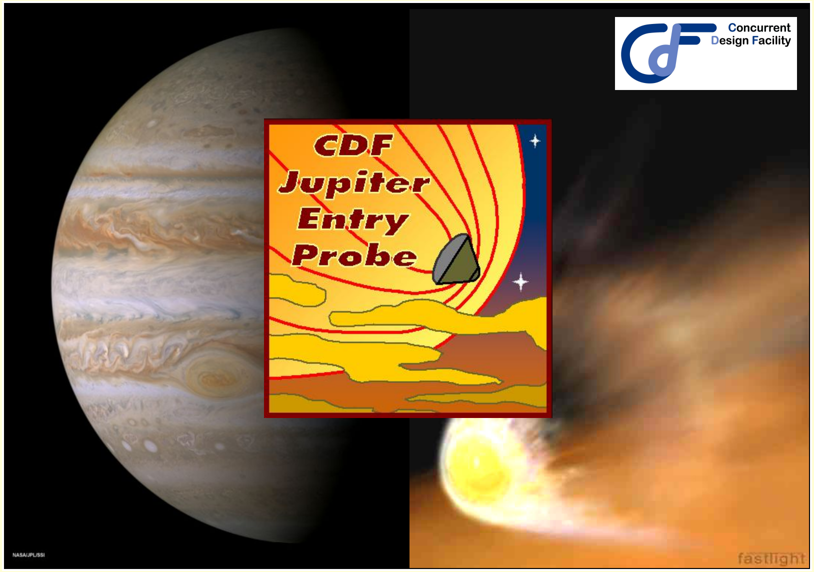
The Jovian Entry Probe:

A Feasibility Study of a Minimum Resource Jovian Entry Probe



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Overview:

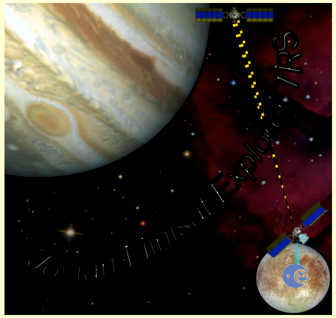
- Context of Jovian technology Reference Studies
- Requirements and constraints
- Design approach
- Mission Analysis
- Aerothermodynamics
- Thermal Protection System
- Resulting configuration
- Conclusion

Jupiter related Technology Reference Studies

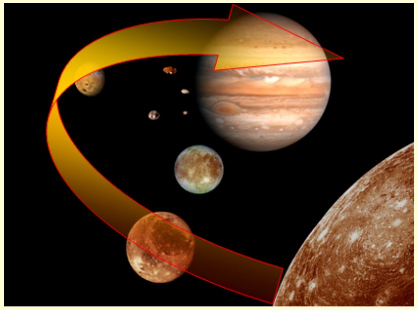
Goal:

Identify and when possible assist in the development of enabling technologies for future science missions to the Jovian system. Furthermore, to support the scientific community in the field of Jovian exploration.

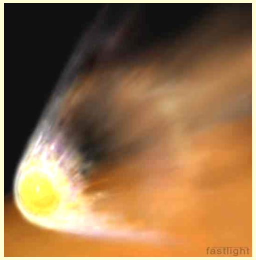
Presently two studies have been completed and a new study has been initiated:



- Jovian Minisat Explorer: Focussing on the exploration of Europa (included Europa polar orbiter and Jovian equatorial relay S/C, implications of RPS, as well as small impactors and Europa lander) ☑



- Jovian System Explorer:
  - Study of the Jovian magnetosphere (one or more magnetospheric S/C)



- Jovian Entry Probe: Study of the Jovian atmosphere
  - one or more entry probes, up to 100 bar ☑

JEP Study requirements and constraints

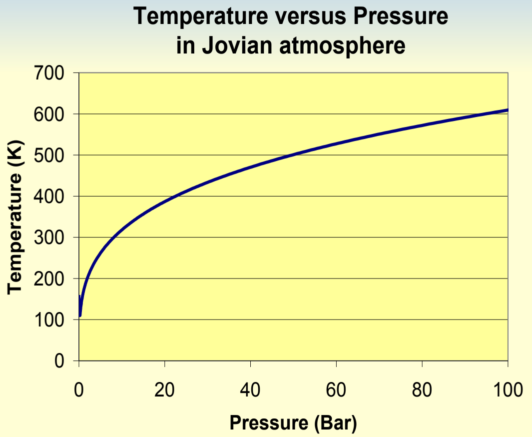
- Carry the probe to Jupiter and release it
- Perform **entry and descent** into the Jovian atmosphere at near equatorial latitude (with an option of non-equatorial descent up to -30deg/+30 deg, if possible)
- Measure atmospheric properties **in-situ** down to an altitude corresponding to **100 bar** using a given Strawman payload
- Transmit the data **in real time** to the accompanying Orbiter
- Achieve a final orbit for magnetospheric measurements with the Orbiter
- Achieve multi-probe mission if mass allows

- Launch vehicle: Soyuz Fregat 2-1b from Kourou
- Preferred launch dates: 2016 or 2023
- **Payload: 12 kg; 30 W; 5 l; 353 bps (Highly integrated)**
- Avoidance of Jovian ring when defining probe approach, while not exceeding distance during comms
- Design shall be compliant with Beagle 2 Enquiry Board recommendations and Huygens Lessons Learned
- Max. heat flux during entry: 500 MW/m^2 (assumed as maximum capability for present TPS technology)

Mission design drivers

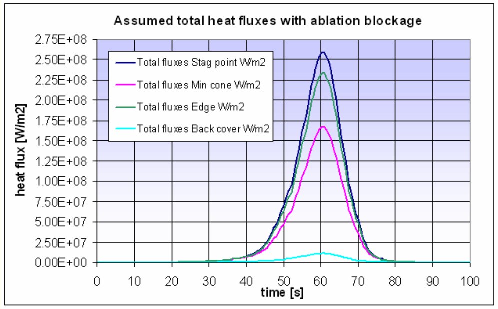
Jupiter atmosphere

- Uncertainties on the physical and chemical parameters
- High temperature, high pressure at low altitude
- Strong attenuation for Comms below 20 bar altitude (100 bar ~24 dB)



High velocity entry

- Can not be reduced below ~ 47 km/s
- Aerothermodynamic phenomena, in this regime and for the Jupiter atmosphere, not well understood (uncertainties in calculation of the heat fluxes/loads)
- Very high aerothermodynamic heat fluxes at the limit of present TPS technology capabilities
- High TPS mass fraction (50-70%)
- Very high g-load (further qualification of components)



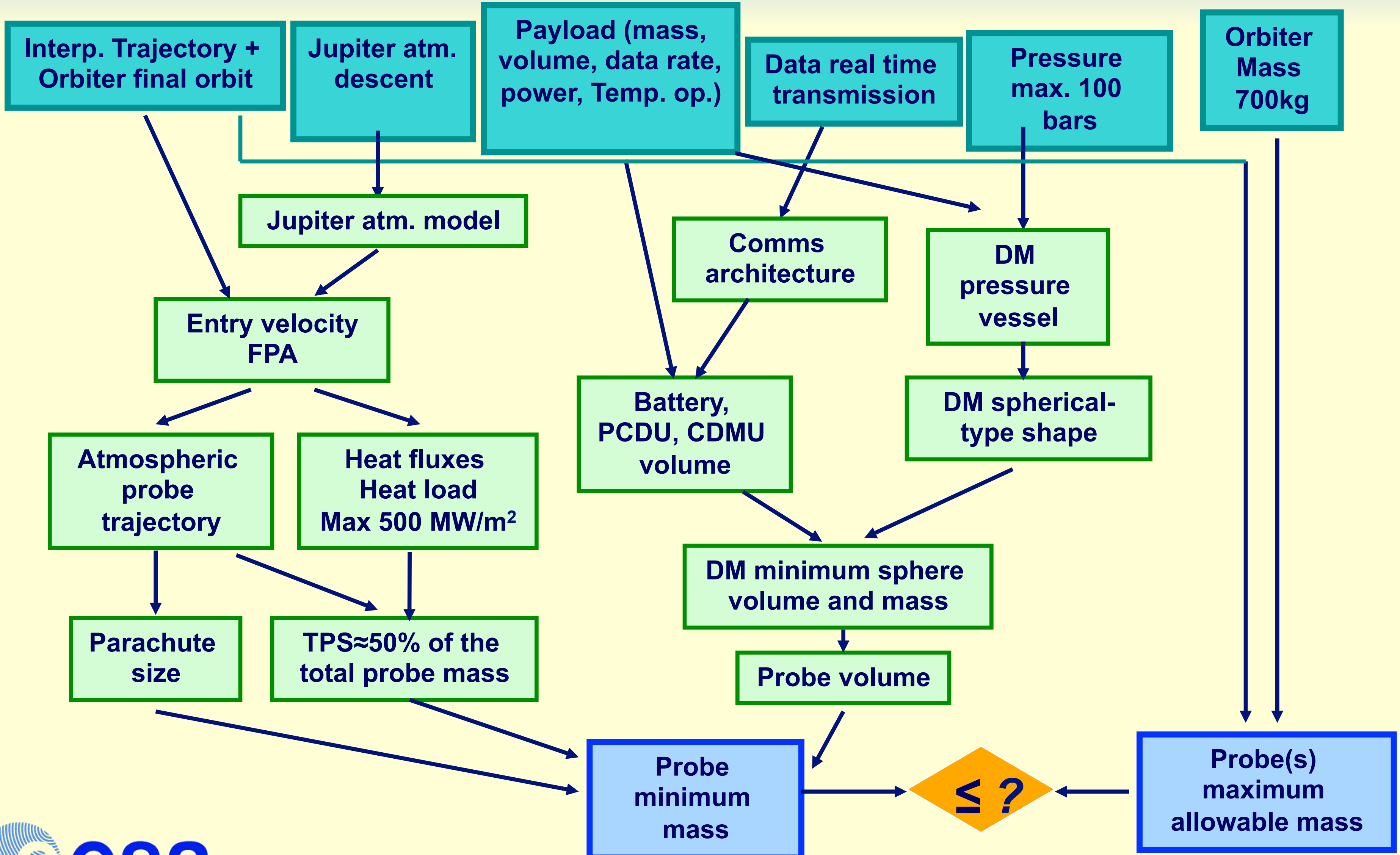
Synchronisation probe/Orbiter (transmission in real time)

- Orbiter to Probe link to be phased with deployment and relay phase

Mass

- Provides a higher limit for the allowable mass (Launcher performances)
- Fulfilment of mission requirements provides a lower limit

Probe design : Concurrent design approach



Baseline Summary

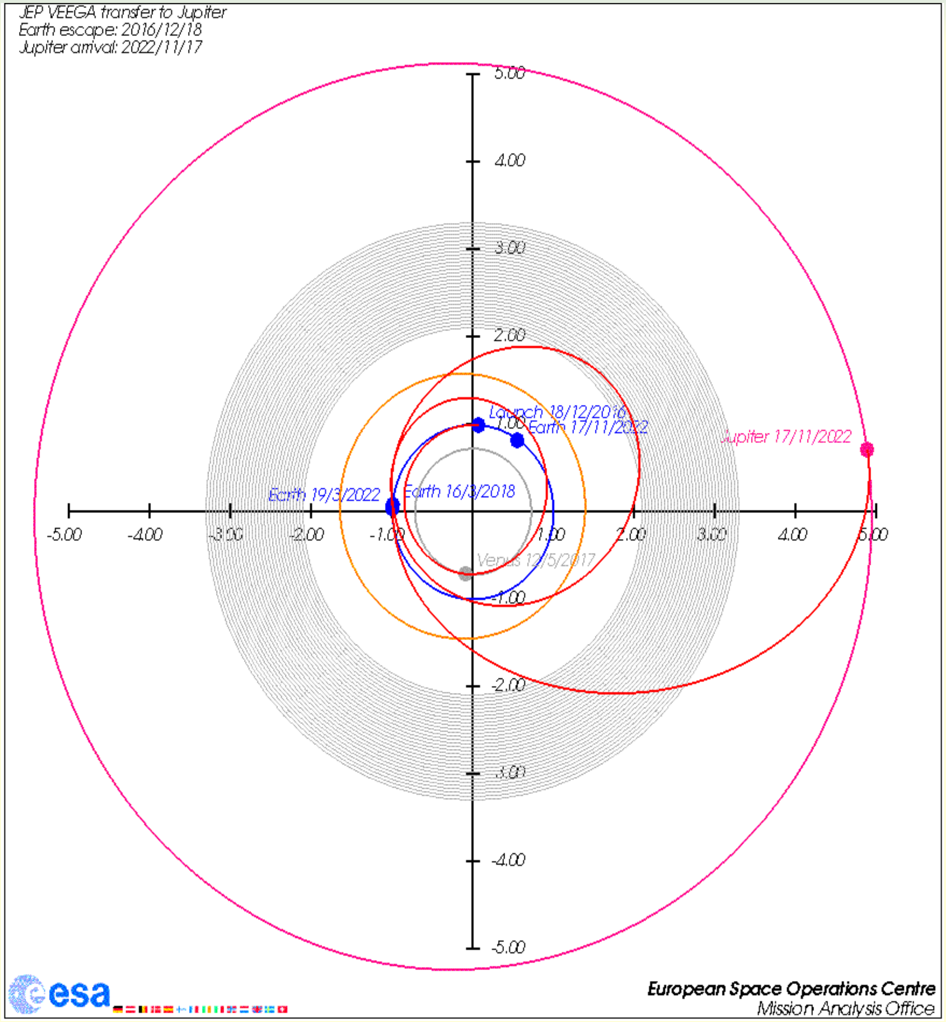
Launch vehicle	Soyuz-Fregat 2-1b		
Launch date	2016	2023	
Number of orbiters	1	2	
Orbiter JOI perijove (Rj)	4	5	
Orbiter JOI apojove (Rj)	200	100	70
Orbiter final perijove (Rj)	15		
Orbiter final apojove (Rj)	200	100	70
Orbiter final inclination	Equatorial	Polar	
Number of probes	1	2	
Probe mass w margin (kg)	150	250	300
Probe release	Hyperbolic, -90d	Capture	
Probe entry latitude (deg)	+3/-7	±15	±30
Max P for descent (bar)	40	100	

Baseline

Not feasible

Alternative

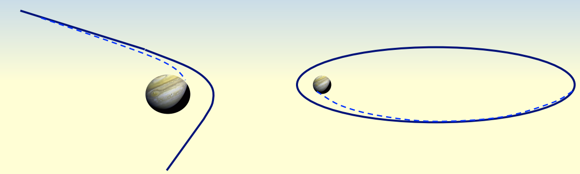
Transfer to Jupiter: VEEGA



VEEGA Transfer Summary

- Earth escape 2016/12/18
- Hyperbolic escape velocity: 3.45 km/s
- Declination -30.5 deg
- No DSMs
- Venus swingby: 2017/5/12, 10137 km
- Earth swingby 1: 2018/3/6, 2489 km
- Earth swingby 2: 2020/3/19, 1423 km
- Arrival: 2022/11/17
- Hyperbolic arrival velocity: 5.2 km/s
- Arrival decl. wrt Jup. Equator: 1.3 deg
- Transfer duration: 2161 days (5.9 y)

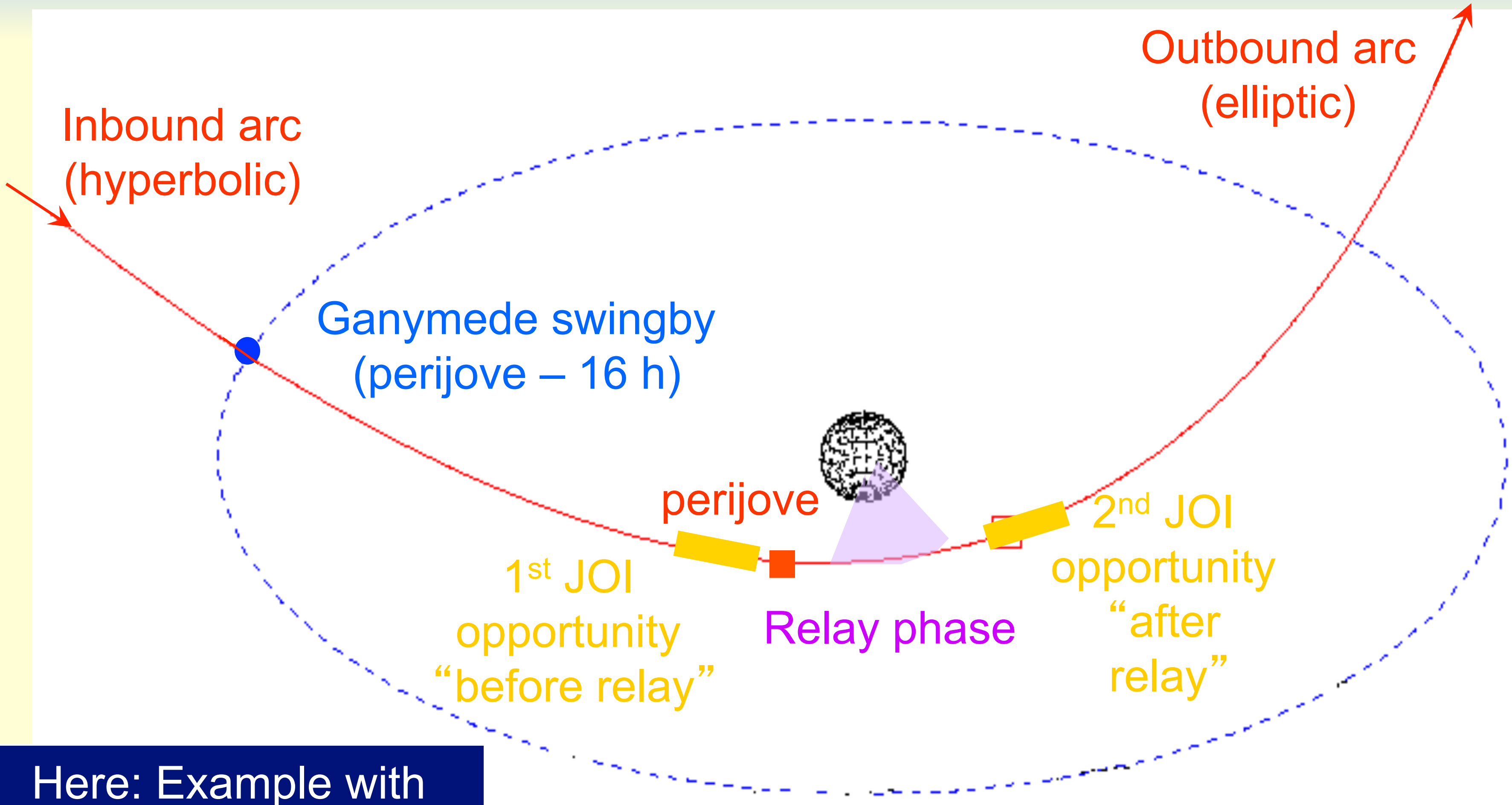
Mission Options - Probe Release



- Assume: 4x200 Rj insertion orbit, 15x200 Rj final orbit, probe release *30d* (worst case for ODM) before entry for hyperbolic case, as best ΔV case JOI for capture (Io swingby)
- Calculate max possible probe mass given 10% launch margin
- Comms between probe and carrier very problematic
- Conclusion: Capture not favourable in terms of mass, entry speed not significantly reduced, direct comms problem => discard this option

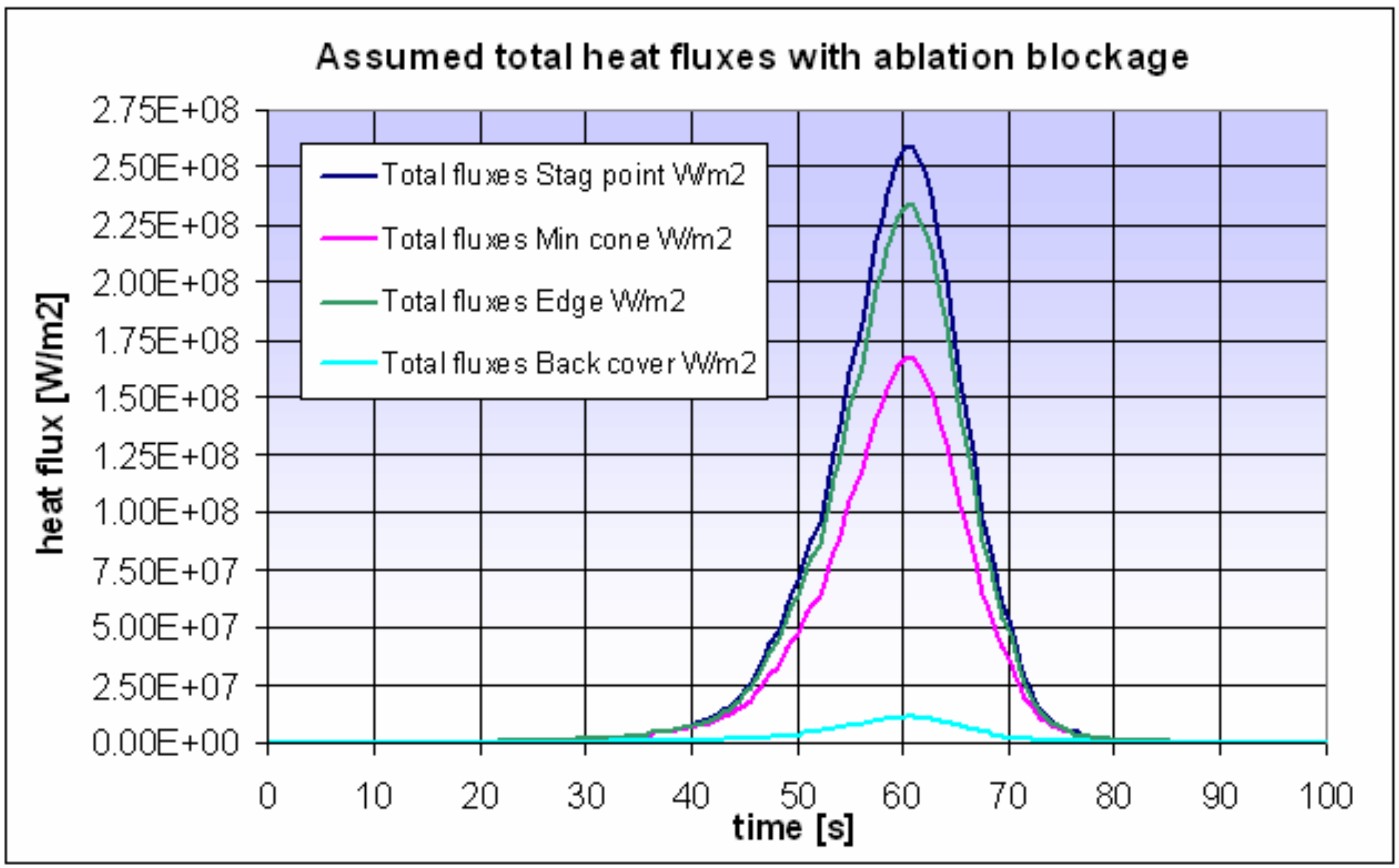
	Hyperbolic	Capture
Max Probe mass	335 kg	230 kg
Radiation	One pass at 4Rj	At least one pass at 4Rj
Comms range	~3 Rj	~3 Rj
Entry velocity	47-48 km/s equatorial	46-47 km/s equatorial
Operational	Short time between JOI, relay	More manoeuvres (PLM, PRM)

Swingby-Augmented JOI



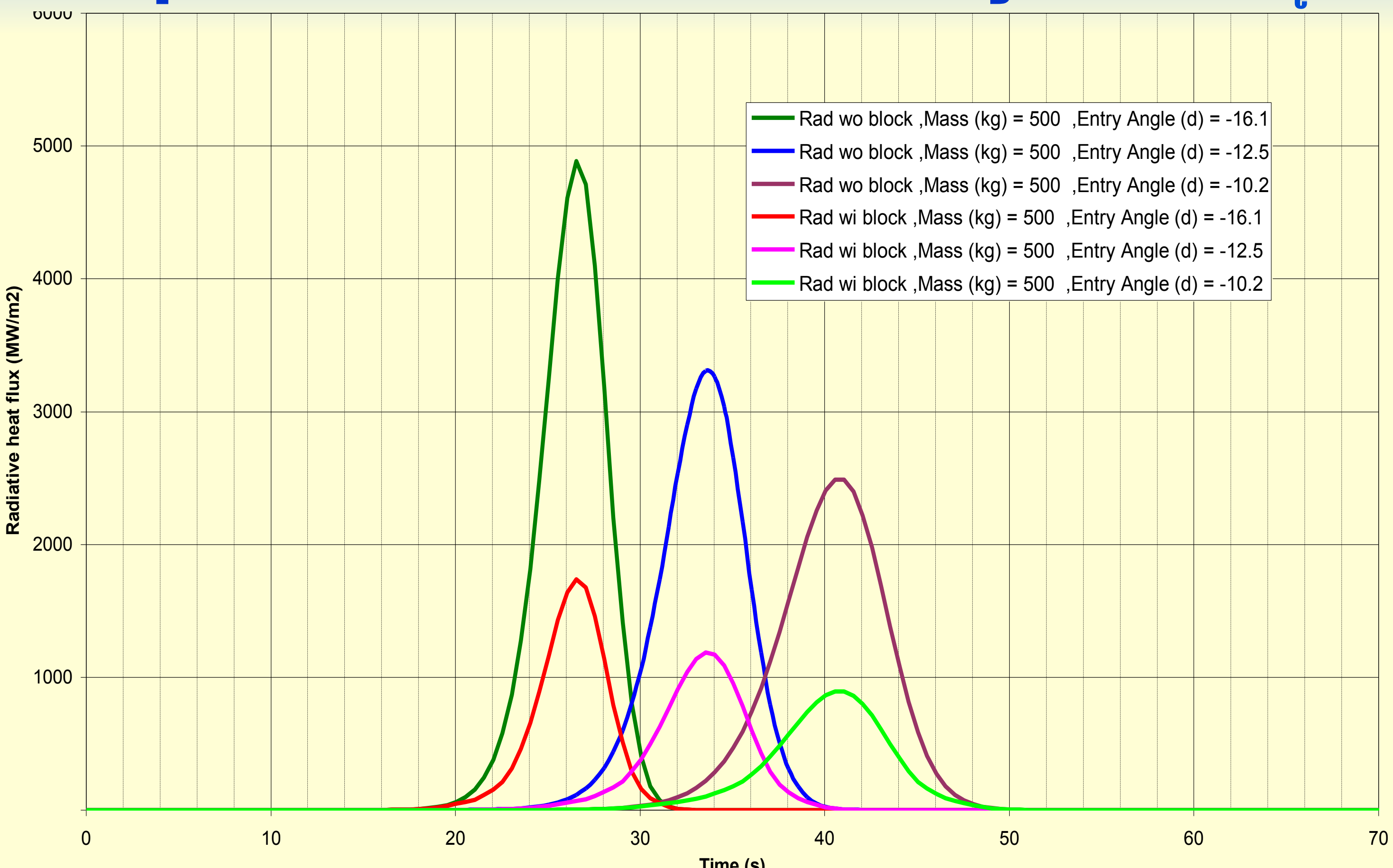
Here: Example with Ganymede swingby
Alternative: Io swingby

Aerothermodynamics (1/2): Total absorbed heat fluxes assumed over JEP surface (100 bar probe)



- **Convective blockage: 90% (conservative assumption)**
- **Base cover: 2.5% of convective and 1.25% of radiative stagnation point flux (literature data)**

Aerothermodynamics (2/2):
Stagnation point Radiative heat fluxes at entry latitudes (V_e > 48-49 km/s)



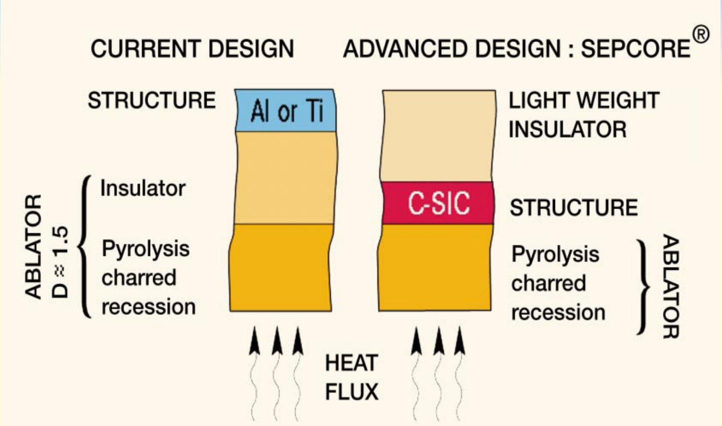
Heat fluxes are in excess of 800 MW/m^2 in all cases.
This is beyond the capability of present TPS technologies.

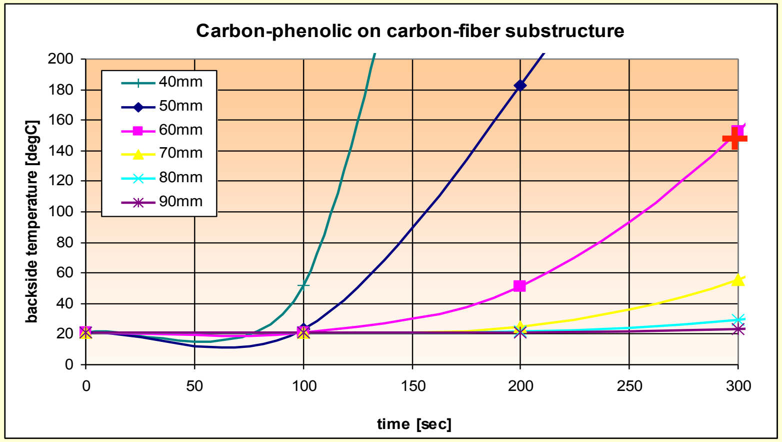
Note: For Jupiter entry probes to higher latitudes larger TPS mass fractions are expected, e.g. for a 30deg latitude the TPS mass fraction probably exceeds 70%

TPS: SEPCORE Concept selected

- The ablator is mounted on a hot structure, which is insulated against the inner compartment using lightweight insulation, possibly fibres

- Considerable mass savings due to reduced ablator thickness and use of more efficient insulation.



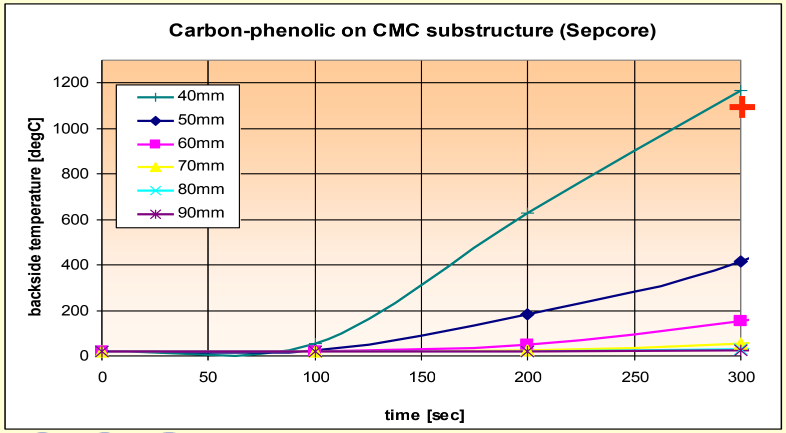


Assumptions:

- **"Classical" heat shield**
- **Separation after 300s**
- **Carbon phenolic on CRFP structure**
- **Assumed limit: 150degC**
- **CFRP backside adiabatic**

Required min. ablator thickness:

- **About 60mm ➔ ≈ 85 kg/m² ablator**



Assumptions:

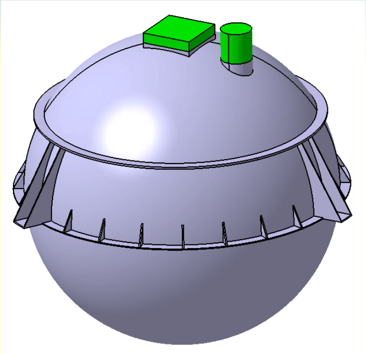
- **SEPCORE concept**
- **Separation after 300s**
- **Carbon phenolic on C/SiC structure**
- **Assumed limit: 1100degC**
- **C/SiC backside adiabatic (conservative)**

Required min. ablator thickness:

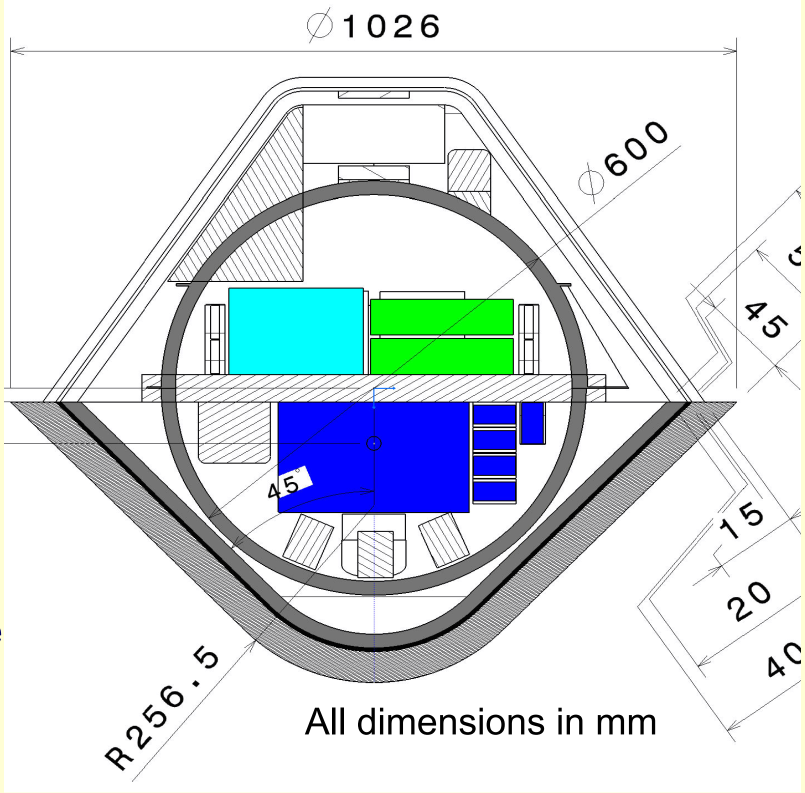
- **About 42mm ➔ ≈ 60 kg/m² ablator**

Overview of probe designs

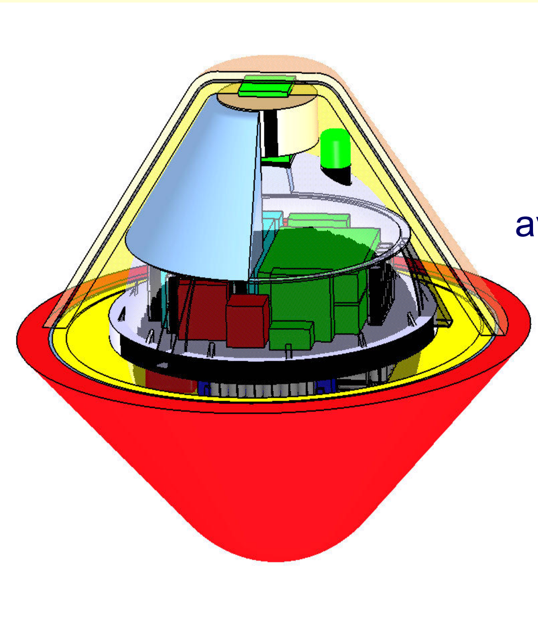
100 bar probe:
- Mass ~ 300 kg
- P/L resource ~ 12 kg, ~30 W (peak), ~350 bps
- Entry latitude between -7 and +3 deg
- One probe + one orbiter
- Descent time = 1 hour
- Variable power comms system to cope with very strong atmospheric attenuation (~24 dB)
- Comparable in mass to the Galileo probe (but 100 bar vs. Galileo's 20 bar)

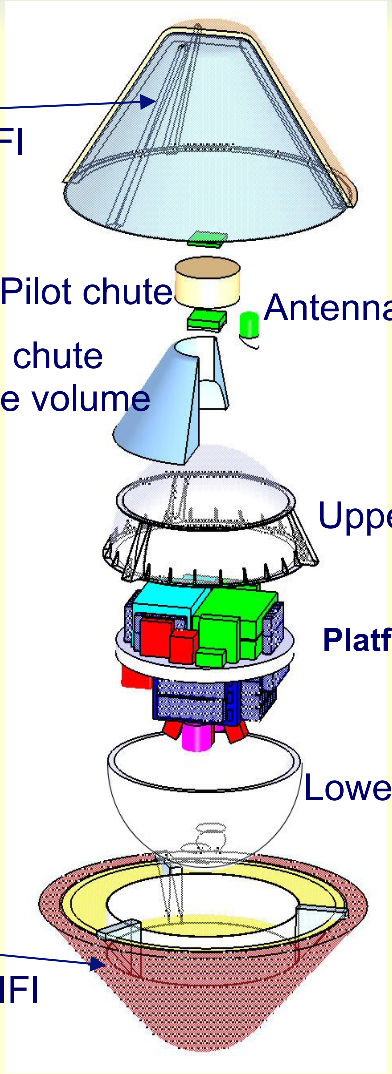


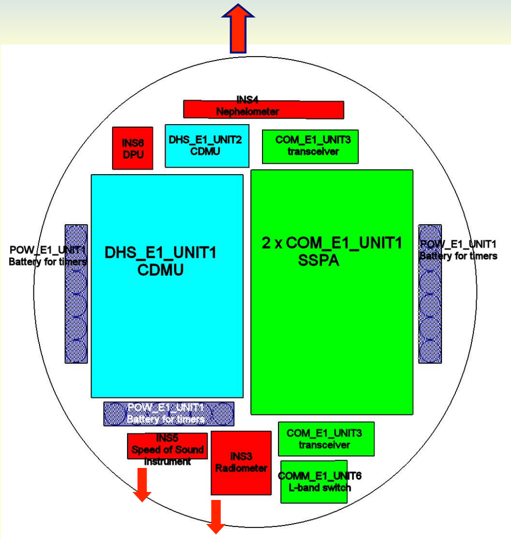
40 bar probe:
- Mass ~ 270 kg
- P/L resource ~ 12 kg, ~30 W (peak), ~350 bps
- Entry latitude between -7 and +3 deg
- Two probes + one orbiter
- Descent time = 1 hour
- Comms scenario complicated but should be feasible

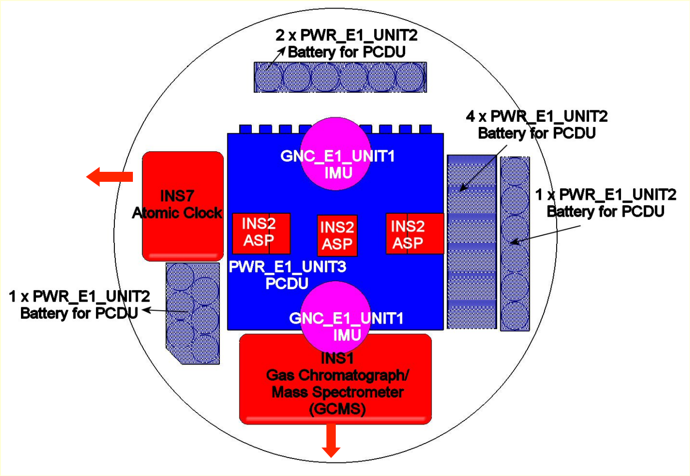


Accommodation









Extended payload analysis

Hypothesis: increase of

- 100% of the P/L mass 17.4 kg
- 100% of the P/L volume 10.8 litres
- 50% of the P/L power 34 W
- 50% of the P/L data rate 530 bps

Impact on volume: DM diameter sphere increases from 600 mm to 650 mm

Impact on probe mass:

Dry mass contributions	Without Margin	Margin %	Margin kg	Total kg	% of Tota
Structure	35 kg	10	3	38	15
Thermal Control	149 kg	19	29	178	71
Mechanisms	8 kg	10	1	9	4
Communications	6 kg	7	0	7	3
Data Handling	10 kg	12	1	12	5
GNC	1 kg	10	0	2	1
Power	16 kg	14	2	18	7
Harness	10 kg	0	0	10	4
Instruments	17 kg	20	3	21	8
DLS	6 kg	10	1	6	3
Total DM mass	96			56 kg	
Total Dry(excl.adapter)	260			301 kg	
System margin (excl.adapter)		20 %		50 kg	
Total Dry with margin (excl.adapter)				351 kg	

JEP Study Conclusions

- Jupiter entry probes face extreme aerothermodynamic challenges: Identification of adequate TPS is very challenging
- Testing in a representative environment is unfeasible, leading to large uncertainties in theoretical models. Generous TPS margins are therefore required
- Suitability of available TPS materials is to be verified
- High latitude entry conditions are beyond current material capabilities
- The minimum probe configuration for the set requirements resulted in a Galileo-class probe, although the maximum depth is increased from 20 to 100 bar
- Due to the very low resources and the atmospheric attenuation, comms are a major problem, driving the probe & S/C design: for this class of probe 100 bars is the limit. Furthermore the distance between probe and relay S/C is limited to the ~4 Rj range
- High complexity and extreme test conditions are major cost drivers
- Single vs. multiple probes = deep vs. “shallow => science trade-off


Any Questions ?

Back-up slides

Scientific rationale for JEP

- Initial assumptions on atmospheric composition: identical abundances as in Sun
- The present knowledge of the Jovian atmosphere is limited. These data have shown that Jupiter's composition is not identical to the Sun's: deviations up to 3 times the solar abundance have been measured
- Composition of atmosphere up to 20 bar is believed to be reasonably well understood, however in situ data very limited
- No quantitative results on O/H in the deep well-mixed atmosphere are available. Water was presumably the original carrier of heavy elements to Jupiter, hence the determination of its abundance in the deep atmosphere is of fundamental importance to the models of formation of Jupiter and the origin of its atmosphere as well as the origin of the solar system
- Furthermore, since meteorological and dynamical effects could cause the mixing ratios of water and possibly other volatiles to vary over the planet, it is essential to measure the full atmospheric composition, simultaneously with the related phenomena, such as winds and cloud properties
- **The best way to accomplish this is by deploying deep multiprobes (50-100 bar) into different regions of Jupiter. However this study shows that with the given limitations this is hard to achieve. A new entry probe, even if with the same capabilities of the Galileo probe would contribute significantly, provided a entry zone is targeted consisting of a cloudy zone to contrast the Galileo Probe's hot spot entry**

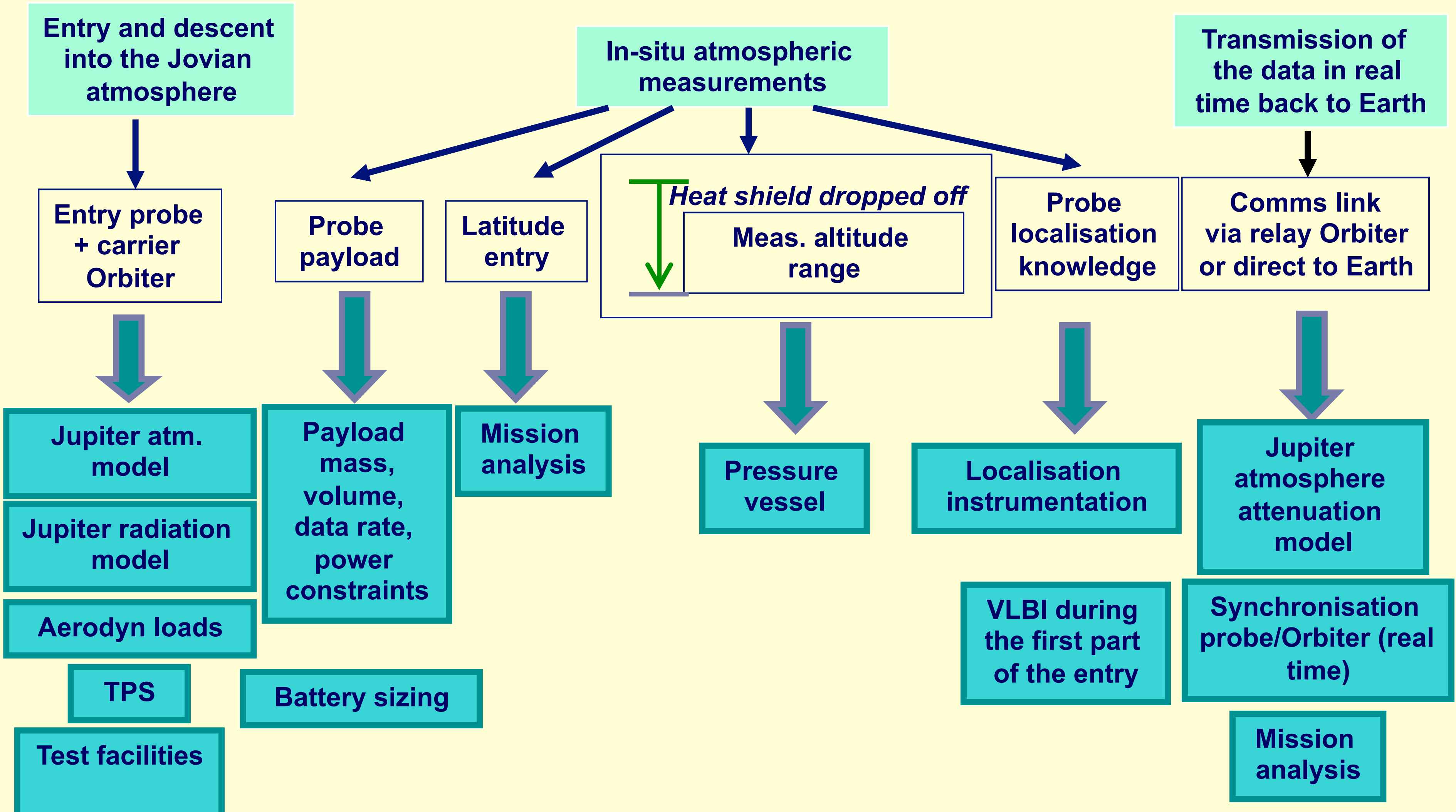
Strawman payload

Instrument	Function
Atmospheric Structure Package (ASP) [accelerometers, gyros, p&T sensors, TPS recession sensors]	• Provide information about temperature, density, pressure, and molecular weight of atmospheric gases. These quantities are to be determined from the measured deceleration of the Probe during the atmospheric entry phase as well as p&T sensors • Gyros: 3 degrees of freedom (for descent reconstruction)
Gas Chromatograph/Mass Spectrometer (GCMS)	Atmospheric composition: constituent mixing ratios; isotopic ratios
USO (Atomic Clocks)	Determine the vertical wind profile with an accuracy of a few m/s Provide data for Probe localisation and trajectory reconstruction
Polarisation nephelometer	Main: Determine cloud location as a function of the pressure level Secondary: Characterise composition, size and shape of cloud particles & aerosols
Radiometer	Vertical temperature profile/radiant energy flux
Speed of Sound Instrument	Speed of sound, through which ortho- to para-H2 ratio is determined (lowest priority as relevance for Jupiter unclear)

P/L Budgets

Instrument	Mass (kg)	Power (W)	Volume (l)	Data rate Bps (compressed)	Duty cycle (%)
GCMS	5	13.5	2.6	250	100
ASP	0.7	0.5	0.5	30	10
USO (Atomic clocks)	0.5	7	1.2	0	100
Nephelometer	0.2	1.7	0.4	40	20
Radiometer	0.3	2.3	0.25	30	10
Speed of Sound Instrument	1	3	0.3	3	100
DPU & co	0.5	0.7	0.15	0	100
Total (inc 20% margin)	10	28.7	5	353 (no margin)	-

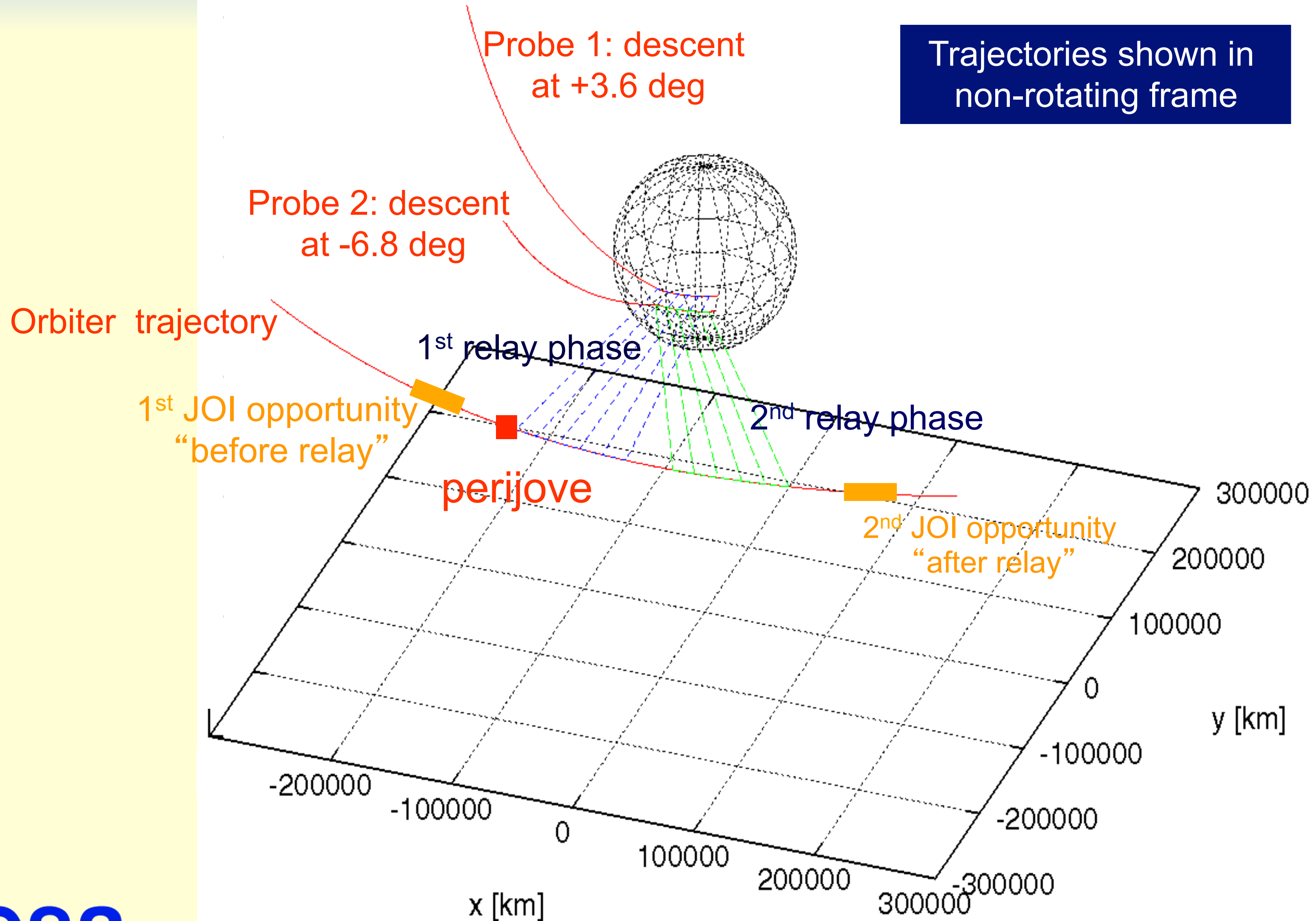
From mission obj. to probe req.



Measurement requirements

- Probe design shall maximise data return by allowing measurements as early as possible after entry (starting at release of front shield)
- Probe design shall allow atmospheric profile reconstruction with an accuracy of 10 km
- Mission design shall allow relay window to the Orbiter as large as possible during descent
- Probe design shall allow transmission at 353 bps during descent
- Probe shall carry, in addition to science payload, flight instrumentation to validate aerothermodynamic and ablation models
- Probe shall be aerodynamically stable during entry and the DM shall be aerodynamically stable during descent (within 5deg)

Two-Probe Entry Geometry



Probe design options

Three probe design options:

	Number Probes	Mass (kg)	Max Pressure (bar)	Entry Latitude (deg)	Required probe design modifications
Baseline **"Minimum probe"**	1	301	100	+3 or -7	
Option 1: **"40-bar probes"**	2	270	40	+3 and -7	Structure, TPS, Comms, Power
~~**Option 2:** **"Non-equatorial probe"**~~	~~1~~		~~100~~	~~-15.6~~	~~Extremely high heat fluxes (heat flux above 900MW/m2) Not affordable with present TPS technology This option has not been further analysed~~
Option 3: **"Extended payload" (mass&volume ×2, data rate & power ×1.5)**	1	351	100	+3 or -7	Instruments, Config (Increase of the DM diameter sphere to 650mm), TPS, structures

Specific design margin on TPS

Worst case atmosphere

↓

Entry mass corresponding to the total mass
including system margins + 10kg

↓

Worst case entry angle

↓

Aerothermodynamic fluxes computed with fix blockage factor

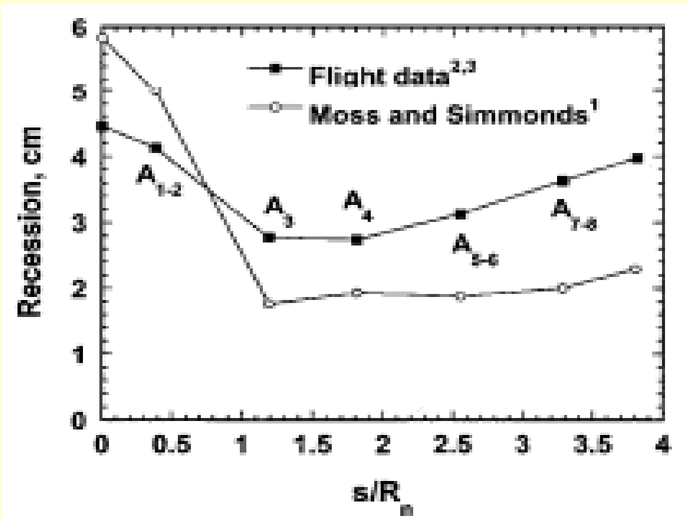
↓

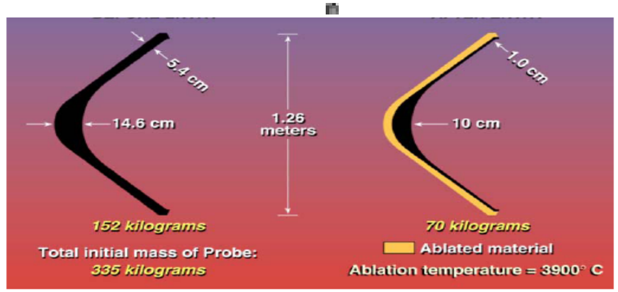
TPS thickness increased by 20%

↓

TPS mass computed with 20% margin

Galileo Recession Data





Ablation data measured during the entry indicated that

- Stagnation point recession was less than predicted
- Ablation at frustum and shoulder was much higher than predicted
- More dissociation of ablation products

Also recent mathematical models are not fully capable to explain the observed behavior.

Possible reasons

- Enhanced turbulence from mass injection
- Particle spallation
- Complex interaction between ablation and shock layer radiation

Preliminary TPS Sizing

TPS based on SEPCORE concept

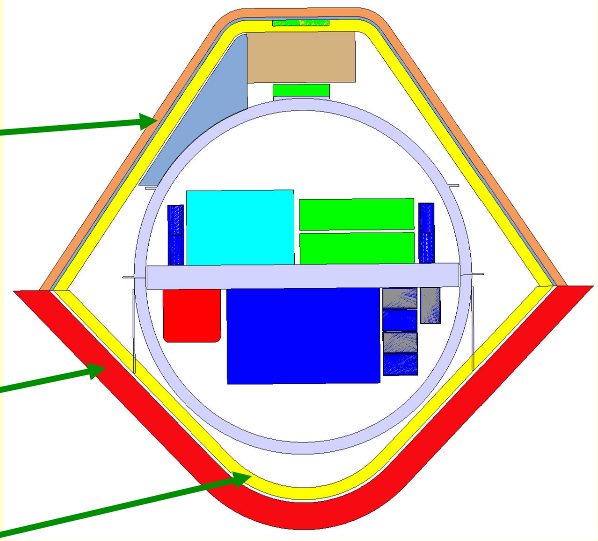
- **Heatshield separation after 170 sec.**
- **Assumed limit at hot structure: 1100degC**

Basecover

- **17mm Nylon-phenolic**
- **Mounted on CMC hot structure (3.2mm)**
- **Rearside insulated by 20mm fibrous insulation (IFI-type)**

Frontshield

- **47mm Carbon phenolic**
- **Constant thickness assumed**
- **Mounted on CMC hot structure (3.2mm)**
- **Rearside insulated by 20mm fibrous insulation (IFI-type)**



Thicknesses include 20% uncertainty. Further 20% system margin are applied on the mass.

Mass budget – Baseline MINIMUM PROBE

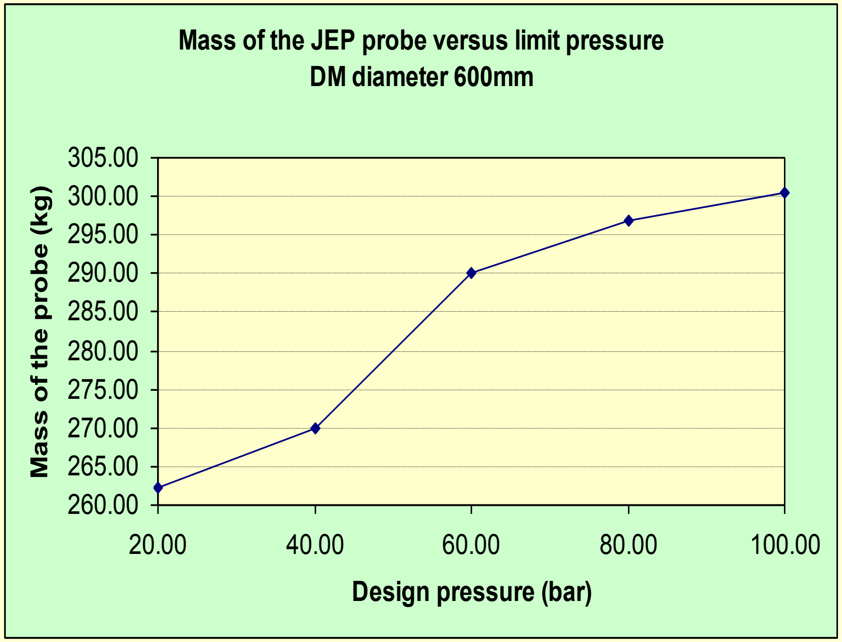
Dry mass contributions	Without Margin	Margin %	Margin kg	Total kg	% of Total
Structure	27.9 kg	10	2.8	30.7	12
Thermal Control	122.0 kg	19	23.7	145.7	58
Mechanisms	8.5 kg	10	0.8	9.3	4
Communications	6.3 kg	7	0.5	6.8	3
Data Handling	10.3 kg	12	1.3	11.5	5
GNC	1.5 kg	10	0.1	1.6	1
Power	15.8 kg	14	2.3	18.1	7
Harness	10.1 kg	0	0.0	10.1	4
Instruments	8.7 kg	20	1.7	10.4	4
DLS	5.7 kg	10	0.6	6.3	3
Total DM mass	**80.5**			**89.2 kg**	
Total Dry(excl.adapter)	**216.7**			**250.5 kg**	
System margin (excl.adapter)		**20 %**		**50.1 kg**	
Total Dry with margin (excl.adapter)				**300.6 kg**	

This is the minimum configuration probe that fulfils all the initial requirements

- It is comparable in mass to the Galileo probe (but 100 bar vs. Galileo's 20 bar)
- Reaching 100 bar is possible but at the expense of a higher DM structural mass and therefore higher probe mass. Only single probe fits into the mission

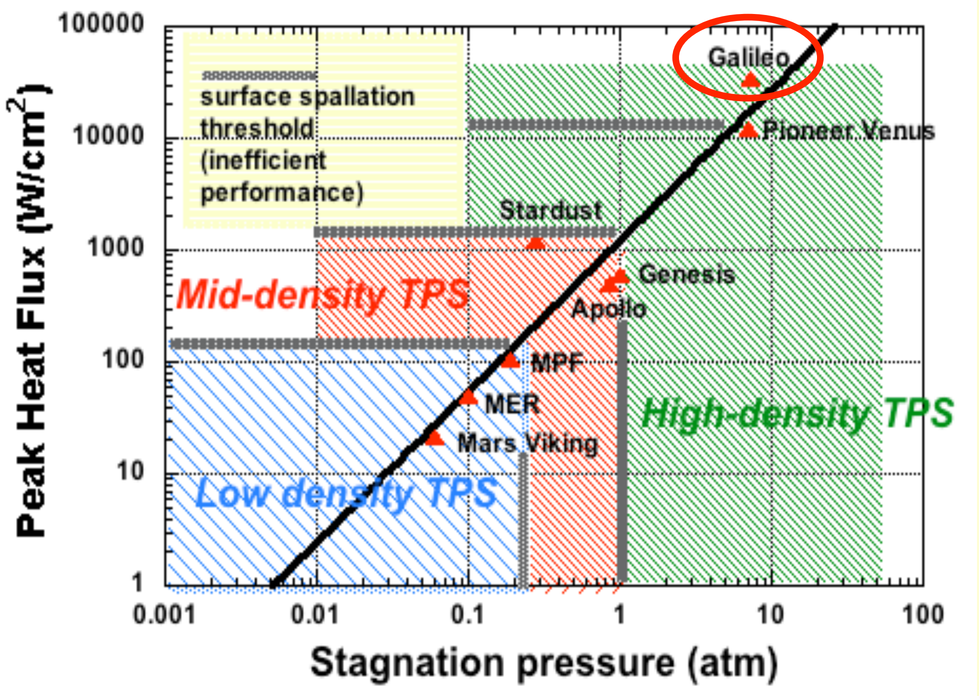
Mass budget for 2 probes at 40 bars

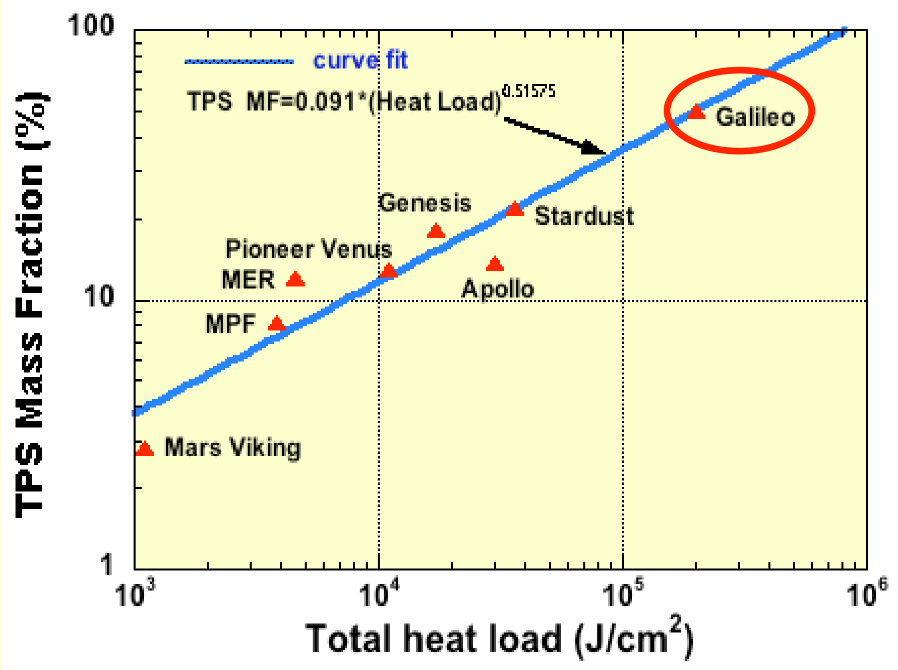
40 bars	Without Margin	Margin		Total	% of Tota
Dry mass contributions		%	kg	kg	
Structure	19 kg	10	2	21	10
Thermal Control	111 kg	20	22	133	61
Mechanisms	8 kg	10	1	9	4
Communications	6 kg	7	0	7	3
Data Handling	10 kg	12	1	12	5
GNC	1 kg	10	0	2	1
Power	14 kg	14	2	16	7
Harness	9 kg	0	0	9	4
Instruments	9 kg	20	2	10	5
DLS	6 kg	10	1	6	3
Total Dry(excl.adapte	194			225 kg	
System margin (excl.adapter)		20 %		45 kg	
Total Dry with margin (excl.adapter)				270 kg	



Limiting the descent to between 20 to 40 bar gives a probe mass reduction which ***just*** allows a two-probe mission with separate latitudes and longitudes at descent and relays in sequence

Mission Environments and TPS Constraints



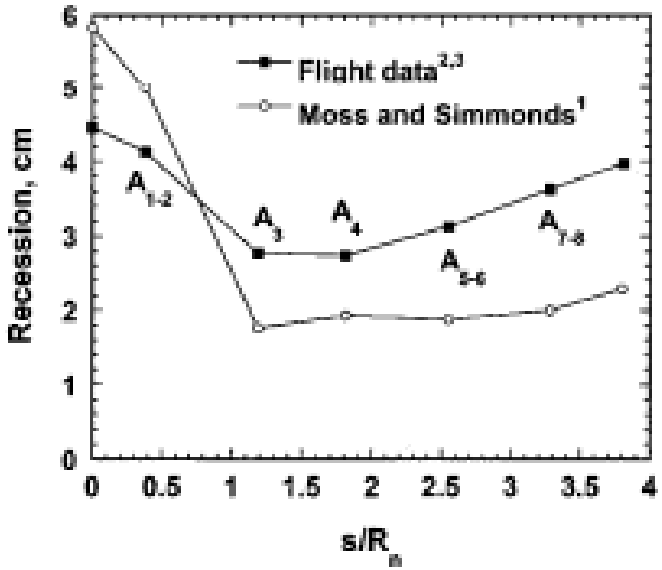


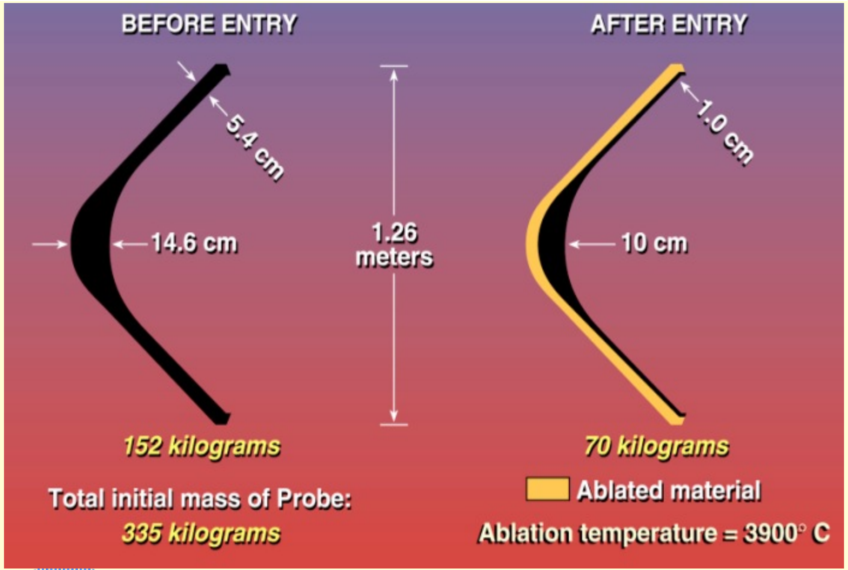
Mission environments for ablative TPS applications and spallation limitations (from B. Laub and E. Venkatapathy, 2003)

TPS mass fraction over integrated heat load (from B. Laub and E. Venkatapathy, 2003)

Note: For Jupiter entry probes to higher latitudes larger TPS mass fractions are expected, e.g. for a 30deg latitude the TPS mass fraction probably exceeds 70%.

Galileo Recession Data





Ablation data measured during the entry indicated that

- Stagnation point recession was less than predicted
- Ablation at frustum and shoulder was much higher than predicted
- More chemical phenomena (dissociation)

Also recent mathematical models are not capable to explain the observed behaviour.

Possible reasons:

- Enhanced turbulence from mass injection
- Particle spallation
- Complex interaction between ablation and shock layer radiation

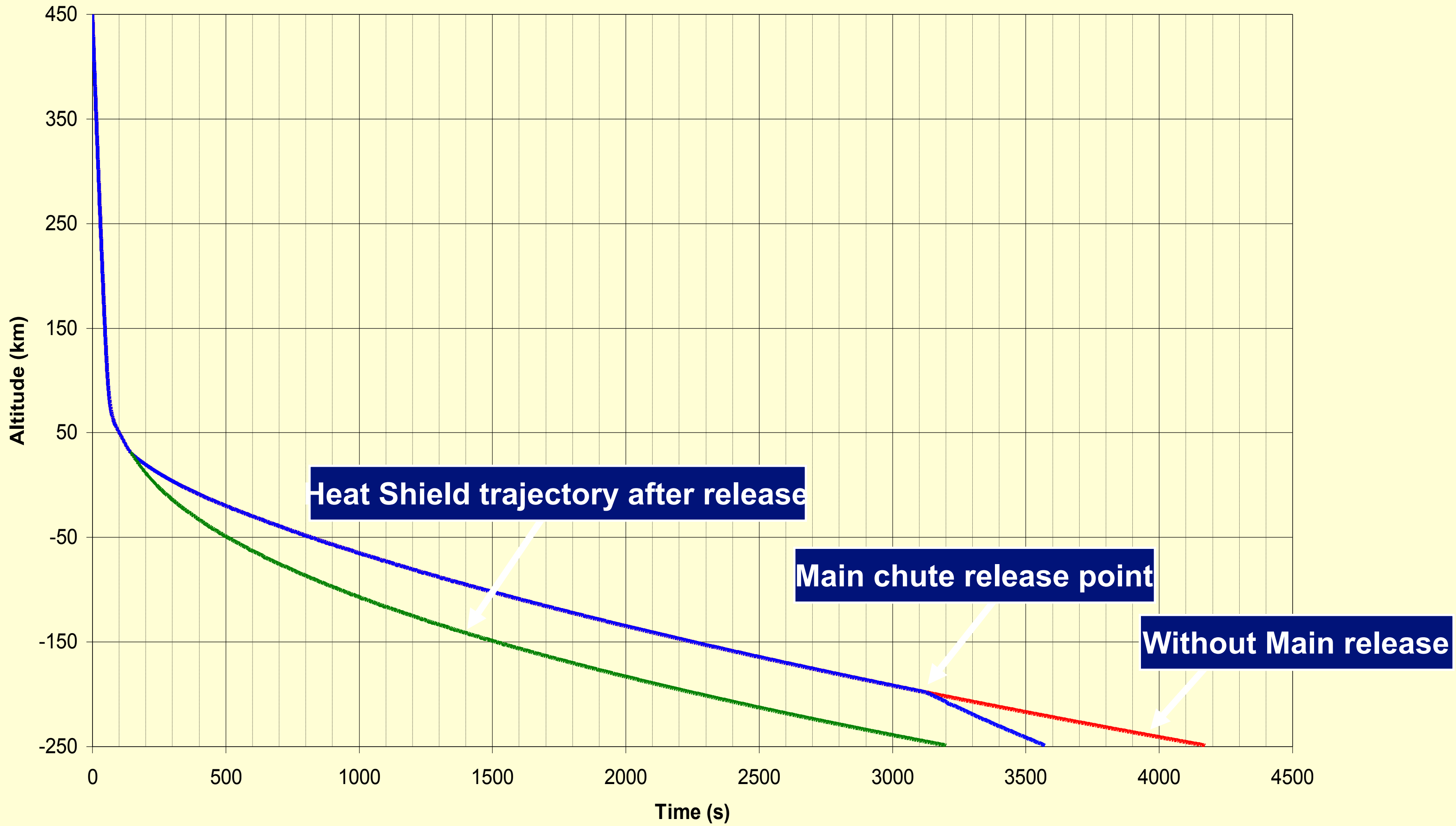
Entry point for Different Inclinations

Assumptions for the option 2 non equatorial analysis*:
Mass = 500 kg
Nose Radius = 0.65 m
Base Diameter = 1.30 m

*Option 2 discarded during Study phase

Inclination [deg]	25	30	35
Entry angle [deg]	-16.1	-12.5	-10.2
Entry velocity [m/s]	48716	49177	49813
Entry altitude [km]		450	
Entry lat. [deg N]	-15.4	-15.7	-16.1
Entry azimuth [deg]	65.0	57.8	51.1
Peak decel. [g]	480	370	300

Option 3 extended payload Altitude versus Time



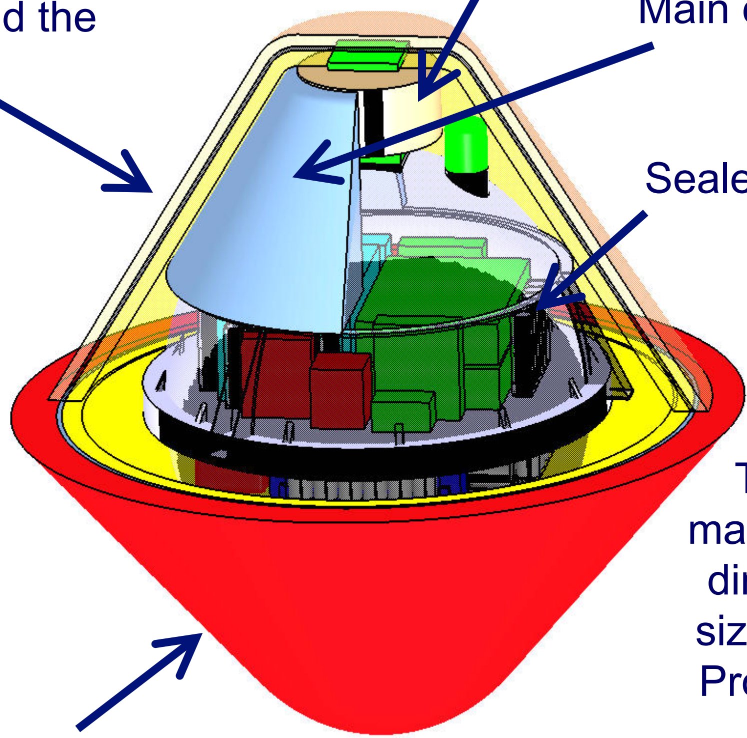
Probe baseline design

Pilot chute for extraction of main chute

Back cover sized by the dimensions of the DM and the mortar

Main chute for separation of front shield from DM

Sealed Descent Module sized for 100 bar external pressure



The overall dimensions and mass of the probe result from the dimensions of the DM which is sized by the equipment volume: Probe Mass cannot be reduced below a certain threshold

“Conventional” Carbon phenolic based Sepcore Front shield

Test facilities (1)

NASA presentation on re-organising arc jet facilities:

Arc Heated Facilities

	Capital Cost	M&R Savings	Overhead	Implementation	Program Impact
Aerothermal	***$***				
JSC to Ames	*30-50 M	Yes	Reduced	2-3 yr	Minor
Ames to JSC	90-150 M	Yes	Reduced	5-6 yr	Major
AEDC to Ames	75-125 M	Yes	Reduced	5-6 yr	Major
Ames to AEDC	80-130 M	Yes	Reduced	5-6 yr	Major
Aeropropulsion					
At Ames		Yes	Reduced	5-6 yr	Minor
At Langley	>100M	Yes	Reduced	5-6 yr	Major
At AEDC		Yes	Reduced	2-3 yr	Minor
Single Site					
Existing Capability**	90-150 M	Yes	Reduced	5-6 yr	Major
New Capability***	~500M	Yes	Reduced	10 - 15 yr	None

* This cost assumes moving considerable equipment and making significant plant upgrades. Cost will be significantly less if the existing Ames power supplies and cooling systems are adequate.

**70 megawatt, ***500 megawatt

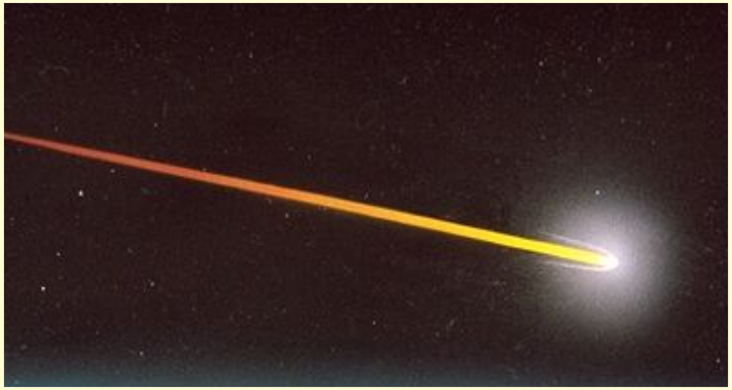
⇒ **New JEP entry test facility in Europe can be expected to cost around 500 M€**

⇒cost more than actual probe, and a very high investment for a facility that may only be used for one project.

Test facilities (2)

Use high-velocity Earth atmosphere entry

- Use multiple Earth and lunar flyby's to accumulate velocity, maybe also use upper stage or dedicated propulsion module to further accelerate test probe.
- At high altitude, Earth's atmosphere is dominated successively by helium, molecular hydrogen, and atomic hydrogen => simulate Jupiter atmosphere entry?

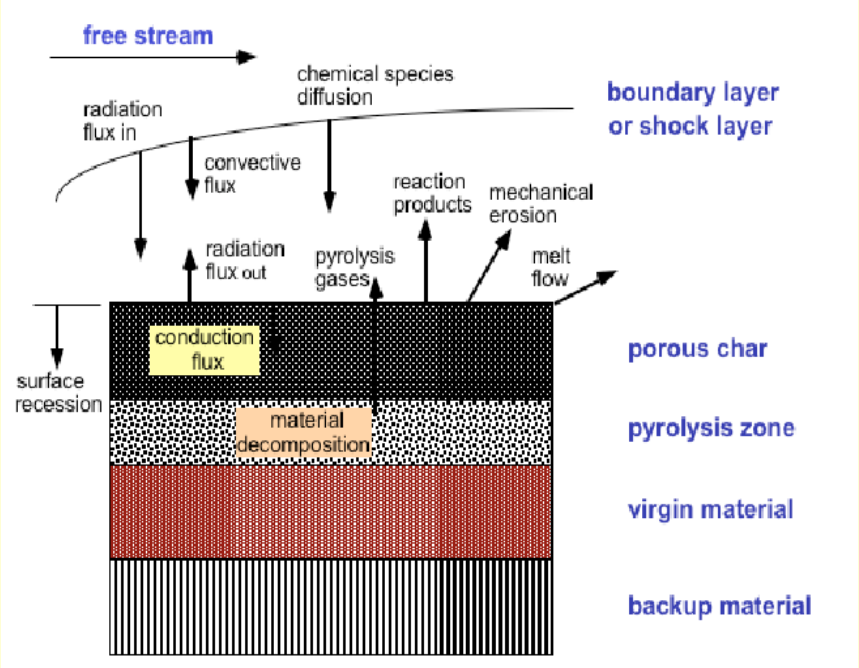


- 34 MW/m^2 expected for EVD (16 from convection, 18 from radiation)
- Share data (and costs?) with other projects requiring high-velocity entry data: Aurora, FLPP reusable launcher studies…
- **Pre-phase A studies on lower-velocity EVD show max velocity about 12.5 km/s.**

Test facilities (3)

Use existing European facilities

- Full simulation of JEP entry conditions very probably not possible with any of the existing facilities:
  - Not same gas velocity
  - Not same atmosphere (can any of the test results for nitrogen atmosphere be extrapolated to He/H atmosphere of Jupiter?)
  - Not same radiative / convective energy ratio



Test facilities (4)

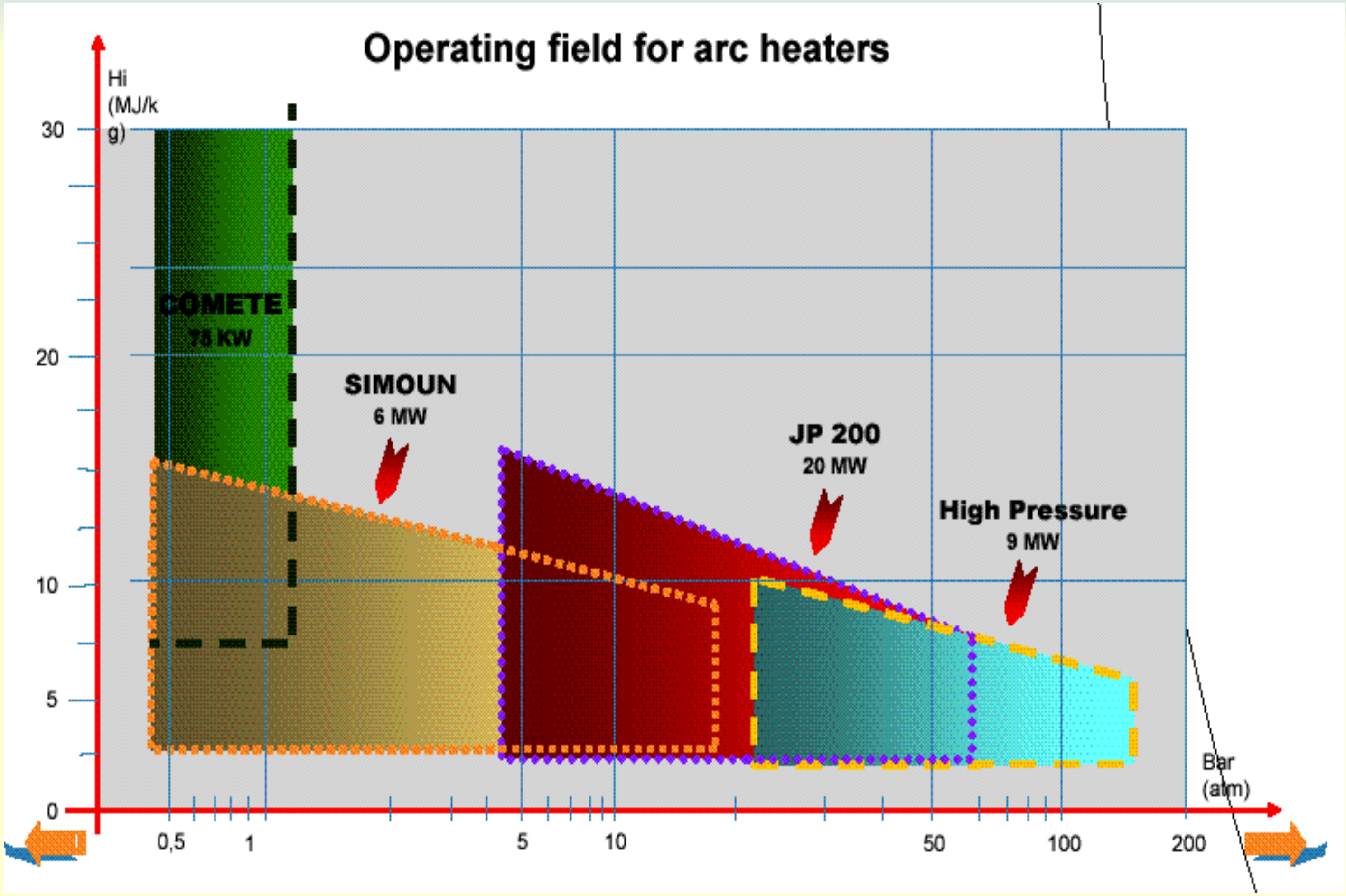
No facility existing achieving the level of heat-flux reaches during a Jupiter entry.

Plasma facilities generally have difficulties in providing radiative fluxes

Most powerful (in terms of heat-flux) European TPS facilities:

- **SCIROCCO (CIRA) - segmented arc heater - 3.8 MW/m^2**
- **L3K (DLR) - segmented arc heater - 4 MW/m^2**
- **Plasmatron (VKI) - 3 MW/m^2**
- **SIMOUN (EADS) – Huels arc heater - 4 MW/m^2**
- **COMETE (EADS) – Plasmatron – 7 MW/m^2**
- **JP 200 (EADS) - Huels arc heater – 25 MW/m^2**
- **High Pressure (EADS) – Huels arc heater – ? MW/m^2**
- **PWK4 (IRS) – Magnetoplasmadynamic generator – 100 MW/m^2**

Test facilities (5)



EADS-ST plasma test facilities

(Source: *Testing of Ablative Material at EADS Space Transportation, J.-M. Bouilly, D. Conte, F. Leleu, P. Plotard, Ablation Working Group, ESTEC, Oct. 13, 2005*).

Test facilities (6)

Three facilities may have an interest for a Jupiter entry in term of heat-flux, however:

- **PWK4 works with subsonic flows;**
- **The two others are dedicated to military activities (French deterrent force) so little information is available. They are both supersonic and only small models (0.05 m) can be tested.**

Possible improvements of SCIROCCO:

- With some modifications of the set-up, heat fluxes in the range of 20 MW/m^2 might be reached for samples of 25 mm.

- Some efforts in this direction are actually investigated in the frame of a technology study related to EVD (AURORA Programme).

Source: *Review of European Facilities for Space Aerothermodynamics, RT 1/06302 DMAE, ONERA, May 2003.*