
Architecture *(lower cost)*	Orbiter with Probe(s)	**Flyby with Probe(s)**				
Approach *(comm, TPS)*	Polar approach	**Equatorial approach**				
Number of probes *(science)*	One	Two	**Three**	Four or more		
Probe size *(heritage)*	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				

Strawman Payload for the Jupiter Deep Probes (1 of 2)

Instrument [Priority]	Measurement Requirement	Rational for Measurement Requirements
GCMS or equivalent [H]	(noble gases and isotopes, C, S, N, O, D/H, 15N/14N), to ± 10%	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.
Atmospheric structure instrument (accelerometers, gyros, pressure and temperature sensors) Recession measurement [H]	Accelerometers: Same accuracy and resolution as Galileo probe ASI Temperature sensors: Absolute accuracy < 0.1%; resolution 0.03 K Pressure sensors: Absolute accuracy < 0.2%; resolution 0.03%	Define static stability to < 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
Ultra-stable oscillator (USO) [H]	Determine vertical profile of winds to within few meters per second	Wind systems on outer planets not well understood. Vertical extent of winds a large unknown.
Nephelometer [H]	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.	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

Assigned Priority: H- high; M- medium

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

Further Ref: AIAA, "Project Galileo Mission and Spacecraft Design", Proc. 21st Aerospace Science Meeting, Reno, NV, January 10-13, 1983

Strawman Payload for the Jupiter Deep Probes (2 of 2)

Instrument [Priority]	Measurement Requirement	Rational for Measurement Requirements
Dedicated He detector, HAD [M]	He/H2, to < 2% (Galileo probe HAD accuracy < 2%; Galileo NMS accuracy < 20%)	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
Net Flux Radiometer [M]	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.	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.
Acoustic detector [M]	Measure atmospheric speed of sound, Cs, to < 0.1%. (Cassini-Huygens acoustic sensor measures Cs to 0.03%)	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. Need to distinguish actual ortho/para ratio from either local equilibrium value or deep high temperature equilibrium value. Requires accurate independent determination of temperature and perhaps mean molecular weight from thermal structure and composition instruments.

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

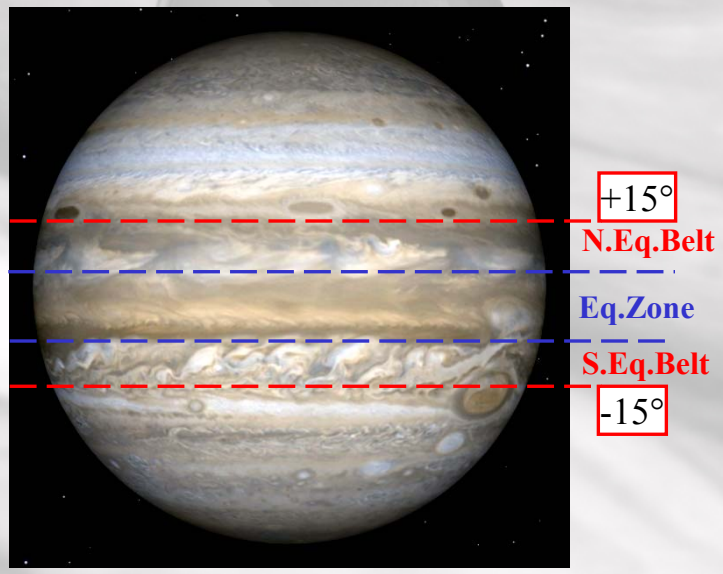
Trajectories: Methodology & Assumptions

- 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

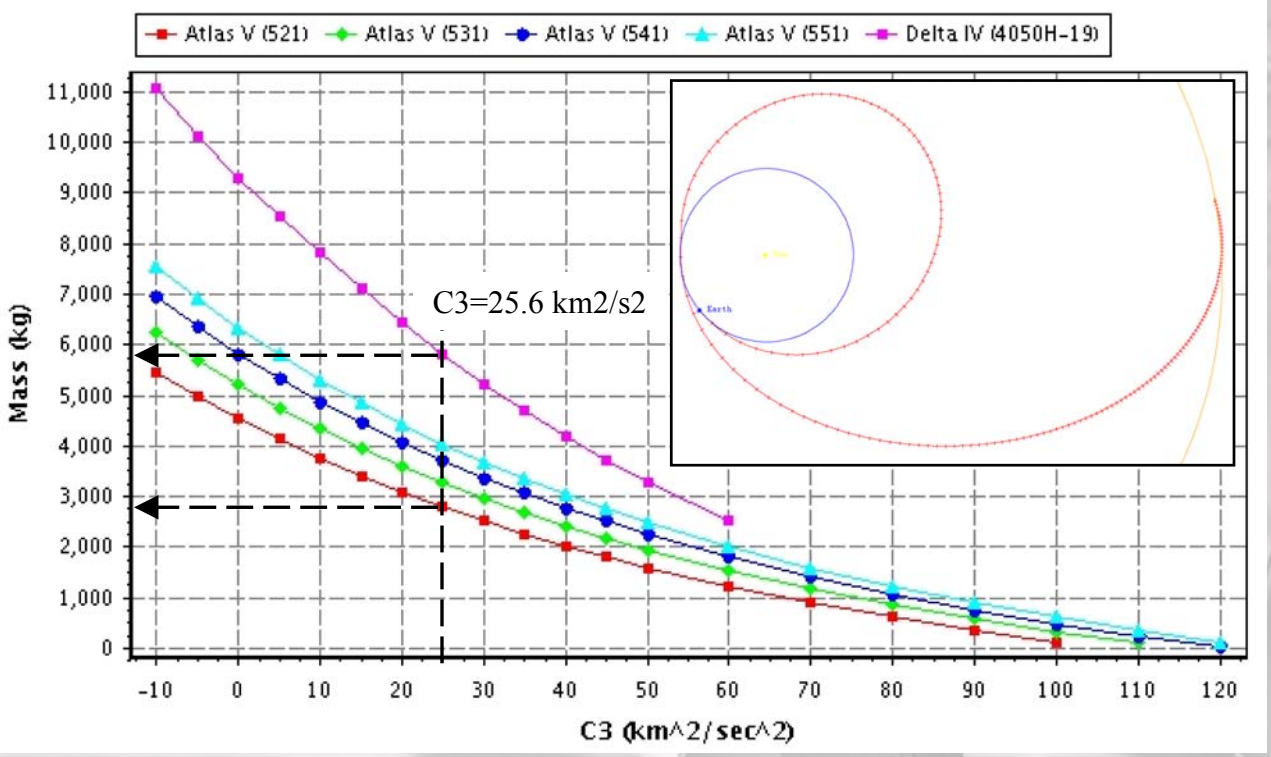
- Various launch opportunities were be assessed, from which a baseline case was identified. The selection was based on delivered mass and launch date in line with potential SSE roadmap opportunities. The delivered mass to Jupiter then was used and partitioned for the probe / probes and the relay / flyby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



Vehicle	Max. Injected Mass*	Net Mass Before JOI
Atlas V (521)	2775.0 kg	**~2280 kg**
Atlas V (531)	3240.0 kg	~2660 kg
Atlas V (541)	3670.0 kg	~3020 kg
Atlas V (551)	3990.0 kg	~3280 kg
Delta IV (4050H-19)	5735.0 kg	**~4740 kg**

*Ref: * http://elvperf.ksc.nasa.gov/elvMap/index.html & R. Haw, JPL*

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

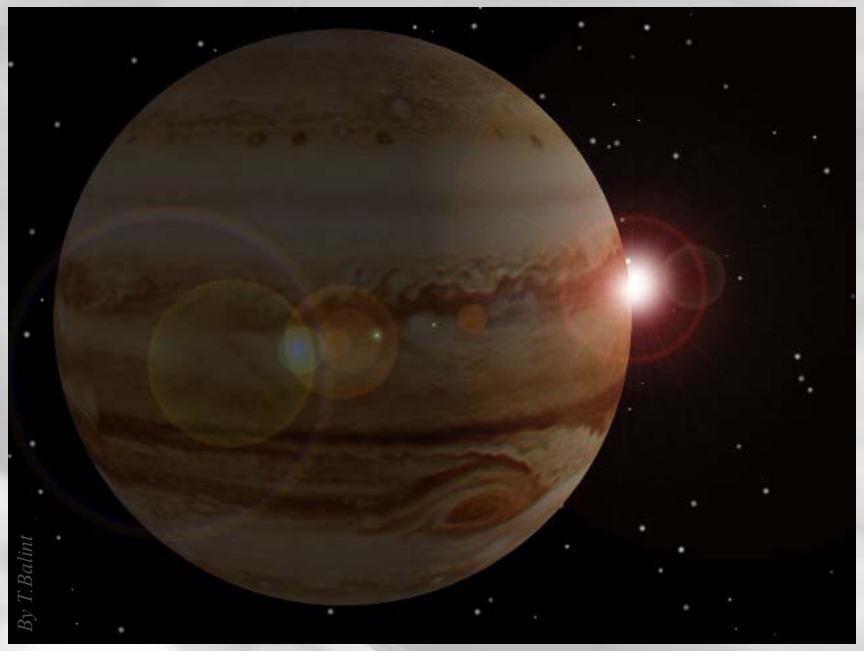
- Approximate cost savings by descoping to Atlas V (521) from Delta IV-H in FY04 is ~$80M *(~$120M vs. ~$200M)*

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

Probe 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(atm) = **~47.3 km/s**



- From a polar orbit (at 30°),
  - probe v(atm) = ~61 km/s
    (Note: due to Jupiter's rotation, velocity varies from ~60 km/s at the Equator to ~61.3km/s at the pole)

- From an equatorial orbit, retrograde direction (at the equator),
  - probe v(atm) = 71.5 km/s

Note: Equatorial plane prograde approach is recommended (TPS issues)

Ref: by R. Haw & T. Balint, JPL

Mission Study Matrix for Jupiter Deep Entry Probes

Option #	Mission Type	Number of Probes	Comments
Option #1	Equatorial Flyby	Single Probe	☒ Science requires multiple probes to avoid Galileo like problems (5μ h.s.)
Option #2	Equatorial Flyby	Multiple (3) Probes	✓ **Three probes, one to the Equator, and one each to +15° and –15°**
Option #3	Equatorial Orbiter	Single Probe	☒ See Option 1 + Galileo mission class, potentially too expensive
Option #4	Equatorial Orbiter	Multiple (3) Probes	☒ Second best choice after Option 2, but orbiter would increase mission cost, and Juno will address remote sensing
Option #5	Polar Flyby	Multiple (3) Probes	☒ One to equator and one each to high longitudes; TPS & Telecom issues
Option #6	Polar Orbiter	Multiple (2) Probes	☒ See Option 6 + Orbiter option would make it too expensive
Option #7	Equatorial approach Polar Orbiter	Multiple (3) Probes	☒ Could satisfy the combined science objectives of Juno & Jupiter Deep Entry Probes, but would be way too costly

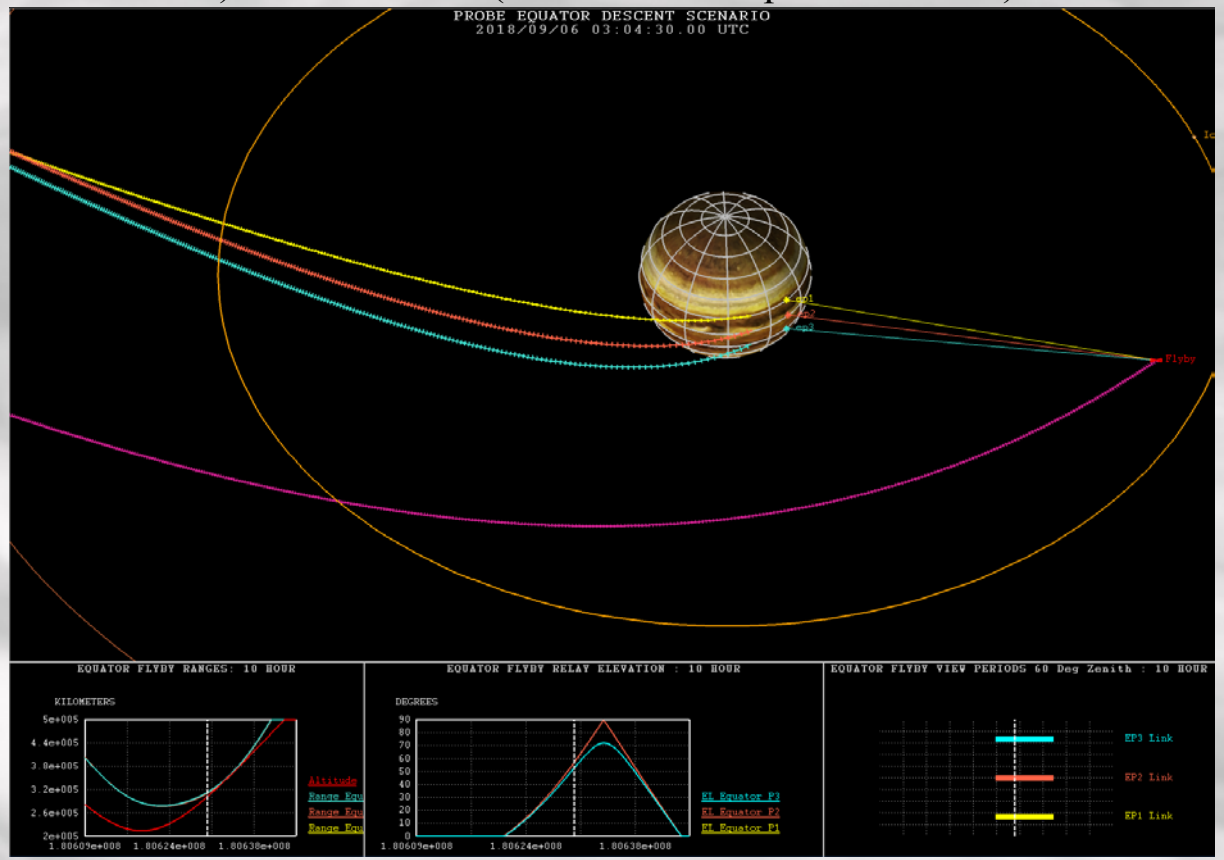
Note: Direct to Earth (DTE) communication was found to be not feasible, due reasons of large distances; large propulsion needs for probe insertion; and high atmospheric absorption

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

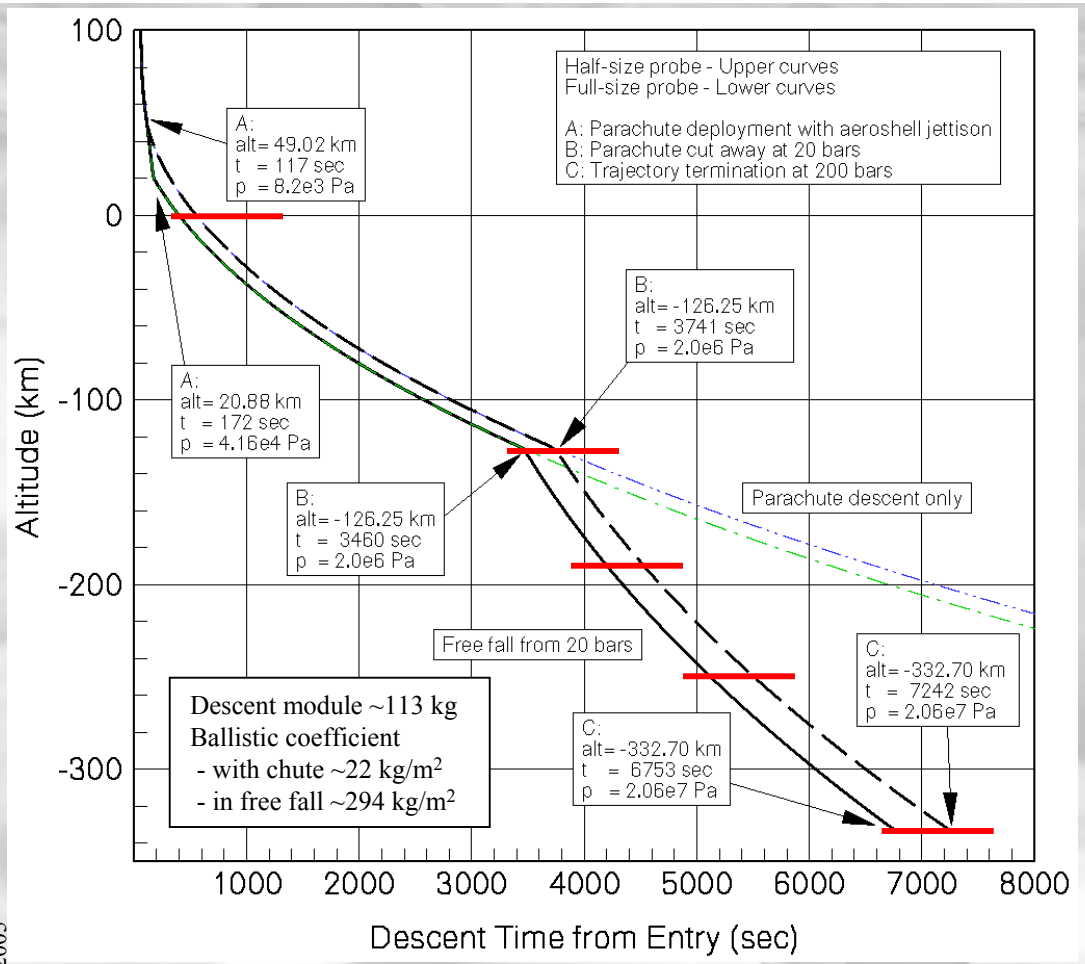


Ref: by R. Carnright, JPL (with input from R. Haw, T. Spilker and T. Balint)

Recommended baseline configuration

Note: additional options are listed in the backup viewgraphs

Probe Descent – On Parachute to 20 bars & Free fall to 200 bars



Probe size	Full size	Half size	*Delta*
Deploy parachute	172 sec	117 sec	*-31.98%*
1 bar (0 km)	408 sec	562 sec	*37.75%*
20 bars (-125.7 km)	3460 sec	3720 sec	7.51%
50 bars (-191.8 km)	4229 sec	4558 sec	7.78%
100 bars (-252.4 km)	**5164 sec**	**5552 sec**	**7.51%**
200 bars (-328.9 km)	6753 sec	7175 sec	6.25%

Ref: G. Allen, P. Wercinski, NASA Ames, May 2005

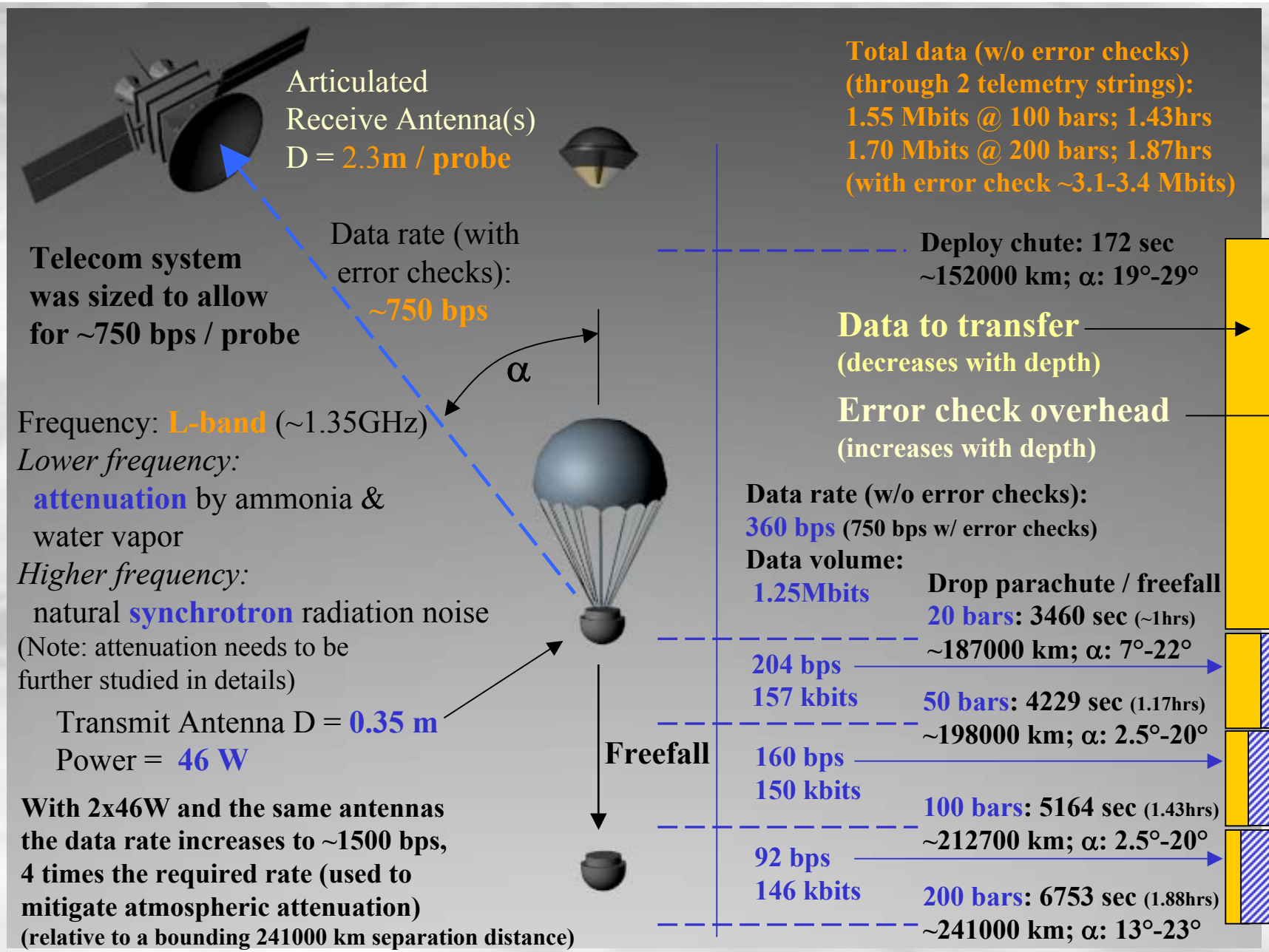
- Descent of a half size probe is only about 6-7 minutes slower over a 1.5 hour descent to 100 bars
- This does not have a significant impact on telecom, pressure vessel or thermal designs
- Note: the thermal calculations were performed for a 2.5 hours descent scenario for a full size probe, which is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

Descent Options & Strategies

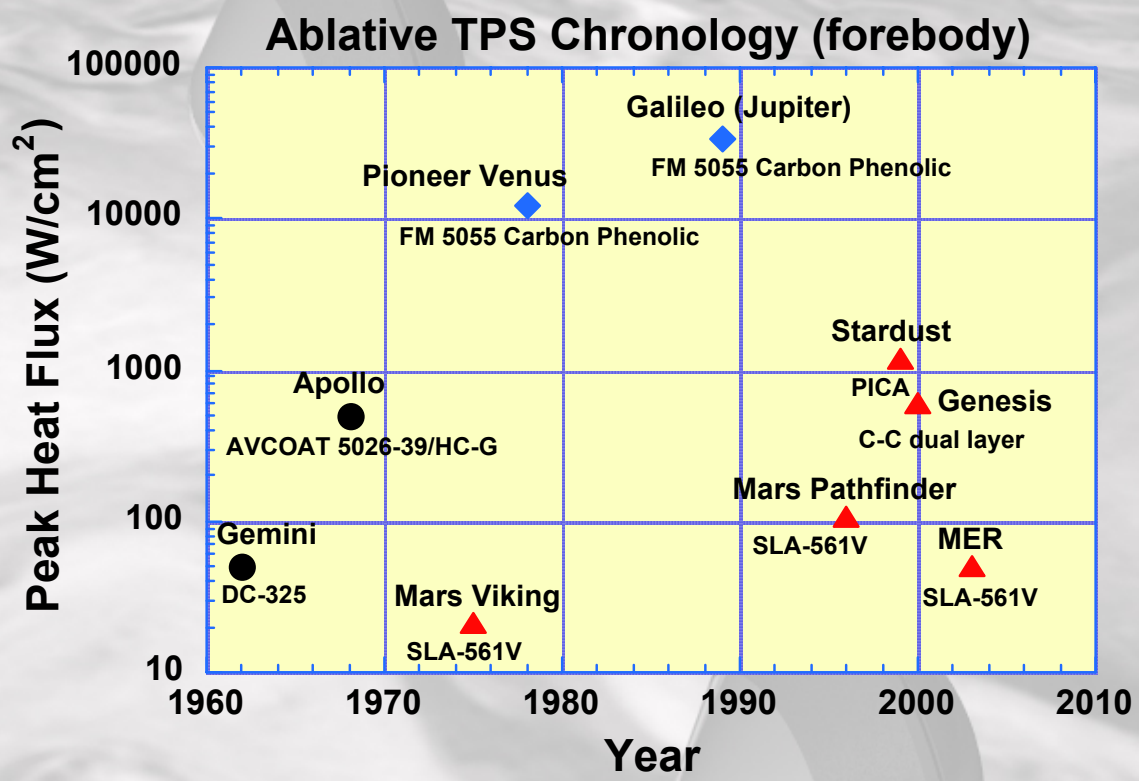
Option	Descent time	Distance to S/C (km)	Probe Comm Angle (Degrees)	Data volume (Mbits)/ Data rate (bps) (req.)	Comment
Parachute only	2.5 hrs max descent time (driven by visiblity with flyby S/C)	~285000 km (slight diff. btw. Eqatorial Probe and +/-15° Probes)	30° for Eq. Probe >30° for Probes to the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

- 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



Technologies: Thermal Protection System Materials



- Still available
- No longer available
- May no longer be available

- **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.**

Ref: B. Laub, ARC, SSE Technology Planning meeting, August 26, 2004

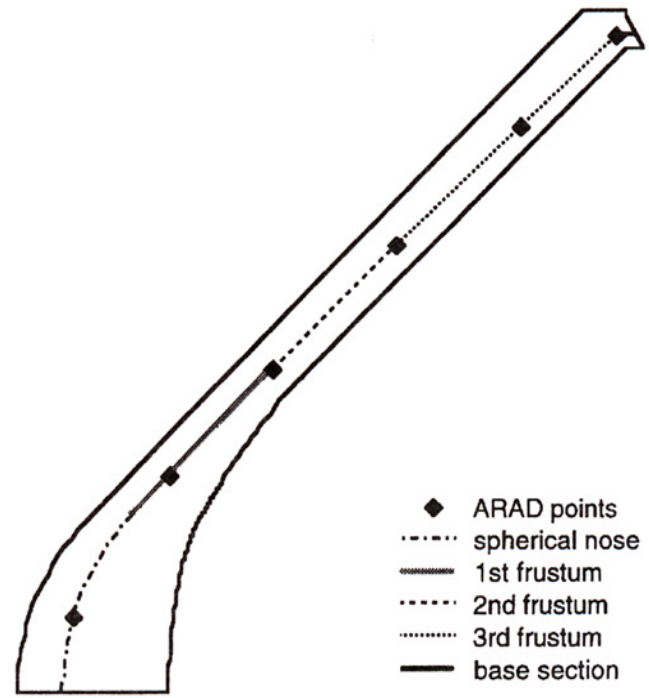
- Jupiter has a hydrogen (85%) & helium (~15%) atmosphere
- During entry the probe encounters multiple environmental factors, such as atmospheric pressure, convective heating, and radiative heating
- Severe radiative heating requires shallow flight paths, posigrade, near-equatorial entries to reduce 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)

Technologies: TPS – Instrumentation of the Heatshield

- To apply atmospheric reconstruction techniques to entry probe accelerometer data, the aerodynamics (drag coefficient) and the mass of the probe need to be know.

- 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.

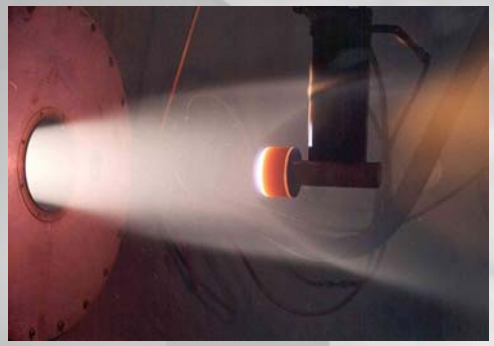


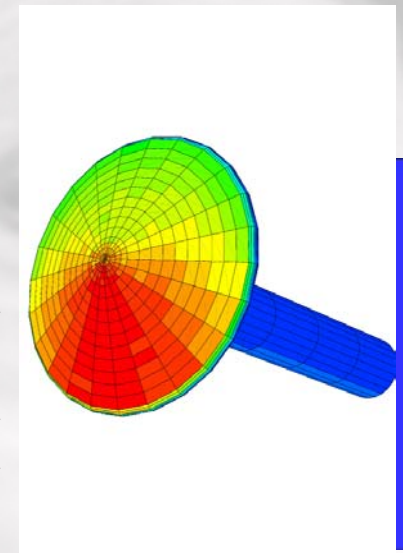
Heat shield shape reconstruction.

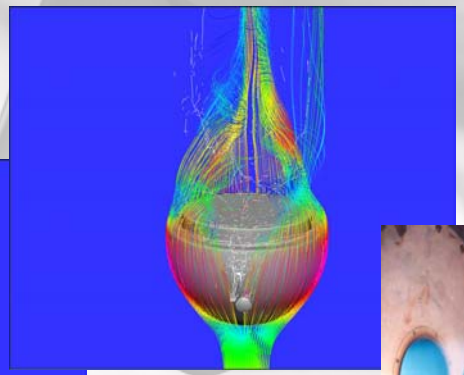
Ref: A. Colaprete, ARC

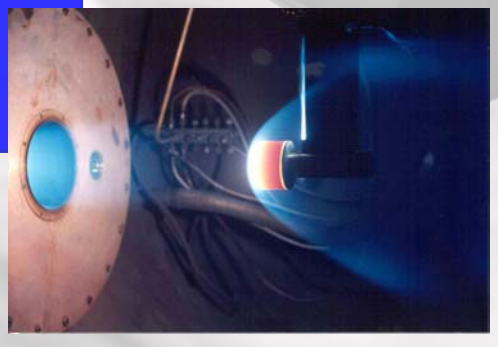
Technologies: TPS Related Facilities and Analysis

- 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

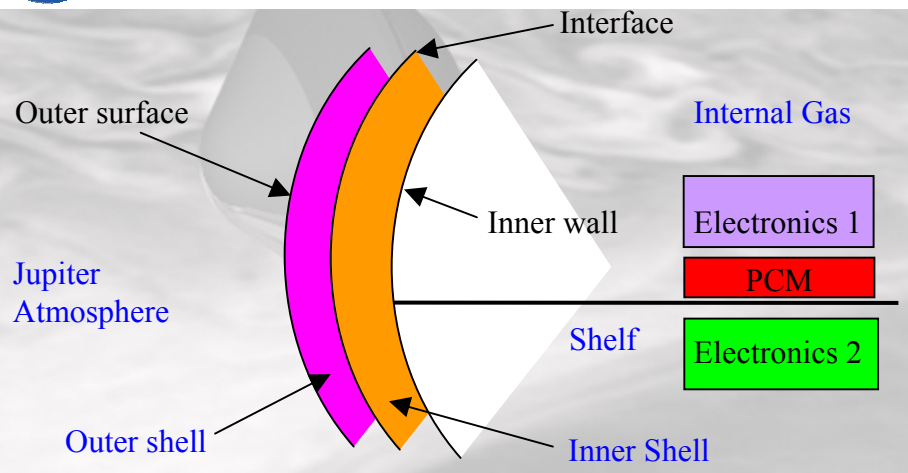
- Cross cutting between the Extreme Environments of Jupiter and Venus (i.e., pressure 100 bars vs. 90 bars; temperature over 460°C vs. similar)

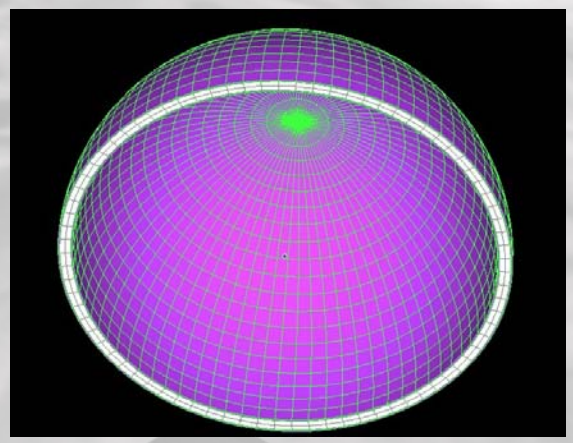
- Several materials are evaluated for pressure vessel shell for Venus Lander and Jupiter Deep Entry Probes missions; Titanium (monolithic shell), Inconel 718 (monolithic and honeycomb sandwich construction), and Titanium Metal matrix
- Advanced thermal technologies such as phase change material thermal 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

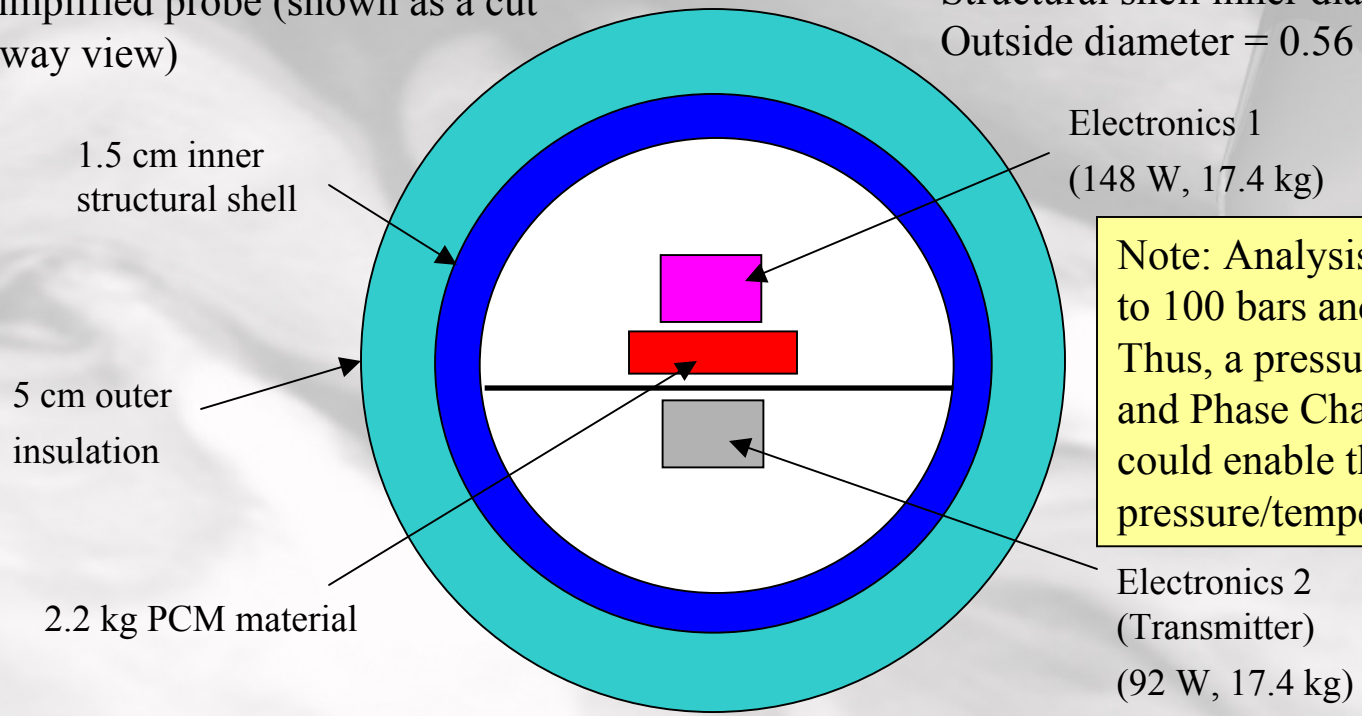
Technologies: Pressure Vessel Design Concept





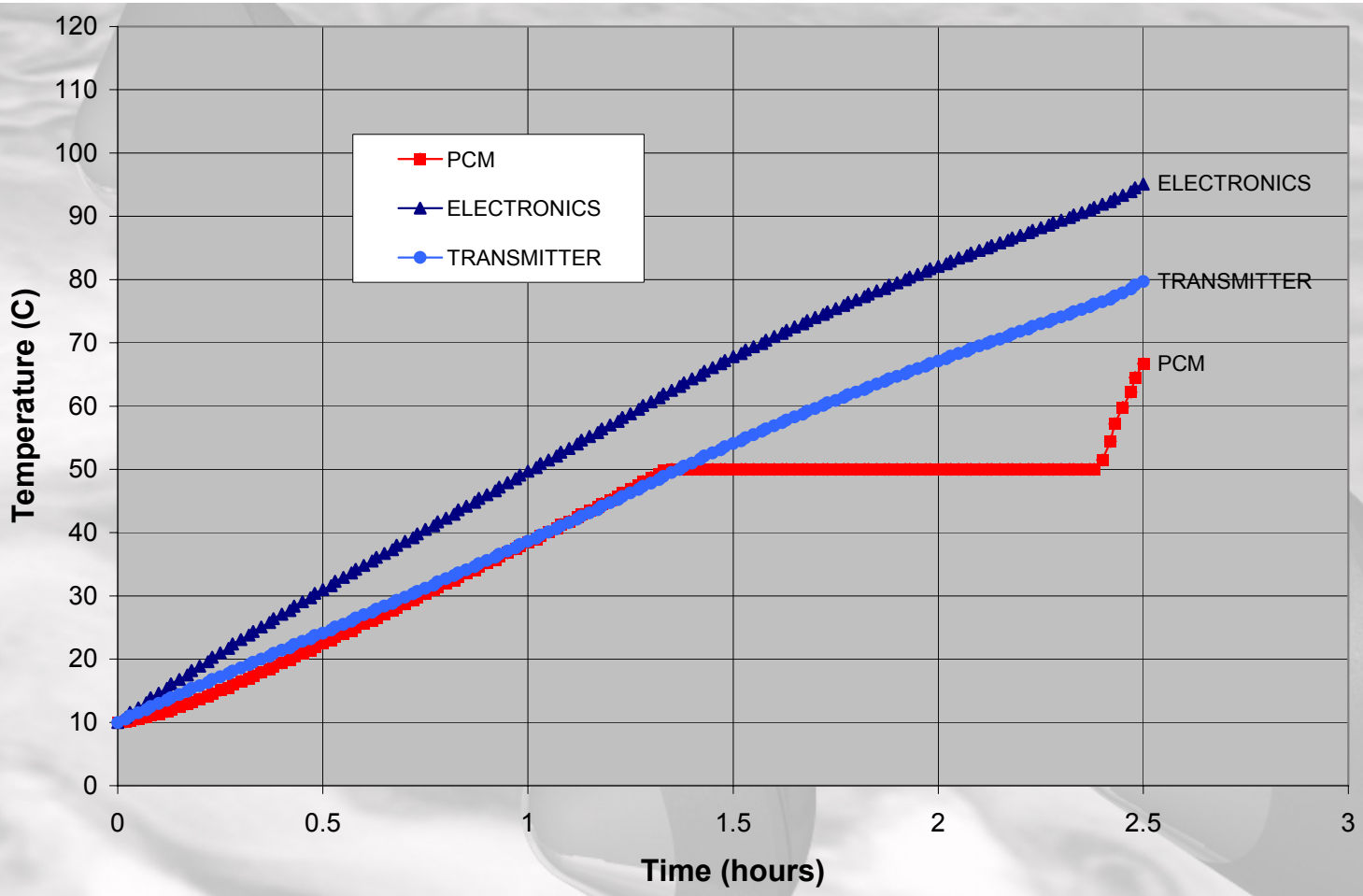
Thermal model represents simplified probe (shown as a cut away view)

(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.

Technologies: Temperature Trends for Jupiter Deep Entry Probes



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

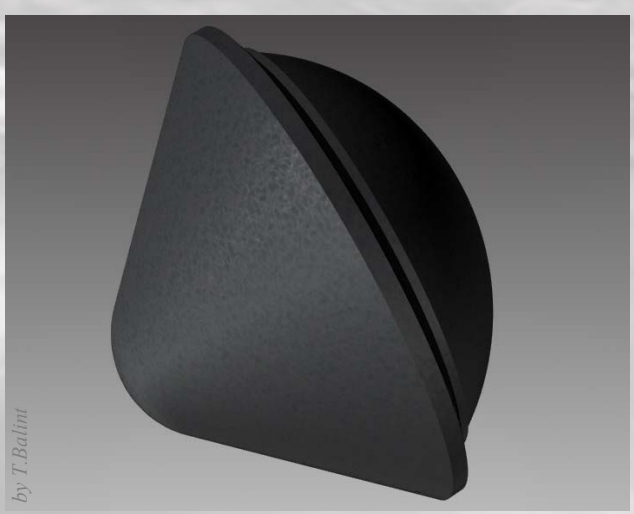
Technologies (partial list)	Availability	Comments
Launch vehicle		Mission class would drive LV selection
Flyby S/C		For the simplest & most cost effective architecture
- GN&C		Heritage based, standard
- Telecom (S/C-Earth)		Heritage, standard store and dump; assumed DSN array (not required)
- Power &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

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?
By T.Balint, JPL, 2005



Backup Slides

References – technology assessments

TPS:

Laub, B., Venkatapathy, E., "Thermal Protection System Technology and Facility Needs for Demanding Future Planetary Missions", Presented at the International Workshop on Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science, Lisbon, Portugal, 6-9 October, 2003

Studies and analyses presented at the NASA Roadmapping meeting at NASA ARC, August 2004

- Wright, M., et al., "Aerothermal Modeling Gaps for Future Planetary Exploration Missions", NASA ARC
- 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:

Young, R., "Entry Probe Workshop: Science Objectives, Required Technology Development", Boulder, CO, April 21-22, 2003

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:
  - Balint, T.S., Whiffen, G.J., Spilker, T.R., 2003, "MIXING MOONS AND ATMOSPHERIC ENTRY PROBES: CHALLENGES AND LIMITATIONS OF A MULTI-OBJECTIVE SCIENCE MISSION TO JUPITER", Paper Number: IAC-2003-Q.2.04, 54th International Astronomical Congress, Bremen, Germany

- Jupiter Multi-probes, polar flyby relay, 3 probes, N-Eq-S
  - Spilker, T, et al., "Jupiter Deep Multiprobes", Decadal Survey Studies, Mission Studies Final Report, April 5, 2002

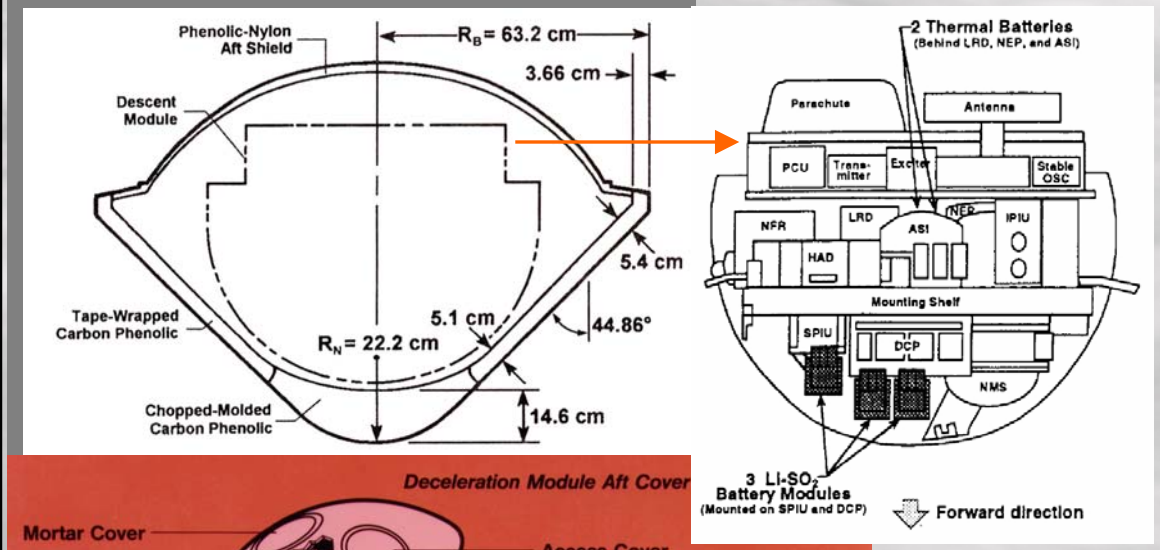
- Jupiter multi-probes, polar orbiter, 3 probes, N-Eq-S
  - Spilker, T., et al., "Jupiter Interior Mission", Decadal Survey Studies, Mission Studies Final Report, April 5, 2002

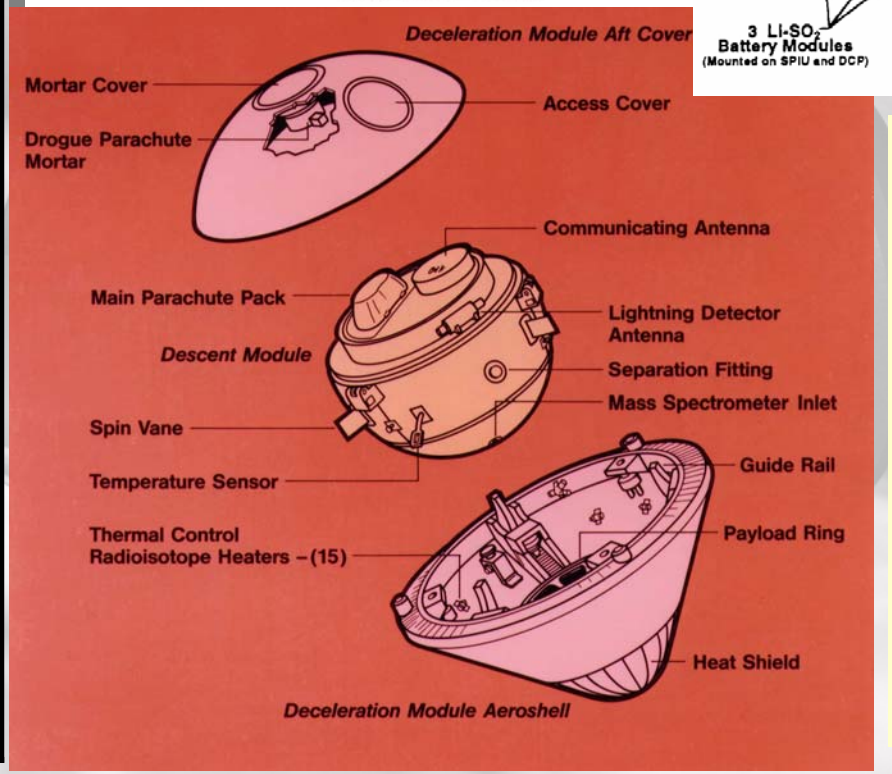
Other

- 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)

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





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

Further Ref: AIAA, "Project Galileo Mission and Spacecraft Design", Proc. 21st Aerospace Science Meeting, Reno, NV, January 10-13, 1983

Galileo Probe Science Instrument Accommodation

Instrument	Mass	Power	Bit rate	Volume	Special Acc. Requirements
Atmosphere structure instrument (ASI)	4.0 kg	6.3 W	18 bps	3100 cm^3	Pressure inlet port; temperature sensor outside boundary layer; 12,408 bits storage
Nephelometer (NEP)	4.8 kg	13.5 W	10 bps	3000 cm^3	Free-stream flow through sample volume; 800 bits data storage; pyro for sensor deployment
Helium abundance detector (HAD)	1.4 kg	1.1 W	4 bps	2400 cm^3	Sample inlet port
Net flux radiometer	3.0 kg	10.0 W	16 bps	3500 cm^3	Unobstructed view 60° cone +/-45° with respect to horizontal
Neutral mass spectrometer (NMS)	12.3 kg	29.3 W	32 bps	9400 cm^3	Sample inlet port at stagnation point
Lighting and radio emission detector/ energetic particle detector (LRD/EPI)	2.5 kg	2.3 W	8 bps	3000 cm^3	Unobstructed 4P Sr FOV; RF transparent section of aft cover, 78° full cone view at 41° to spin axis
Total	**28 kg**	**62.5 W**	**128 bps+**	**24,400 cm^3**	

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

Ref.s: Proc. AIAA'83, 21st Aerospace Science Meeting, Jan. 10-13, 1983, Reno, NV & Personal communications with Rich Young, February 2005

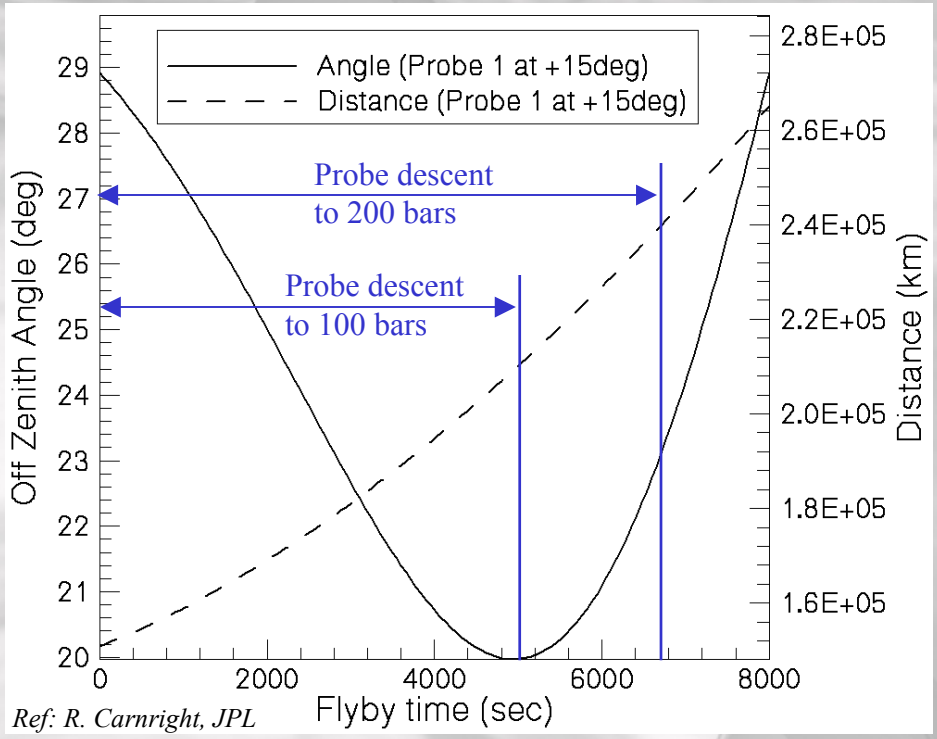
Note: Instrument suite sizes pressure vessel mass / volume / thermal

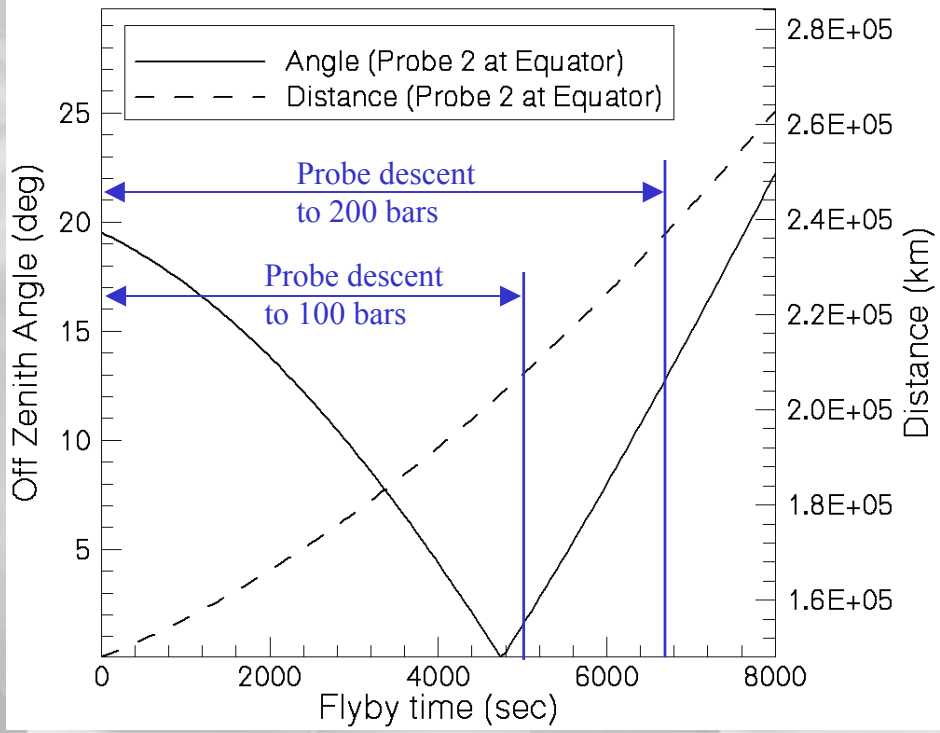
Galileo Probe Science Instruments

Instrument	Description
Atmosphere Structure Instrument	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.
Neutral Mass Spectrometer	Analyzes the composition of gases by measuring their molecular weights.
Nephelometer	Locates and measures cloud particles in the immediate vicinity of the Galileo Probe. This instrument uses measurements of scatterred light from a laser beam directed at an arm extending from the Probe to detect and study cloud particles.
Lightning and Radio Emissions Detector	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.
Helium Abundance Detector	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.
Net Flux Radiometer	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.
Energetic Particles Instrument	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.
Relay Radio Science Experiments	Variations in the Probe's radio signals to the Orbiter will be used to determine wind speeds and atmospheric absorptions.
Doppler Wind Experiment	Uses variations in the frequency of the radio signal from the Probe to derive variation of wind speed with altitude in Jupiter's atmosphere.

Ref: Personal communications with Rich Young, February 2005

Probe Off Zenith Angles & Ranges During Descent





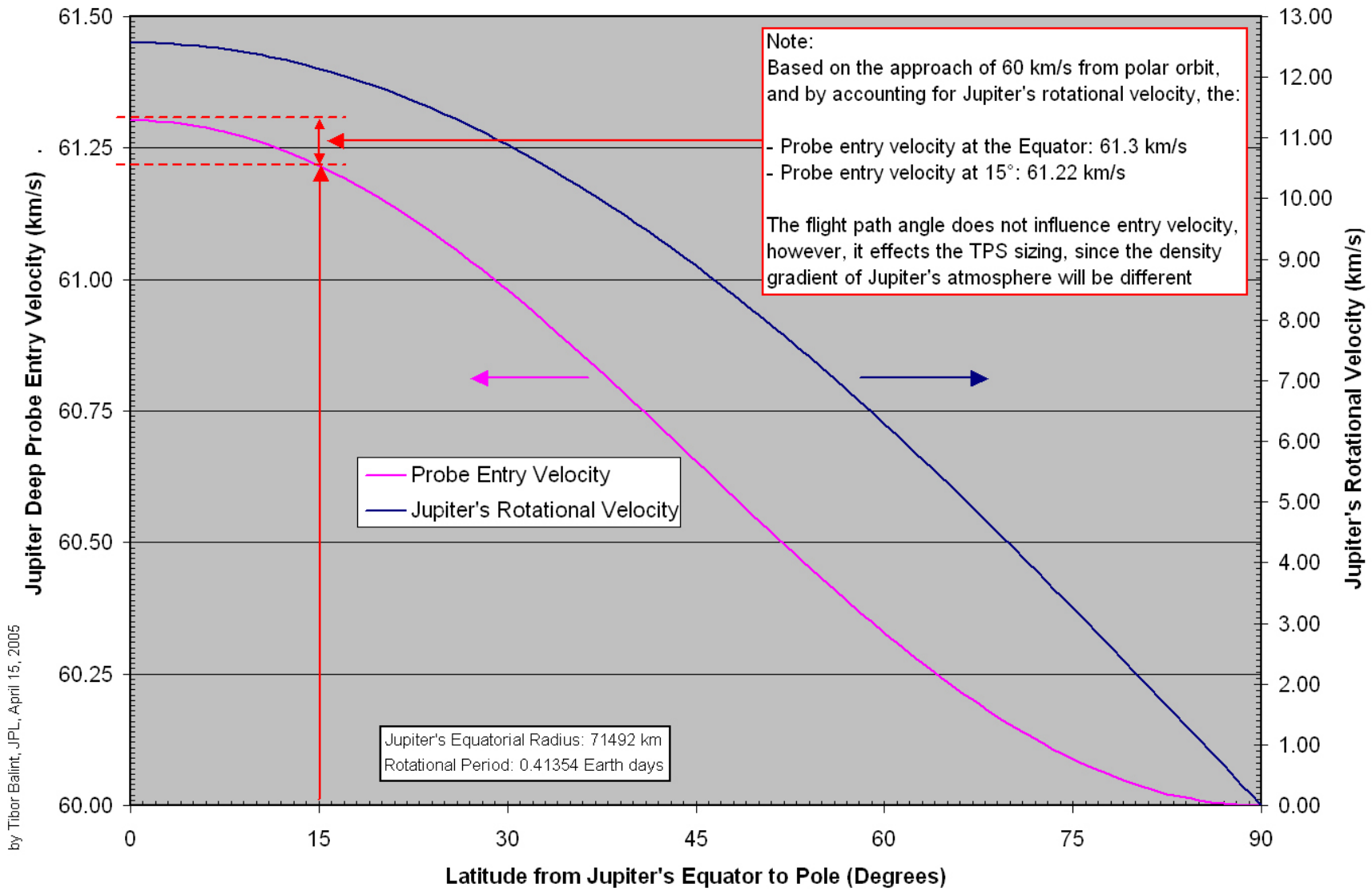
Good phasing for the probes:

- **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**

		Probe 1 & 2 (+/-15°)		Probe 3 (Equatorial)	
Full size probe	**Time (sec)**	**Angle (deg)**	**Range (km)**	**Angle (deg)**	**Range (km)**
Deploy chute	172	28.6°	152200	19.1°	149350
20 bars	3460	21.6°	187300	7.2°	184700
100 bars	**5164**	**20°**	**212700**	**2.5°**	**210050**
200 bars	6753	23.2°	241000	13.1°	238000
Note: due to symmetry, the results for Probe 1 and 3 are the same					

Pre-decisional – For discussion purposes only

Variation of Entry Velocity from Polar Orbit



From polar orbit, the difference in probe velocity based on latitude access is negligible

Trajectories: From Earth to Jupiter

Rentry = 71942 km (Rj+450km)
Mu Jup = 1.27E+08 km^3/s^2

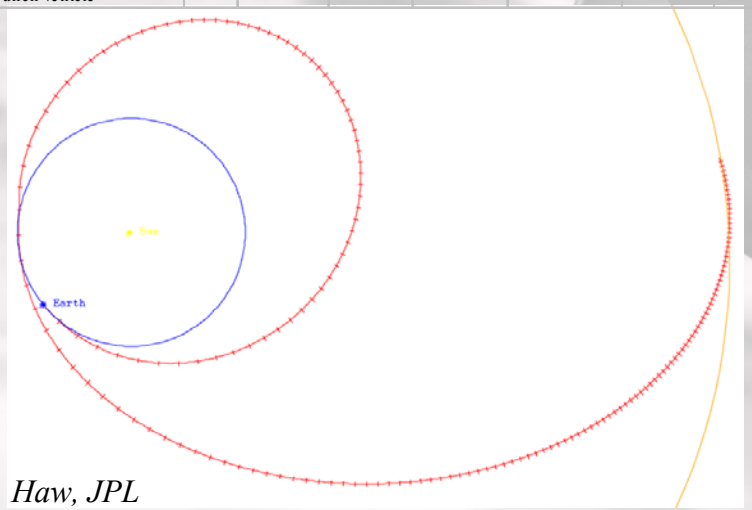
Note: L/V & trajectory bound maximum deliverable mass to Jupiter

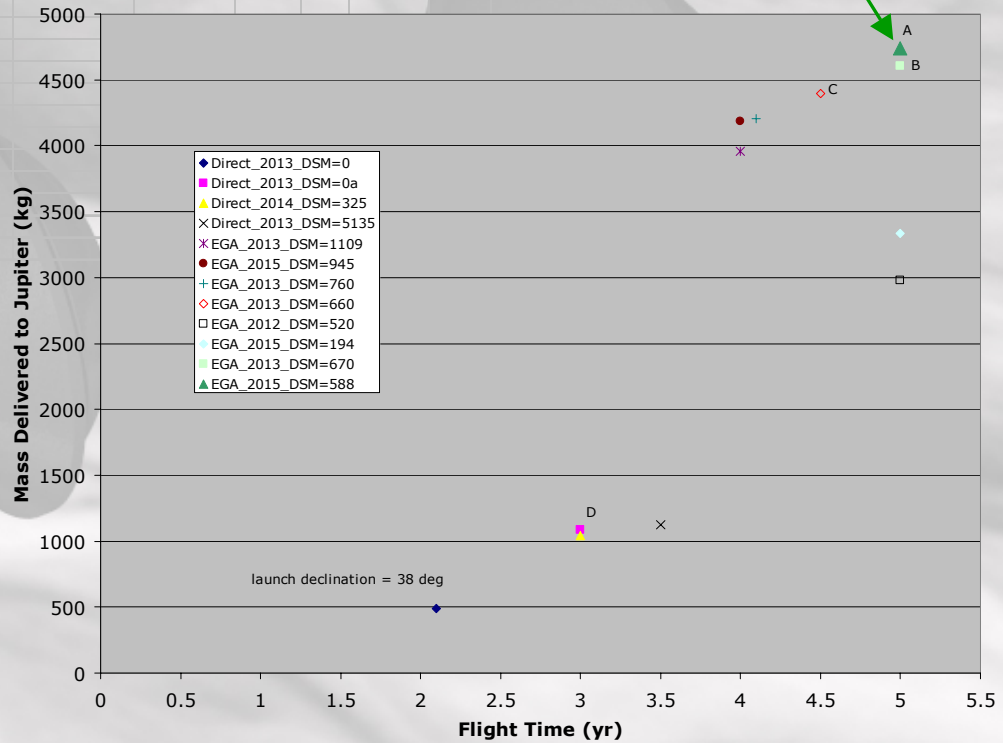
	LD	AD	DLA (deg)	C3 (km^2/s^2)	DSM TCM (m/s)	DSM date	Swingby date	Vinf at Jup (km/s)	DAP (deg)	DAP (rad)	Ventry inert (km/s)	Flt time (yr)	Mnet (kg)	Inj mass (kg)	LV
Direct	9/18/2013	11/3/2015	38.1	90.3	-	-	-	6.6	-6.3	-0.109955743	59.71	2.1	490	490	DIVH
D	9/20/2013	9/21/2016	19.2	80.1	-	-	-	5.3	0.1	0.001745329	59.58	3	1086	1086	DIVH
	10/21/2014	10/22/2017	16	79	325	8/9/2015	-	5.4	2.3	0.040142573	59.59	3	1040	1159	DIVH
	11/20/2013	6/11/2017	29.4	22.2	5135	9/1/2015	-	9.3	0.3	0.005235988	60.07	3.5	1125	6158	DIVH
EGA	12/21/2013	1/12/2018	0.6	25.8	775, 334	2014, 2016	10/25/2015	6.8	4.8	0.083775804	59.73	4	3958	5730	DIVH
	1/22/2015	1/22/2019	-10.9	25.8	700, 245	2016, 2017	11/26/2016	7.1	5.2	0.090757121	59.77	4	4188	5730	DIVH
	10/11/2013	12/3/2017	22.6	28.6	760	10/11/2014	12/3/2015	7.5	0.6	0.010471976	59.82	4.1	4206	5410	DIVH
C	10/10/2013	4/11/2018	22.3	28.1	660	10/20/2014	12/1/2015	6.1	-0.6	-0.010471976	59.66	4.5	4395	5460	DIVH
	12/6/2012	12/7/2017	6.6	47.3	520	6/18/2014	10/20/2015	7.4	8.5	0.148352986	59.81	5	2980	3539	DIVH
	2/11/2015	2/12/2020	-18.3	47.1	194	9/5/2016	1/13/2018	7.2	4.4	0.076794487	59.78	5	3337	3560	DIVH
B	12/30/2013	12/30/2018	-3.4	25.6	670	12/29/2014	11/8/2015	5.6	4.4	0.076794487	59.61	5	4606	5750	DIVH
A	1/30/2015	1/21/2020	-14.8	25.6	588	2/3/2016	12/11/2016	5.7	4	0.06981317	59.62	5	4737	5755	DIVH
	1/30/2015	1/21/2020	-14.8	25.6	588	2/3/2016	12/11/2016	5.7	4	0.06981317	59.62	5	3288	4000	AV551

Because of its higher approach velocity and greater mass, the propellant mass expended during JOI for option A is ~50 kg more than used in option B.
But this is still less than the difference between the two Mnets.
Option C uses ~60 kg less propellant than option A (higher velocity, less mass).

LD	Launch Date
AD	Arrival Date
DLA	Declination of launch asymptote
DSM TCM	Deep Space Maneuver / Trajectory Correction Maneuver
DAP	Declination of Approach Asymptote
Mnet	Net Mass
Inj mass	Injection mass
LV	Launch vehicle

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





Ref: R. Haw, JPL

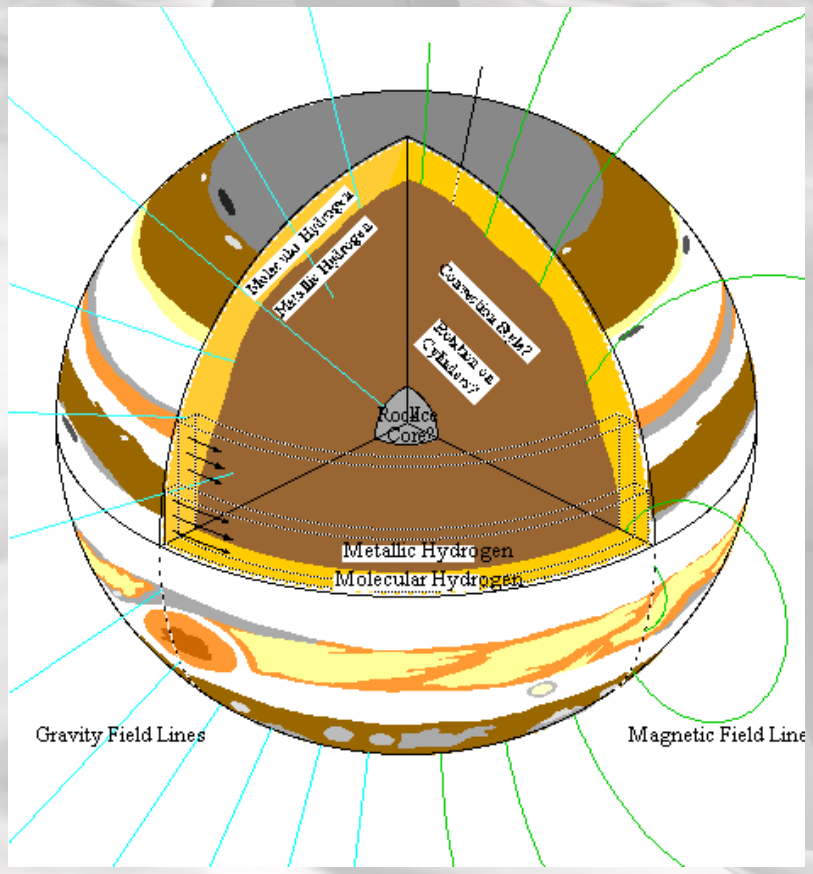
By Tibor Balint, JPL, June 9-10, 2005

Data Rates from Instruments

	Data rate (b/s) to 20 bar, per telemetry string	Data rate (b/s) 20-50 bar, per telemetry string	Data rate (b/s) 50-100 bar, per telemetry string	Data rate (b/s) 100-200 bar, per telemetry string
Atmosperic Structure Instrument (ASI)	24	24	24	18
Helium Abundance Detector (HAD)	4	0	0	0
Neutral Mass Spectrometer (NMS)	64	32	20	10
Nephelometer (NEP)	24	10	0	0
Ultra-Stable Oscillator (USO)	0	0	0	0
Net Flux Radiometer (NFR)	24	12	12	6
PLAYBACK OF ENTRY DATA and MISCELLANEOUS	40	24	24	12
Subtotal	180	102	80	46
BIT RATE = 2 x TOTAL for each telemetry string	360	204	160	92
	Total science bits to 20 bars in 1.4 hrs	Total science bits 20-50 bars in 0.3 hrs	Total science bits 50-100 bars in 0.4 hrs	
Actual descent from Gary/Paul	**3460**	**769**	**935**	**1589**
	1.8E+06	2.2E+05	2.3E+05	
Actual data, updated based on descent	**1.25E+06**	**1.57E+05**	**1.50E+05**	**1.46E+05**
\	2.3E+06			
Updated: down to 100 bar	**1.55E+06**			
Updated: down to 200 bar	**1.70E+06**			
Data rate (average)				
over 2.5 hours descent	252			
upadated 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
- Spacecraft visits
  - 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

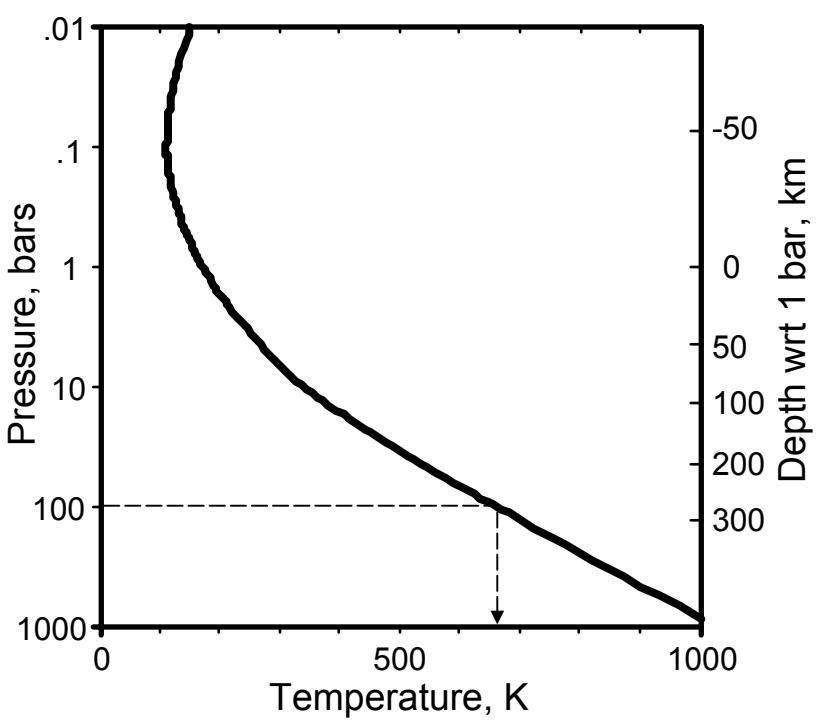
- Turbulent, zonally-organized atmosphere
  - Some features stable on 100-year time scales

Ref.: Spilker, T., "Jupiter Deep Multiprobes", Decadal Survey Studies, Final Report, April 5, 2002

Model of Jupiter's Atmosphere

- Composition
  - H_2 ~85%, He ~14%, CH_4 ~0.2%
  - H_2O, NH_3, H_2S, organics, noble gases
  - PH_3? CO?
  - Probably many others, especially at depth
- Clouds
  - NH_3, 0.25-1 bars
  - NH_4SH, (NH_3 + H_2S), 2-3 bars
  - H_2O, 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 ~110 K at the 0.1 bar tropopause
  - Increases with depth below the tropopause: 165 K at 1 bar, >670K (>400°C) at 100 bars; >1000K at 1000 bars;



Ref.: Spilker, T., "Jupiter Deep Multiprobes", Decadal Survey Studies, Final Report, April 5, 2002

Further ref.: Atreya, S.K., Wong, A-S., "Coupled clouds and chemistry of the giant planets – a case for multiprobes", Kluwer Academic Publishers, 2004

Science Objective for Jupiter Deep Entry Probes

- **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

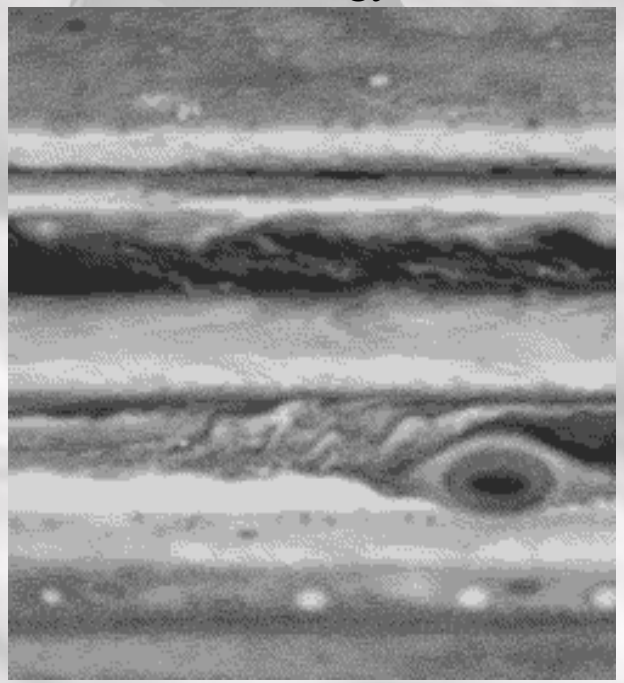
References:
- 1997 Astrophysical Analogs in the Solar System Campaign Science Working Group ("AACSWG")
- 2001 SSE Decadal Survey Giant Planets Panel
- T. Spilker, "Jupiter Deep Multiprobes", Decadal Survey Studies, Final Report, April 5, 2002

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
  - Hydrogen sulfide
  - Water vapor
  - Temp, press
  - Ortho-to-para H_2
  - Wind speed
  - Cloud particle composition size & bulk particle density
  - (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"



Ref. http://photojournal.jpl.nasa.gov

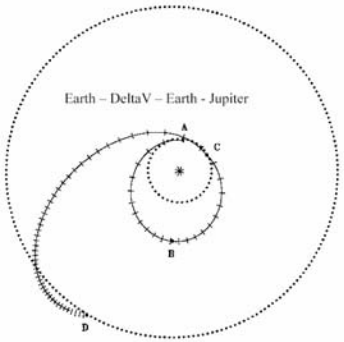
- *Shall be defined through discussions with the science community, such as OPAG and SSES*

(Note: throughout this study, Rich Young contacted as a contact point to the science community)

Jupiter Deep Multiprobes Mission Design Example

Jupiter Deep Multiprobes

Mission Design



Maneuver	DV (m/s)
Trajectory correction maneuvers	60
Deep space maneuver	660
Probe and relay targeting	144
DV margin	56
Total	920

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 km²/s² (w/30 day window)
- ΔV-EGA to Jupiter
- 5.8 years trip time

LV: Delta IV – 4040

1190 kg capability at this C3

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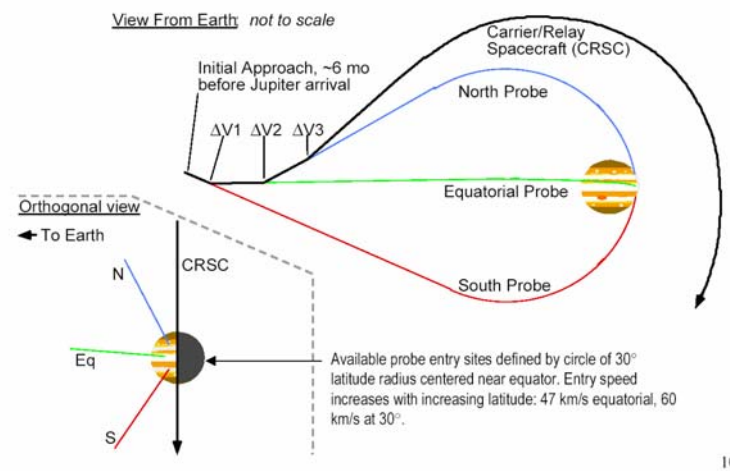
Solar System Exploration

Jupiter Deep Multiprobes

Jupiter Approach Trajectories



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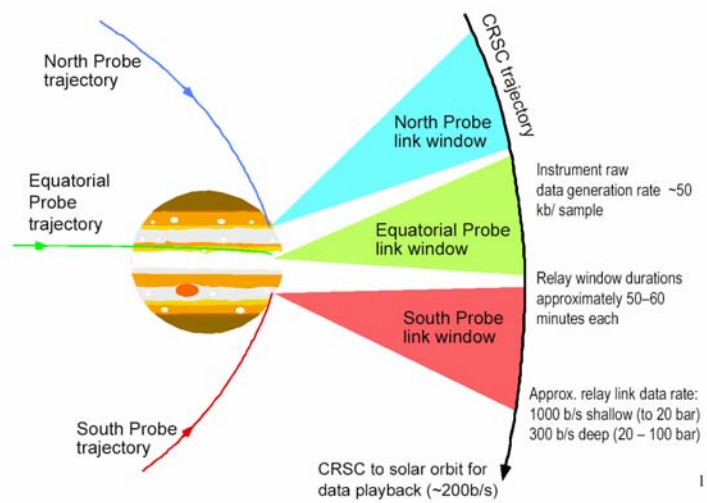
Solar System Exploration

Relay Geometry and Strategy



11

Solar System Exploration

- 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