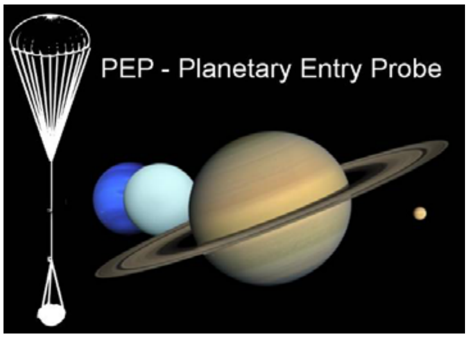
PEP
Planetary Entry Probes

Intro

IFP

ESTEC, 30th June 2010

Prepared by the PEP/ CDF* Team



(*) ESTEC Concurrent Design Facility

Introduction

- PEP: Planetary entry probes
- On request of SRE-PA
- Assess the feasibility and preliminary design of entry and descent probes to investigate the characteristics of Planetary atmospheres of:
  – Venus
  – Saturn
  – Uranus
  – Neptune
- In preparation of the next Cosmic Vision call
- Sixteen sessions (14 April – 30 June)
- Today is the Internal Final Presentation (IFP)
  – This is also a final iteration to verify each other's results
  – Science issues should be discussed off-line

Study objectives

- Assess the feasibility and preliminary design of entry and descent probes to investigate the characteristics of Planetary atmospheres of:
  - Venus
  - Saturn
  - Uranus
  - Neptune
- Enhance the ESA knowledge of entry and descent conditions at these planets
- Provide the Scientific community with a starting point for future mission proposals
- Allow ESA technical preparation for better evaluation of future mission proposals related to this study
- Produce an overview of the entry conditions and required technologies for all relevant target in our Solar System

Study flow

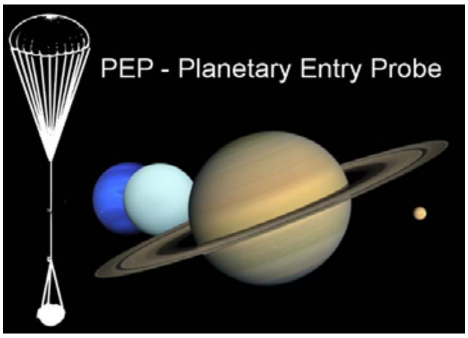
- First six sessions were dedicated to a Venus entry probe
- Remaining sessions to Outer planets
- The JEP CDF study on JEP was often taken as a starting point
  - Though finally, many changes were made w.r.t. JEP
- Report layout will correspond to study flow
  - Three parts: Venus, Outer Planets, and synthesis
  - Synthesis will also be compiled separately for attachment to the Call for Proposals

Agenda

- 9:30 – 13:00: systems, mission, aerothermodynamics, thermal, EDS
- 13:00-14:00: lunch break
- 14:00-17:00: payload, configuration, structures, mechanisms, GNC, power, comms, DHS, GS & Ops, Programmatics, risk, cost

PEP
Planetary Entry Probes

Systems



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Focus of PEP CDF Study

– Definition of entry conditions and required technologies for the investigated planets

– Preliminary design of the probe with a focus on the Entry and Descent System (EDS), for an overall probe mass of ~300kg (ref. JEP CDF Study)

– Parametric approach (as far as possible)

– Identification of system design commonalities, similarities and differences between the four planets

Requirements

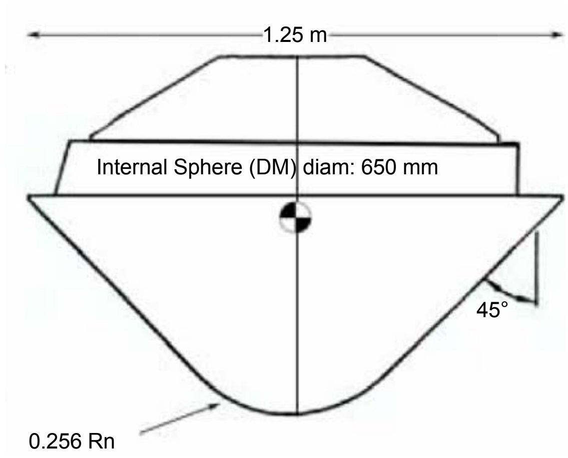
	MISSION REQUIREMENTS
SR-1	Mission launch timeframe 2020-2035.
SR-2	Launcher shall be Soyuz-Fregat 2-1b from Kourou (baseline), Ariane 5 ECA (backup).
SR-3	The mission design shall be composed of a carrier and a Planetary Entry Probe (PEP)
SR-4	The PEP shall perform a direct entry.
SR-5	The carrier shall perform a deflection manoeuver to have a fly-by trajectory and achieve a telecom relay function.
SR-6	During entry and descent, the apparent carrier elevation will be at least deg (TBC) with respect to the local horizon to optimise the communication budget.
SR-7	During entry and descent, the carrier to PEP range shall not exceed km (TBC) to optimise the communication budget.
SR-8	The time between probe separation and entry date shall be minimised to keep the FPA error as low as possible and in any case lower than TBD deg.
SR-9	Mission design shall allow the PEP to perform entry in the planet atmosphere at near equatorial latitude (baseline) or up to TBD deg latitude (option). *This requirement is not applicable to Uranus due to its tilted polar axis. Specific entry trajectories*
SR-10	The PEP shall perform an entry followed by a parachute phase.
SR-11	The probe shall operate down to an altitude corresponding to at least 30 bars and up to 100 bars pressure
SR-12	The PEP data shall be transmitted in real time to the carrier, which shall serve as a relay to the Earth.
SR-13	The PEP coast phase and entry should occur in visibility from Earth (TBC).
SR-14	If mass margins are sufficient, the mission shall achieve 2 probes release.

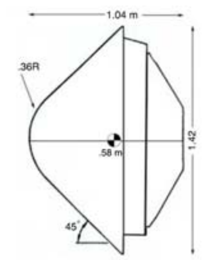
	SYSTEM REQUIREMENTS
SR-15	The PEP mass shall be minimised (reference mass envelope taken from the Jupiter Entry Probe CDF design ~ 300 kg)
SR-16	The ballistic coefficient of the PEP shall be in the range (TBD).
SR-17	The PEP half cone angle shall be set to 45 deg as a starting point.
SR-18	The PEP shall be compatible with the payload interface requirements as defined in the payload requirements section.
SR-19	The PEP shall carry, in addition to science payload, flight instrumentation to validate aerothermodynamic and ablation models
SR-20	For the design of the PEP the following mass margins shall be used: • Conventional maturity margins for all sub-systems, between 5 and 20% depending on the level of maturity to be agreed with the Agency • A system margin of 20 % on top of all PEP equipments, except for the heat shield material (back and forward) • The heat shield mass will be computed using the aerothermodynamics data including their margins and based on a PEP mass including margins (and heat shield mass) as defined above • A 50% maturity margin shall be added to the mass of the heat shield material computed as mentioned above if the current TRL is lower than 5
SR-21	The PEP shall be uncontrolled and unguided after release.
	EDS REQUIREMENTS
SR-22	The PEP entry and descent system (EDS) shall be composed of a front shield, a back cover (both being jettisoned after the entry phase), a parachute system (deployed at the end of the entry phase) composed by one or two parachutes (possibly featuring a pilot chute)
SR-23	The PEP shall accommodate and operate the payload and the avionics and power subsystems in a descent module compatible with the atmospheric conditions down to 100 bars (target) / 30 bars (threshold).
	COMMUNICATION REQUIREMENTS
SR-24	The PEP communication subsystem shall transmit periodically a minimum telemetry set of critical parameters to the carrier during the coast phase.
SR-25	The PEP communication subsystem shall maintain a communication link with the carrier during entry and descent (except during RF blackout) and shall relay in real time the flight and payload measurements data.
SR-26	RF carrier recovery and Doppler tracking shall be performed from Earth after separation.

	AERODYNAMIC REQUIREMENTS
SR-27	The PEP shall be aerodynamically stable during entry.
SR-28	The descent module and its parachute shall be aerodynamically stable during descent.
	PAYLOAD REQUIREMENTS
SR-29	The PEP shall accommodate, carry and operate the model payload defined.
	VENUS SPECIFIC REQUIREMENTS
SR-30	The Venus PEP analyses shall **consider 2 scenarios**: one scenario where the PEP is released as a **piggyback** during a GAM of a larger mission (Laplace mission shall be considered as a reference), and one scenario featuring a **stand alone mission** as for outer planets
SR-31	Note: DTE refers to science payload and Probe telemetry data, not to RF carrier recovery and Doppler tracking from Earth, which is specified in any case, provided in visibility from Earth
SR-31	In the case of a DTE link, no deflection manoeuvre nor relay function shall be considered for the carrier.
SR-32	The Venus PEP shall be sized to sustain the **surface pressure of 92 bars** (but no landing system shall be analysed).
SR-33	The Venus PEP shall **operate down to the surface**
SR-23	As an option, the feasibility of releasing the parachute before reaching the surface (in order to accelerate the final descent phase) shall be analysed, including analyses of the descent module stability

Geometry

Geometry of the Probe





Picture: Pioneer Venus Geometry

Pioneer Venus Aerodynamic Parameters

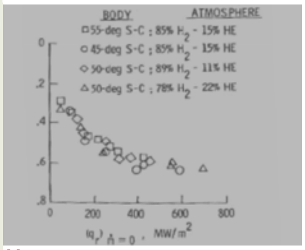
- Pioneer Venus
  - CoG/diam = 580.000/1420 = 0.410
- PEP Venus
  - CoG/diam = 456.418/1250 = 0.365

CoG properly placed from stability point of view (ref. Pioneer Venus).
Outer planets:
TPS thickness increase improve the stability

Margin Philosophy

Margin Philosophy for TPS Sizing

General Philosophy	VENUS	SATURN	URANUS	NEPTUNE
HEAT FLUXES	HEAT FLUXES	HEAT FLUXES	HEAT FLUXES	HEAT FLUXES
Heat Flux Margin	0 %	100 %	100 %	100 %
Blockage	0 %	20 %	20 %	20 %
TPS	TPS	TPS	TPS	TPS
TPS Margin	50 % thickness 20 %maturity	50 % thickness 20 %maturity	50 % thickness 20 %maturity	50 % thickness 20 %maturity



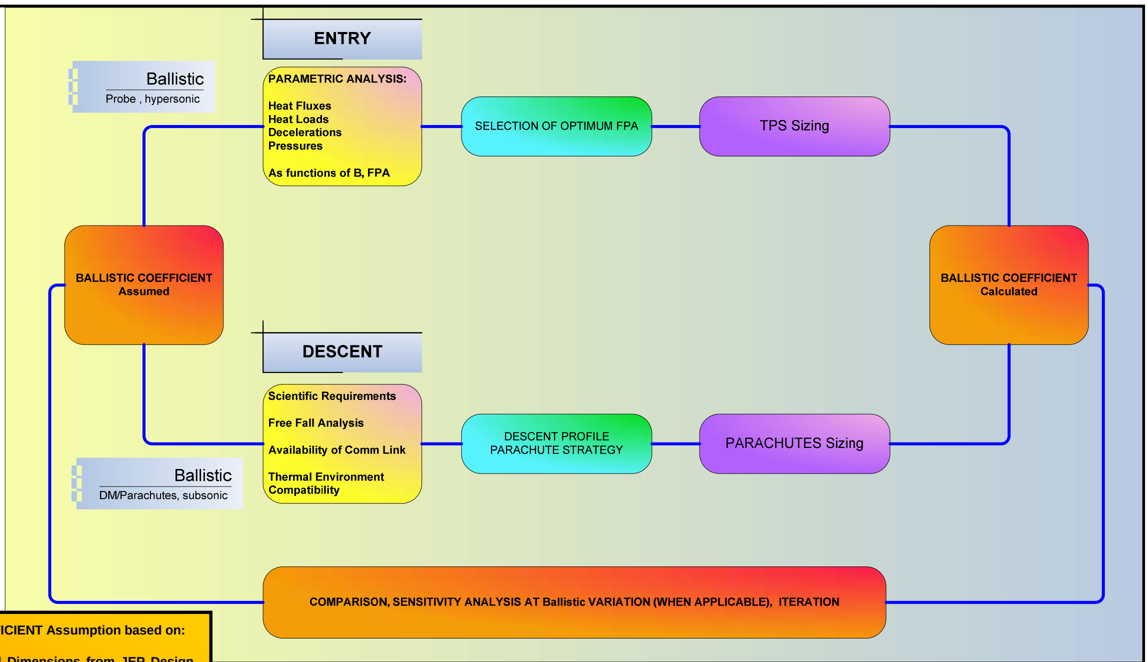
Venus:

- Correlations for Heat Fluxes available (Pioneer Venus) -> low margin on the Heat Fluxes
- Blockage impact on Heat Fluxes in Pioneer Venus shown in vfg 29-30
- Not taking margin on heat fluxes and not considering Blockage is a Conservative Approach

Outer planets:

- No Correlations for Heat Fluxes (100% margin)
- ~ 10 0 MW/m² (wo margin) Max Heat Fluxes → Blockage ~ 0 .4-0.5 (max). Average is lower, 80% fluxes pass through TPS →Blockage ~ 20%

Design Process

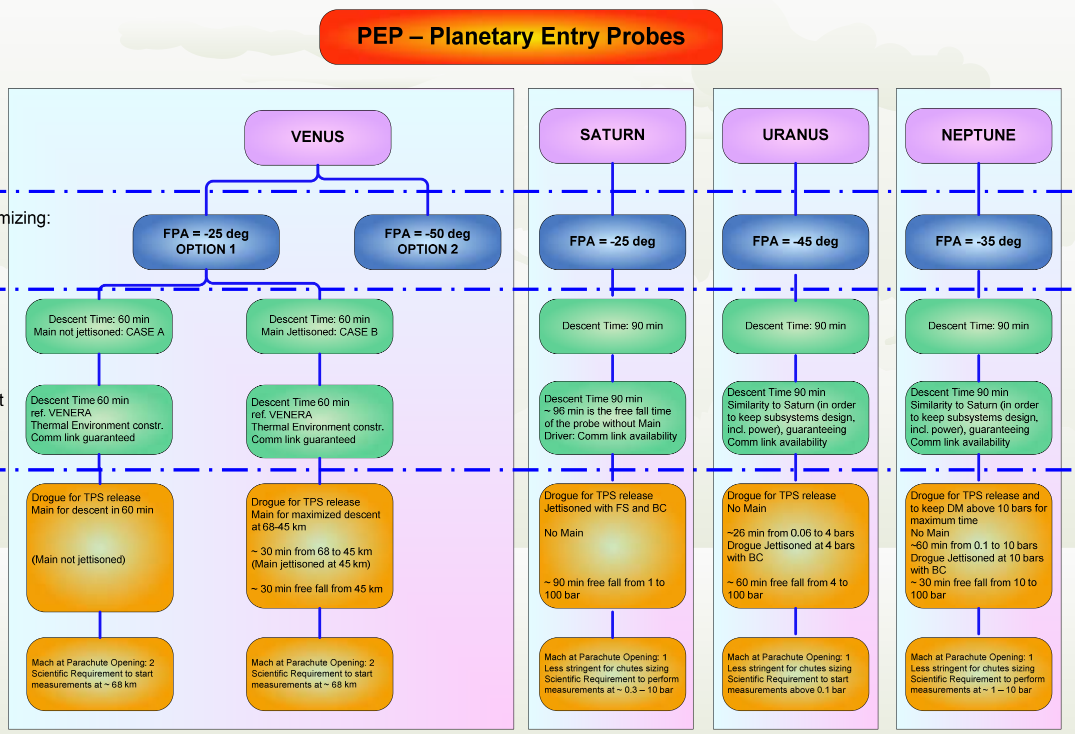


BALLISTIC COEFFICIENT Assumption based on:

VENUS: Mass and Dimensions from JEP Design refined for PEP Venus, including accommodation of PEP/PL, and anticipating TPS

OUTER PLANETS: mass of 300kg (JEP) and dimensions coming from PEP Venus design

System Overview



Optimum FPA, minimizing:
- Heat Fluxes
- Max Deceleration

Descent Time:

Rationale for descent time selection and constraints

Descent Strategy

Parachutes

Mach at Parachute Opening (selection and constraints)

Assumptions

AREA	ASSUMPTION ITEM	VALUE	UNIT	REMARKS
Geometry	Front Shield Cone Angle	45	deg	
	Nose Radius	0.256	m	JEP ref.
Comms	Telecommand Capability during Coasting	No		Ref. vfg 35
	Frequency Band	UHF		400 MHz
	Comms Duration during Coasting	1	hour	(6 slots of 10 min)
Aerothermodynamics	Mach at Parachute Opening	M ~ 2 Venus M ~ 1 Outer Planets		Due to Scientific Requirements Better Scenario for Parachute Opening
Margin Philosophy	TPS sizing	50 20	% %	Thickness Margin Maturity Margin
	Heat Flux Margin	0 100	% %	Venus Outer Planets
	Blockage	0 20	% %	Venus Outer Planets
System Modes	1. Coast 2. Intermediate Mode (Mode 2), including: a. Entry b. Parachute Deployment Sequence 3. Descent	All planets: 20 days All planets: 106 s Venus: 60 min Outer Planets: 90 min	days s min min	Mode 2 (Intermediate): For power subsystem sizing purposes, a + b: assumed of constant duration. The actual duration has a different value for each planet (ref vgf 18), but this has a minor impact on the design (same order of magnitude)

System Trade - Offs

AREA			Planet	REMARKS
Mission Architecture	Dedicated Mission	Piggyback Mission Architecture	Venus	Piggyback Option: Laplace Mission Architecture
Mission Analysis	Transfer Scenarios		All	
Coast Duration	Several durations investigated		All	20 days coasting has been baseline for all planets
Entry Conditions	Daylight Entry	Night Entry	All	Outer Planets: night entry = not in visibility from Earth
	Earth Visibility	No Earth visibility	All	
Inertial FPA	- 25 deg	- 50 deg	Venus	For all the planets an optimization of the entry inertial FPA has been performed, for Venus 2 dedicated options (FPA -25deg and FPA -50 deg) have been studied)
Thermal	TPS Concepts and Materials		All	
	RHU	No RHU	All	Need during Coasting to be checked (later phases)
Communications	DTE	Relay Orbiter	Venus	Outer Planets: DTE not feasible
	Comms during entry	No comms during entry	All	Flight housekeeping data can be transmitted out of the blackout period
GNC	IMU	No IMU	All	

System Trade – Offs (cont'd)

AREA			Planet	REMARKS
Main Parachute Type	Disk Gap Band	Conical Ribbon	All	
Number of Parachutes	Main parachute	No main parachute	All	Drogue is needed for TPS release. Need for main is related to free fall duration of DM sphere, compared with the scientific requirements to perform measurements at a specified pressure/altitude, maintaining link with the carrier
Main Chute Jettisoning	No jettisoning	Jettisoning at 45 km	Venus	To maximize scientific measurements at interesting altitudes (68 – 45 km)
Drogue Chute Jettisoning	No jettisoning	Jettisoning at given pressure (or altitude)	Outer Planets	To maximize scientific measurements at interesting pressures
Parachute sizing	Based on TPS release	Based on descent time	All	
Mach at Parachute Opening	M ~ 2	M ~ 1	All	

System Modes and Duration

MODE NAME	DESCRIPTION	DURATION
Coast	From probe's release from carrier till atmosphere entry. The probe uses its own Power system and timer switches to activate automatic sequences. NO Telecommand Capability assumed.	20 days
Intermediate	From the point where the probe reaches the interface altitude to the Front Shield Release and Main Parachute Deployment (when applicable). During this phase the probe relays flight instrumentation data. A black-out is caused by a plasma sheath around the probe	~106.20 s • Atmospheric Entry • Parachute Deployment Sequence and Front Shield Release
Descent	After the Front Heat Shield release the DM is ready to: -perform scientific measurements, -relay data (communication window allows link budget with compatible range and elevation), - survive Thermal Environment	~ 60 minutes VENUS (VENERA) ~ 90 minutes OUTER PLANETS

ATMOSPHERE ENTRY AND PARACHUTE DEPLOYMENT/TPS RELEASE SEQUENCE

VENUS: M = 2 at 36.8 s from atmosphere interface + 20 s for drogue opening, 30s for FS release, 2s for BC release, 20s for main opening

SATURN: M = 1 at 76.0 s from atmosphere interface + 30 s for drogue opening and TPS release
BC is released at 106.20 s from atmosphere interface

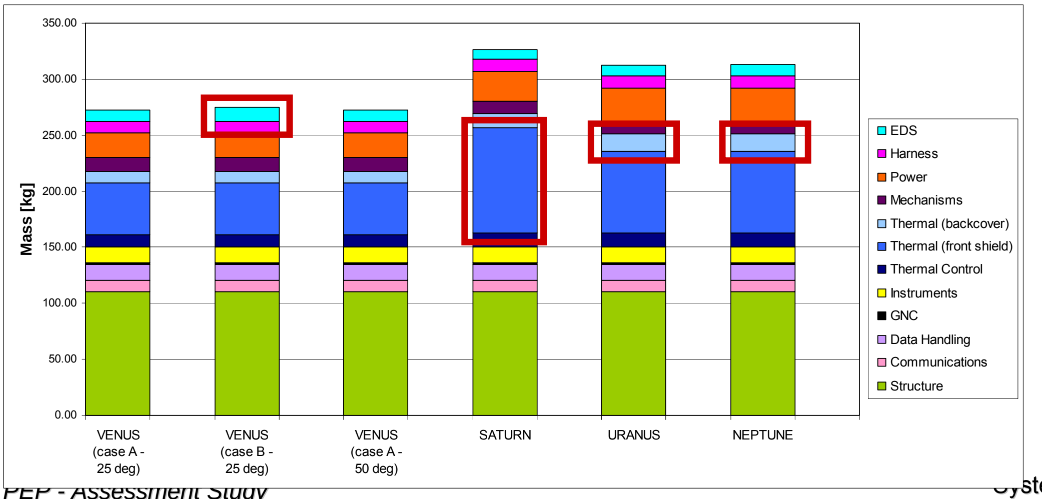
URANUS: M = 1 at 65.0 s from atmosphere interface + 30 s for drogue opening and TPS release.
BC is released at t = 1625 s from atmosphere interface

NEPTUNE: M = 1 at 58.7 s from atmosphere interface + 30 s for drogue opening and TPS release.
BC is released at t = 3260 s from atmosphere interface

[1] Blackout is related to the velocity of the probe, the density of the atmosphere, the geometry of the heat shields, and the peak of the heat loads. The blackout period assessment is out of the scope of this study. In any case it shall be shorter than the entry phase duration.

System Charts

Overview Probe Masses



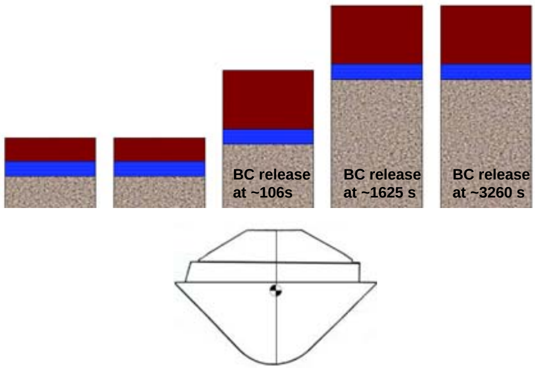
272.71	274.88	254.10	326.25	312.38	313.34	Launch Mass [kg]

Subsystem Level

Thermal Design - TPS

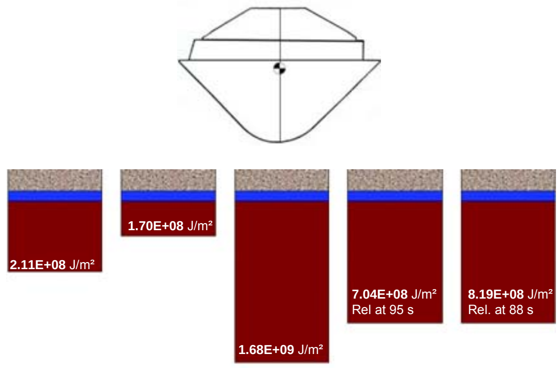
	Venus FPA = -25°	Venus FPA = -50°	Saturn FPA = -25°	Uranus FPA = -45°	Neptune FPA = -35°
THICKNESS					
Front Shield Ablator	CP **16.2mm** (31.0kg) Narmco4028 **23.4mm** (44.77kg) FM5055 **26.1mm** (49.94)	CP **8.1mm** (15.5kg) Narmco4028 **13.5**mm (25.83kg) FM5055 **11.7mm** (22.39kg)	CP **36.9mm** (70.6kg) Narmco4028 **49.5**mm (94.71 kg) FM5055 **54.9mm** (105.04 kg)	CP **27.9mm** (53.38kg) Narmco4028 **38.7** mm (74.05 kg) FM5055 **42.3** (80.93 kg)	CP **27.9mm** (53.38kg) Narmco4028 **38.7** mm (74.05 kg) FM5055 **42.3** (80.93 kg)
Front Shield C/SiC	2.4 mm	2.4 mm	2.4 mm	2.4 mm	2.4 mm
Front Shield IFI	5 mm	5 mm	5 mm	5 mm	5 mm
Back Cover Ablator	3.6 mm	3.6 mm	9 mm	9 mm (3.07 kg)	9 mm (3.07 kg)
Back Cover C/SiC	2.4 mm	2.4 mm	2.4 mm	2.4 mm	2.4 mm
Back Cover IFI	5 mm	5 mm	10 mm	20 mm	20 mm
MASS					
Front Shield C/SiC+IFI	8.11 kg	8.11 kg	8.11 kg	8.11 kg	8.11 kg
Back Cover C/SiC+IFI	7.62 kg	7.62 kg	8.62 kg	10.62 kg	10.62 kg
Total Front Shield (Ablator+C/SiC+IFI)	CP 16.2mm (**39.11kg**) Narmco4028 23.4mm (**52.88kg**) FM5055 26.1mm (**58.05kg**)	CP 8.1mm (**23.61kg**) Narmco4028 13.5mm (**33.94kg**) FM5055 11.7mm (**30.5kg**)	CP 36.9mm (**78.71kg**) Narmco4028 49.5mm (**102.82kg**) FM5055 54.9 (**113.15 kg**)	CP 27.9mm (**61.49kg**) Narmco4028 38.7 mm (**82.16kg**) FM5055 42.3 (**89.05 kg**)	CP 27.9mm (**61.49kg**) Narmco4028 38.7 mm (**82.16kg**) FM5055 42.3 (**89.05 kg**)
Total Back Cover (Ablator+C/SiC+IFI)	PICA-likeCP 3.6mm (**8.85kg**)	PICA-likeCP 3.6mm (**8.85 kg**)	PICA-likeCP 9mm (**11.69kg**)	PICA-likeCP 9mm (**13.69kg**)	PICA-likeCP 9mm (**13.69kg**)

Back cover



	Venus (FPA -25)	Venus (FPA -50)	Saturn	Uranus	Neptune
Ablator	3.6 mm	3.6 mm	9.0 mm	9.0 mm	9.0 mm
C/SiC	2.4 mm	2.4 mm	2.4 mm	2.4 mm	2.4 mm
IFI	5.0 mm	5.0 mm	10.0 mm	20.0 mm	20.0 mm

Front shield



	Venus (FPA -25)	Venus (FPA -50)	Saturn	Uranus	Neptune
Ablator	16.2 mm	8.1 mm	36.9 mm	27.9 mm	27.9 mm
C/SiC	2.4 mm	2.4 mm	2.4 mm	2.4 mm	2.4 mm
IFI	5.0 mm	5.0 mm	5.0 mm	5.0 mm	5.0 mm

EDS Strategy & Design

	Venus FPA = -25° A	Venus FPA = -25° B	Saturn FPA = -25°	Uranus FPA = -45°	Neptune FPA = -35°
Number of Parachutes	2 Parachutes 1 drogue for TPS release 1 main for descent	2 Parachutes 1 drogue for TPS release 1 main for descent	1 Parachute 1 drogue for TPS release	1 Parachute 1 drogue for TPS release	1 Parachute 1 drogue for TPS release and to meet a given descent time to 10 bars
Mach at Parachute Opening	M ~ 2	M ~ 2	M ~ 1	M ~ 1	M ~ 1
Altitude, Pressure at Parachute Opening	68 km, 0.11094 bar	68 km, 0.11094 bar	0.1-0.5 bar	0.05-0.06 bar	0.1 bar
Altitude, Pressure at Parachute Jettisoning	~ 0 km, 92 bar	~ 45 km	Jettisoning after TPS release	4 bars	8-10 bars
Descent Timeline	60 minutes	30 min at 68-45 km 30 min at 45-0 km	90 min free fall from 1 to 100 bar Drogue released with FS and BC	~ 26 min from 0.06 to 4 bars with drogue and BC ~ 64 min free fall from 4 to 100 bars	~ 60 min from 0.1 to 8-10 bars with droge and BC ~ 30 min free fall from 10 to 100 bars

PEP – Subsystems Design

Same Design for All Planets	
Communication	
Link	Telemetry Link: 200 bps during Coast; 2 kbps during descent
Power	
Coast	On: 86W; Av. 0.5W
Entry	On: 53W; Av. 37W
Descent	On: 416W; Av. 412W
Payload	Ref. Back-up slides for detailed definition
DHS	uC+SCOC3 (MTU, CDMU, uRTU, DPU) – 11.56 kg incl margins
GNC	3 Timer Units for wake up, 2 g-switch to backup timer units, 1 IMU
Structure	Panel Thicknesses sized to stand 100 bar; max deceleration and max dynamic pressure impact to be further investigated

Summary

	Venus FPA = -25°	Venus FPA = -50°	Saturn FPA = -25°	Uranus FPA = -45°	Neptune FPA = -35°
Launch Date	03/11/2020		2025 – 2029 (several scenarios investigated) 02/03/25 baseline	S3/2026 vs S4/2028 28/12/29 baseline	2026/09/05
Transfer Time	0.33 years		8.6 – 9.78 years	18.5 vs 16.4 years	19.3 years
Inertial Velocity	11.8 km/s		36.0 km/s	21.7 km/s	24.7 km/s
Inertial FPA	-25° Option 1	-50° Option 2	- 25°	- 45°	- 35°
Mach at Parachute Opening	M ~ 2		M ~ 1	M ~ 1	M ~ 1
Number of Parachutes	1 drogue for TPS Release 1 main for desc. From ~68 km to 92 bar (CASE A) 1 main for desc from 68-45km, then free fall (CASE B)		1 drogue for TPS Release	1 drogue sized for TPS Release and kept till 4 bars (~26 min), and consequent free fall to 100 bar (~1 hour)	1 drogue sized for TPS Release and to reach 10 bars in ~ 1 hour
Parachute Strategy	CASE A: descent from ~68 to 92 bar in 60 min CASE B: descent from 65 to 45 km in 30 min, 30 min free fall		Descent from 1 to 100 bar in 90 min	Descent from 0.06 bar to 4 bars with drogue chute and BC, in ~26 min, Drogue and BC release and free fall to 100 bar in ~1 hour	Descent from 0.1 bar to 10 bars with drogue chute and BC, in ~60 min, Drogue and BC release and free fall to 100 bar in ~30 min
Descent Time	60 min (driven by thermal environment)		90 min (driven by available communication link with the carrier (range and elevation optimization)	90 min (driven by available communication link with the carrier (range and elevation optimization)	90 min (driven by available communication link with the carrier (range and elevation optimization)
Max Deceleration	~ 250 g	~ 360 g	~ 250 g	~ 300 g	~ 325 g
Max Heat Fluxes	59.5 MW/m² at 23.5 s from entry	83.37 MW/m² at 12.9 s from entry	114 MW/m² at 33.0 s from entry	104.04 MW/m² at 30s from entry	95.98 MW/m² at 37.1s from entry
Tot Heat Loads	2.11E+08 J/m²	1.70E+08 J/m²	1.68E+09 J/m²	7.04E+08 J/m²	8.19E+08 J/m²
Probe Mass	272.71 kg CASE A 274.87 kg CASE B	254.10 kg CASE A	326.25 kg	312.37 kg	313.34 kg
Probe Ballistic Coeff	202.01 kg/m² CASE A 203.62 kg/m² CASE B	188.24 kg/m²	241.67 kg/m²	231.40 kg/m²	232.12 kg/m²

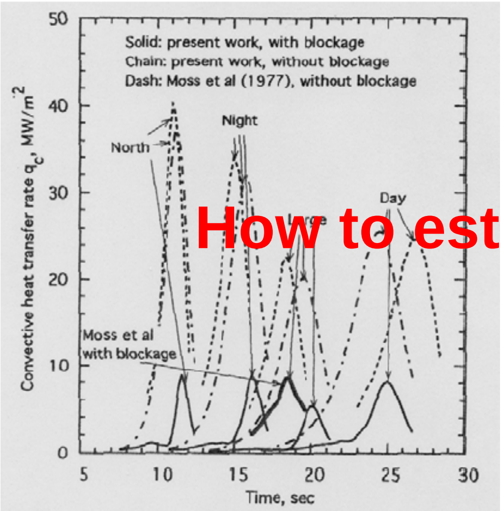
Back-up Slides

TPS Mass Fraction

	VENUS (case A)		VENUS (case B)		VENUS Option 2		SATURN		URANUS		NEPTUNE	
Thermal (front shield)	45.85	kg	45.85	kg	27.52	kg	93.92	kg	73.00	kg	73.00	kg
Thermal (backcover)	10.13	kg	10.13	kg	9.85	kg	12.89	kg	15.40	kg	15.40	kg
Launch mass	272.71	kg	274.88	kg	254.10	kg	326.25	kg	312.38	kg	313.34	kg
FS Mass Fraction	16.81%		16.68%		10.83%		28.79%		23.37%		23.30%	
BC Mass Fraction	3.71%		3.69%		3.88%		3.95%		4.93%		4.91%	
TPS Mass Fraction	20.53%		20.36%		14.71%		32.74%		28.30%		28.21%	
Entry Velocity	11.8	km/s	11.8	km/s	11.8	km/s	36	km/s	21.7	km/s	24.7	km/s
FPA	25	deg	25	deg	50	deg	25	deg	45	deg	35	deg
Ballistic Coefficient	202	kg/m²	204	kg/m²	188	kg/m²	242	kg/m²	231	kg/m²	232	kg/m²

	PIONEER VENUS		MARS Expl. Rovers		HUYGENS (Titan)	
FS Mass Fraction	8.83%		9.60%		25.00%	
BC Mass Fraction	1.52%		2.00%		5.10%	
TPS Mass Fraction	10.35%		11.60%		30.10%	
Entry Velocity	11.54	km/s	5.55	km/s	6.2	km/s
FPA	32.4	deg	11.5	deg	64	deg
Ballistic Coefficient	180	kg/m²	137	kg/m²	50	kg/m²

Reconstructing Pioneer-Venus entry: convective heat flux



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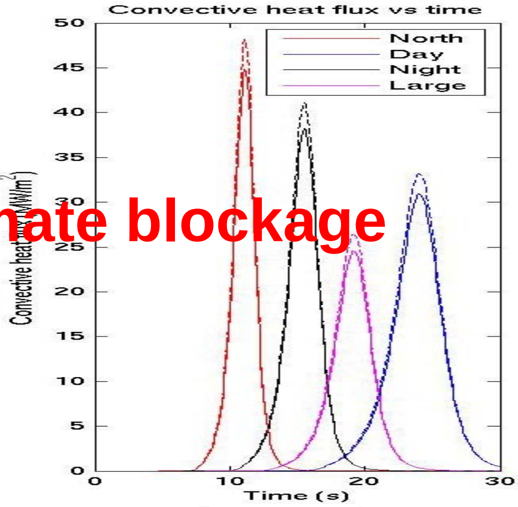
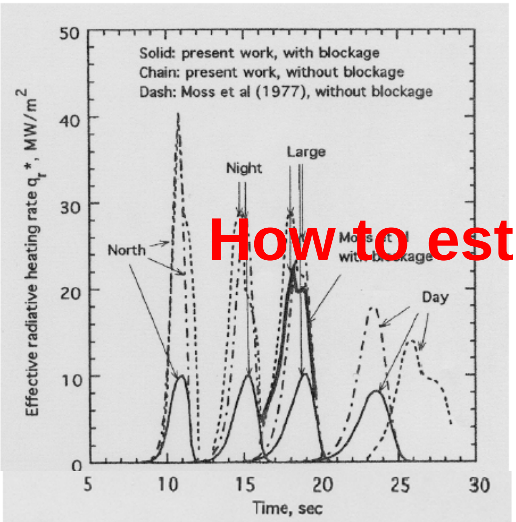


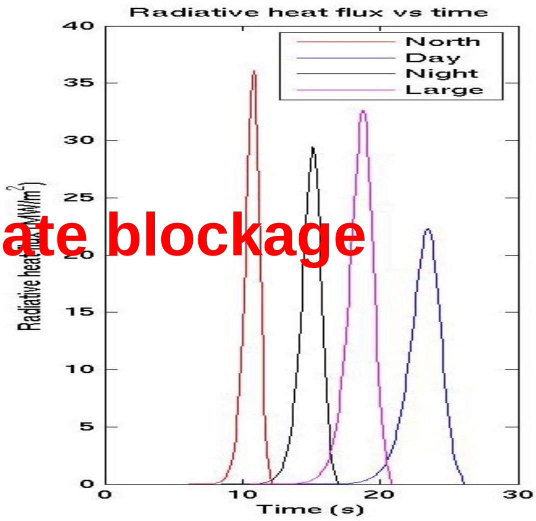
Reconstruction

How to estimate blockage

Reconstructing Pioneer-Venus entry: radiative heat flux



Park, JTHT Vol. 13,1999



Reconstruction

How to estimate blockage

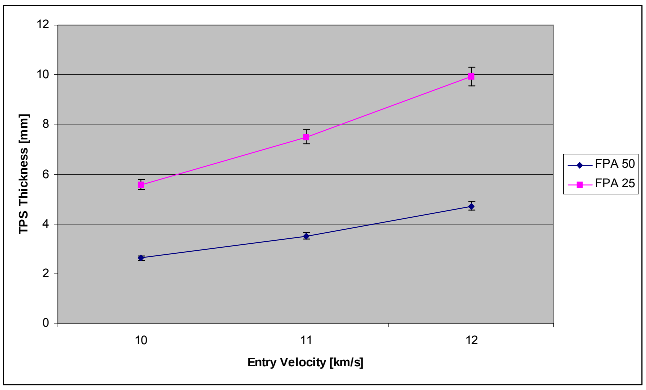
PEP Payload Definition

	Mass [kg] w/o margin	X*Y*X [mm]	Power [W]	Data rate [kb/s]	Data vol. [kb]	Duty cycle in 1 h
ASI/MET	1.25	ACC,TEM, PPI 205x30Ø (outside) 50x50x50 other	1 sby. 5 ave. 10 max.	0.16 ------------------ **CANbus**	5900/h 590 compressed	var. cont.
MS	5.0	250x200x100	4 sby. 8 ave. 10 max.	0.13 ------------------- **CANbus**	4800/h (6 samples) 480 compressed	1/10'
Doppler Wind	1.5	150x150x118	10 ave. 18 max.	-	-	cont.
Camera	1.2	100x100x200	8 ave. 10 max.	1.747 ------------------- **Spacewire**	75.5 Mb/h 6290 kbit comp.	1/10'
Photometer	0.3	30x30x80	1 ave. 2 max.	0.00026	16 bit/minute 0.96 kbit/h	Cont.
DPU and power conv.	1.0	50x50x100	3	-	-	-
Σ	10.25			2.037	7360.5	

PEP Payload Accommodation Requirements

	ACOOMMODATION REQUIREMENTS	
ASI/MET	ACC TEM PPI	Close to the center of mass 1 inlet 1 inlet
MS	2 INLETS	
Doppler Wind	NONE	
Camera	Downward looking, 15° field of view	
Photometer	Upward looking, 30° field of view	
DPU and power conv.	none	

Sensitivity Analysis - Venus



Assumption:

• error in FPA ± 1 degree

• error in ballistic coefficient ± 18.5 kg/ m²

Thickness of TPS various with 3.75 % for FPA of 25 degrees 3.68 % for FPA of 50 degrees.

→ TPS thickness not very sensitive to errors/variation in:

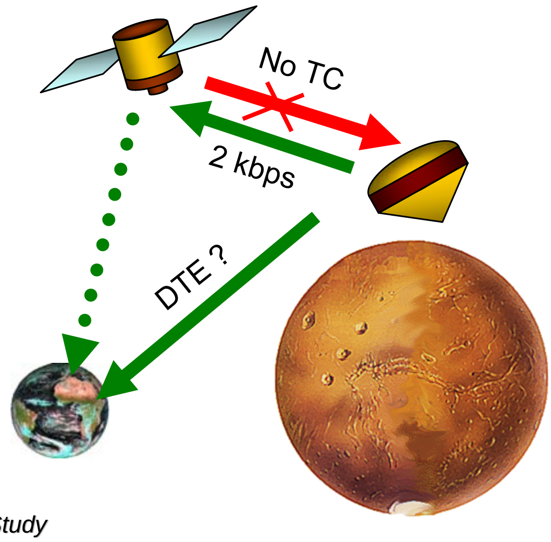
FPA and ballistic coefficient

COSPAR Planetary Protection Policy

Venus, Saturn, Uranus, Neptune: Category II

- Category II missions comprise all types of missions to those target bodies where there is significant interest relative to the process of chemical evolution and the origin of life, but where there is only a remote chance that contamination carried by a spacecraft could jeopardize future exploration.
  The requirements are for simple documentation only.
  Preparation of a short planetary protection plan is required for these flight projects primarily to outline intended or potential impact targets, brief Pre- and Post-launch analyses detailing impact strategies, and a Post-encounter and End-of-Mission Report which will provide the location of impact if such an event occurs.

Telecommands link (carrier to probe) is not required.

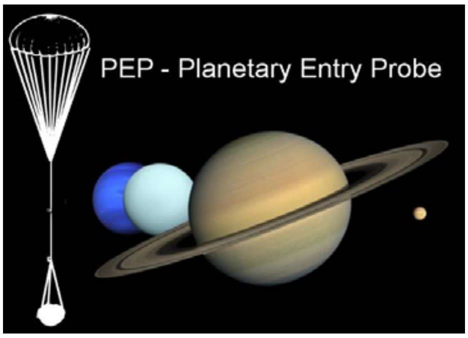


PEP
Planetary Entry Probes

Mission Analysis

IFP

ESTEC, 30th June 2010



Prepared by the PEP/ CDF* Team

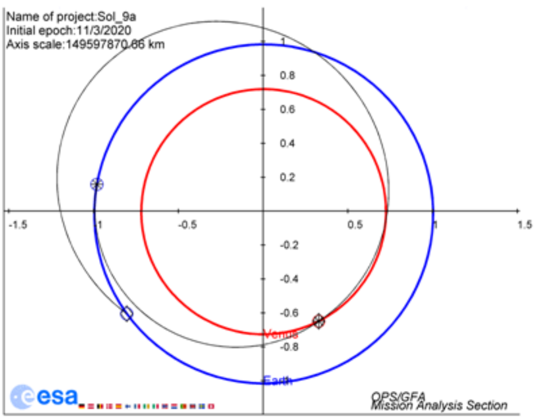
(*) ESTEC Concurrent Design Facility

VENUS

Contents

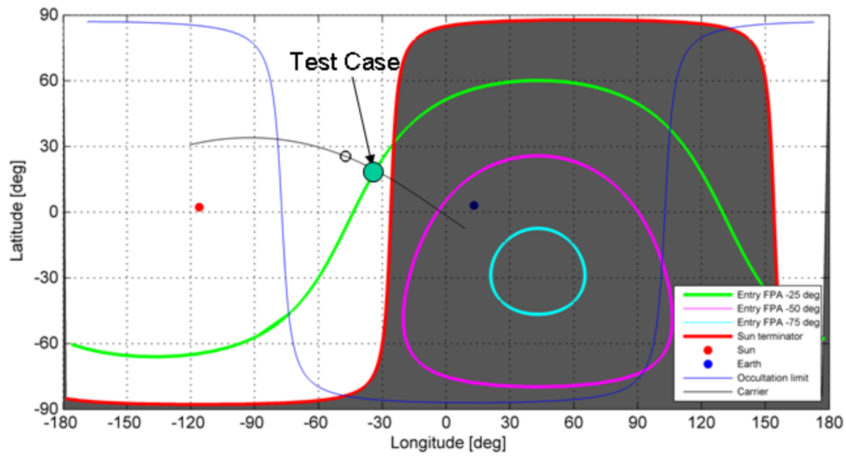
- Piggy-back scenario: Laplace
- Dedicated mission:
  - – Relay with the carrier
  - – DTE

Piggy-back Scenario: JGO launch in 2020



- Launch date: 2020/03/11
- Vinf: 3.38 km/s
- Sequence: VEEGA (only VE represented)
- T1 type transfer to Venus
- Venus GA: 2020/07/01
- Vinf: 6.39 km/s
- Swing-by altitude: 21,100 km

EIP



EIP altitude:
200 km

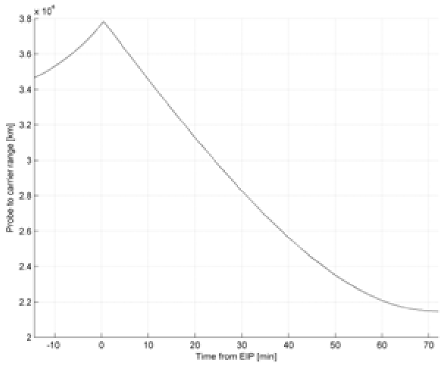
Probe-Carrier Link

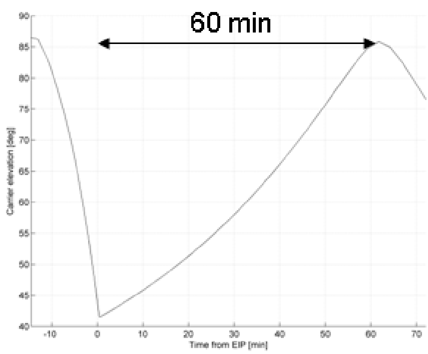
- Objective: Max elevation and Min range after a given delay
- Constraints:
  - Carrier pericentre → 1 degree of freedom of the ODM
  - Elevation of 90 deg after a given delay → Along-track component of the ODM
  - Rotation of the atmosphere → 1 degree of freedom of the ODM

  →ODM fully defined

  →No degree of freedom to have the minimum range after the same delay (the larger the FPA, the larger the difference)

Range-Elevation

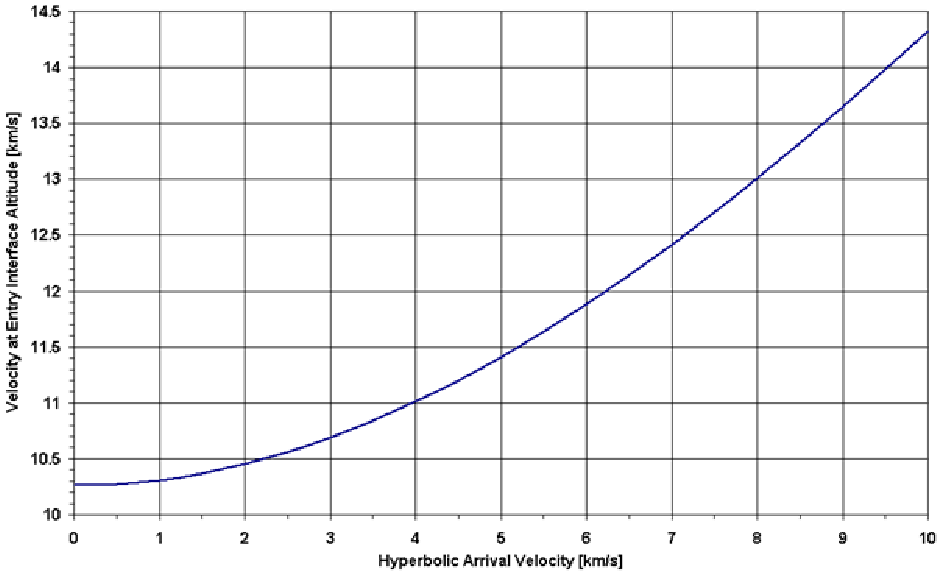




Relay with the Carrier

		Generic	Ariane	Soyuz direct	Soyuz GTO
2021 T1	Departure	2021/10/23	2021/10/26	2021/10/26	2021/10/25
	Arr.mass [kg]	Depends on LV	3867	1392	1815
	Arr. vel., dist.[km/s, AU]	5.416 / 0.38	6.199 / 0.35	6.188 / 0.34	5.798 / 0.35
2021 T2	Departure	2021/10/29	2021/11/12	2021/11/12	2021/11/4
	Arr.mass [kg]	Depends on LV	4378	1584	2001
	Arr. vel., dist.[km/s, AU]	4.764 / 0.81	5.479 / 0.98	5.453 / 0.97	5.021 / 0.9
2023 T1	Departure	2023/5/29	Not practical	Not practical	Not practical
	Arr.mass [kg]	Depends on LV			
	Arr. vel., dist.[km/s, AU]	3.662 / 0.43			
2023 T2	Departure	2023/5/18	2023/5/20	2023/5/21	2023/5/22
	Arr.mass [kg]	Depends on LV	4952	1762	2090
	Arr. vel., dist.[km/s, AU]	3.904 / 0.64	3.789 / 0.72	3.810 / 0.72	3.777 / 0.71
2024 T1	Departure	2024/12/25	2024/12/25	2024/12/25	2024/12/25
	Arr.mass [kg]	Depends on LV	4897	1748	2080
	Arr. vel., dist.[km/s, AU]	3.789 / 0.51	3.784 / 0.51	3.784 / 0.51	3.784 / 0.51
2024 T2	Departure	2024/10/30	Not practical	Not practical	Not practical
	Arr.mass [kg]	Depends on LV			
	Arr. vel., dist.[km/s, AU]	4.088 / 0.48			
2026 T1	Departure	2026/7/28	2026/7/29	2026/7/29	2026/7/29
	Arr.mass [kg]	Depends on LV	4867	1739	2074
	Arr. vel., dist.[km/s, AU]	4.931 / 0.4	4.900 / 0.41	4.899 / 0.41	4.899 / 0.41
2026 T2	Departure	2026/9/21	Not practical	Not practical	2026/9/21
	Arr.mass [kg]	Depends on LV			1778
	Arr. vel., dist.[km/s, AU]	7.591 / 1.1			7.574 / 1.1
2028 T1	Departure	2028/3/10	2028/3/10	2028/3/10	2028/3/10
	Arr.mass [kg]	Depends on LV	4252	1545	1920
	Arr. vel., dist.[km/s, AU]	6.016 / 0.4	6.154 / 0.4	6.152 / 0.4	6.151 / 0.4
2028 T2	Departure	2028/4/2	2028/4/26	2028/4/7	2028/4/6
	Arr.mass [kg]	Depends on LV	3900	1404	1874
	Arr. vel., dist.[km/s, AU]	6.130 / 1.0	7.852 / 1.04	6.502 / 1.04	6.488 / 1.04

V_inf to V_EIP

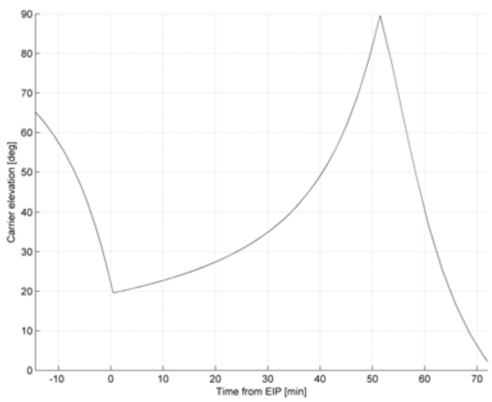


Sun illumination Probe to Carrier Link

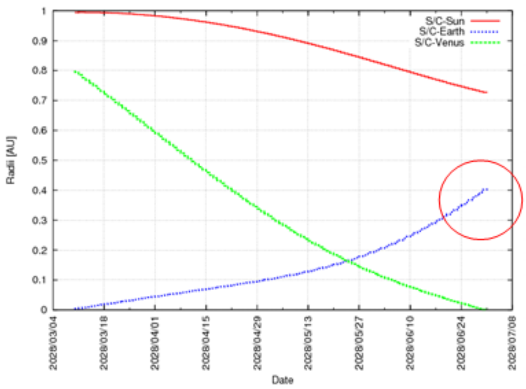
- T2 transfers: The entry is in daylight for all FPA
- T1 transfers:
  - The entry is always in daylight for a FPA of -25 deg
  - The entry is in daylight for a FPA of -50 deg in 2024 and 2026
  - The entry is never in daylight for a FPA of -75 deg

→ A low FPA is recommended

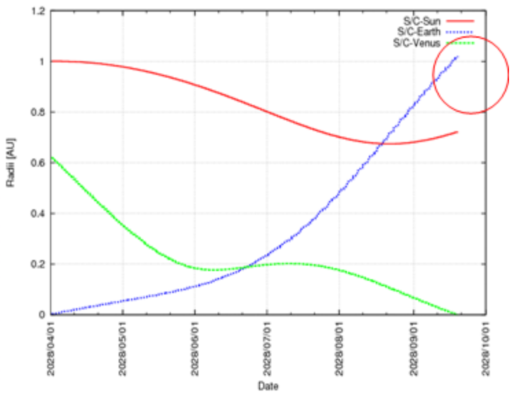
- In order to have a probe visibility of 60 min, a minimum pericentre altitude of 5000 km is recommended



DTE



T1



T2

Earth Link

- T2 transfers: The entry is in daylight and Earth visibility for all FPA
- T1 transfers:
  - The entry is in Earth visibility for all FPA
  - The entry is in daylight for a FPA of -25 deg
  - The entry is in daylight for a FPA of -50 deg in 2024 and 2026
  - The entry is never in daylight for a FPA of -75 deg
- An Earth elevation of 90 deg is reached for FPA between 55 and 60 deg

→ A medium FPA is recommended

OUTER PLANETS

Comparison

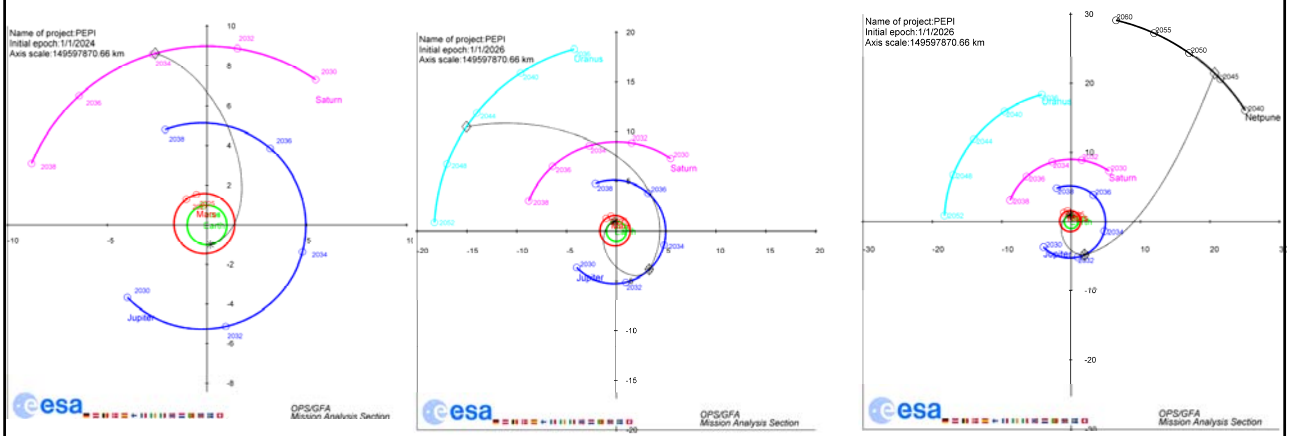
- Commonalities:
  - Transfer time
  - Distance to Earth → Carrier for relay
  - Large radius → Probe to carrier range
  - Fast atmosphere rotation → Entry conditions, modified ODM
- Specificities:
  - Saturn: rings → Adapted strategies
  - Uranus: North pole tilt (but with no impact on mission analysis)

Interplanetary transfer

Isp	s	For 400 N							Venus		Earth		Jupiter		Saturn	Uranus	Neptune								
CAS	DEPARTURE				(2)	CRUISE											ARRIVAL to 1 Rs + 20 Tkm x 180 Rs						TOTAL/FINAL		
	date	V-inf	dec	kg	m/s	m/s	swb	m/s	swb	m/s	swb	m/s	swb	m/s	swb	m/s	date	kg	V-inf	ras	dec	m/s	m/s	kg	yea
Saturn	02/03/25	3.983	27			0		0	21/09/25	0	04/07/26	37	02/07/29	0		0	33/12/08	0	6.361	41	9.3		37	0	8.8
Uranus	28/12/29	4.138	0	3550		0	29/12/29	0	30/05/28	1	31/04/14	0	33/04/14	185	36/01/30	2	45/05/22		5.905	123	21.1		188	3338	16.4
Neptune	05/09/26	3.414	-38			0		0	22/02/27	13	27/12/27	0	27/12/29	0	32/05/17	0	46/01/06	0	8.100	28	10.0		13	0	19.3

- Typical transfers are reported (a detailed analysis of possible transfers is subject to an in-going study)
- Possibility of transfers to Uranus via Saturn not analysed, but should be feasible → Double probe
- Fast transfer: Direct Earth to Jupiter. But P/L mass very low (less than 1 ton with AR5 ECB)

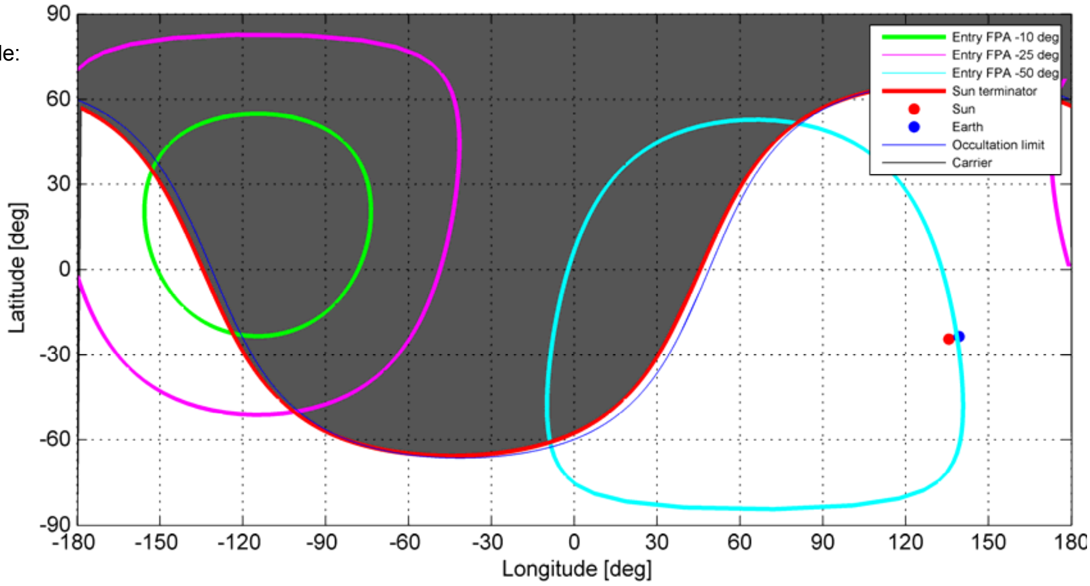
Interplanetary transfer (Cont'd)



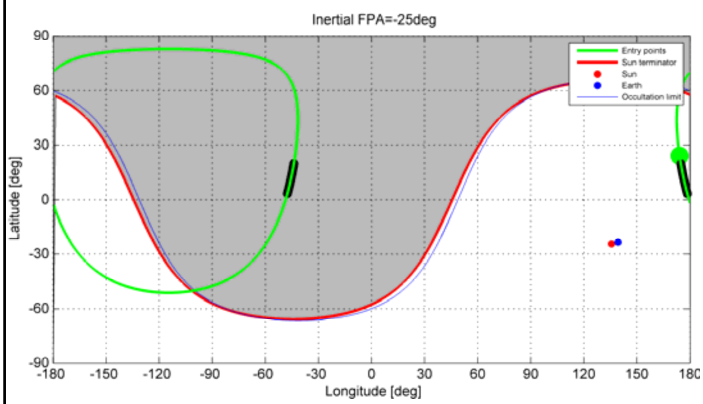
Saturn: Entry

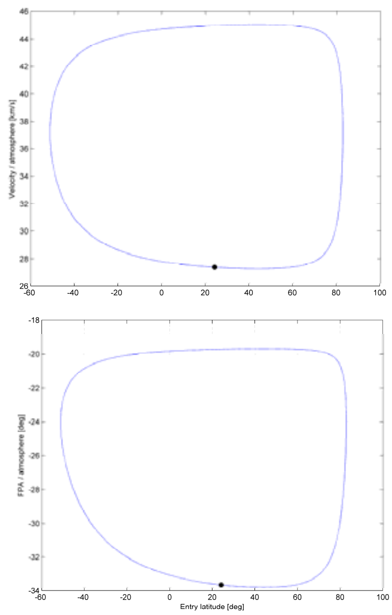
EIP altitude:

700 km



Saturn: Entry with FPA = - 25 deg





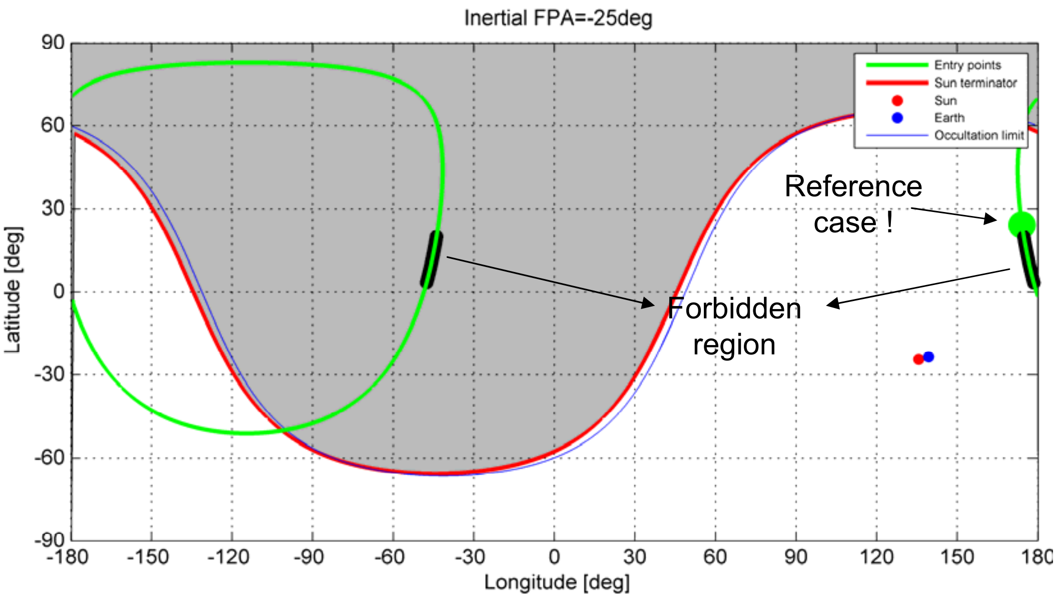
Atmosphere rotation period: 0.44 days

Atmosphere interface velocity: 10 km/s

Saturn rings

Ring or Region	Inner Radius (r_{in}) [km]	Inner Radius (r_{in}) [R_S]	Outer Radius (r_{out}) [km]	Outer Radius (r_{out}) [R_S]	Half Thickness (t_{ring}) [km]
D Ring	66970	1.11	74470	1.23	1
C Ring	74500	1.23	92000	1.52	1
B Ring	92000	1.52	117400	1.95	1
Cassini Division	117400	1.95	122170	2.03	–
A Ring	122170	2.03	136780	2.27	2
F Ring	140180	2.32	140260	2.32	50
Jan/Ep Debris	149600	2.48	153300	2.54	900
G Ring	165000	2.73	176000	2.92	720
Mimas Debris	181170	3.00	189870	3.15	4800
E Ring	180000	2.98	300000	4.97	10000

Ascending Node in the Rings



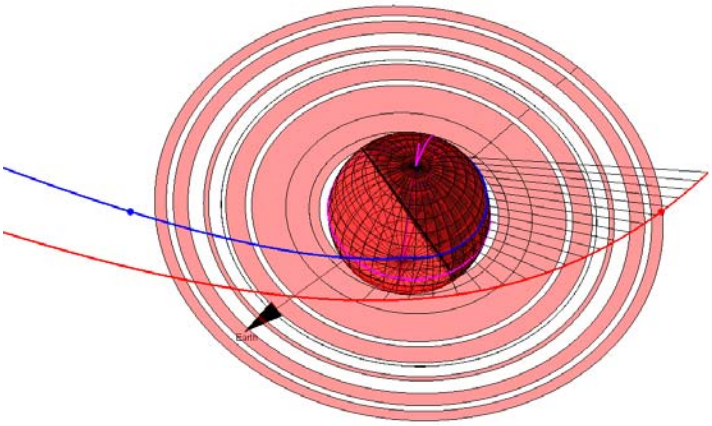
Selection of the Pericentre Radius

- Objective 1:
  - Carrier first node farther than the rings or,
  - Carrier first node in the gap between the F and G rings: a la Cassini → HGA used as protection
- Operations:
  - Carrier pointing at the probe during descent
  - Carrier pointing at the Earth for data relay → Long enough to reach the second node!
- → Objective 2:
  - Carrier second node farther than the rings or,
  - Carrier second node in the gap between the F and G rings: a la Cassini → HGA used as protection
- Objective 3:
  - Probe first node farther than the rings or,
  - Probe first node in the gap between the F and G rings: a la Cassini

→ Impact on possible carrier pericentre radius and probe entry latitude

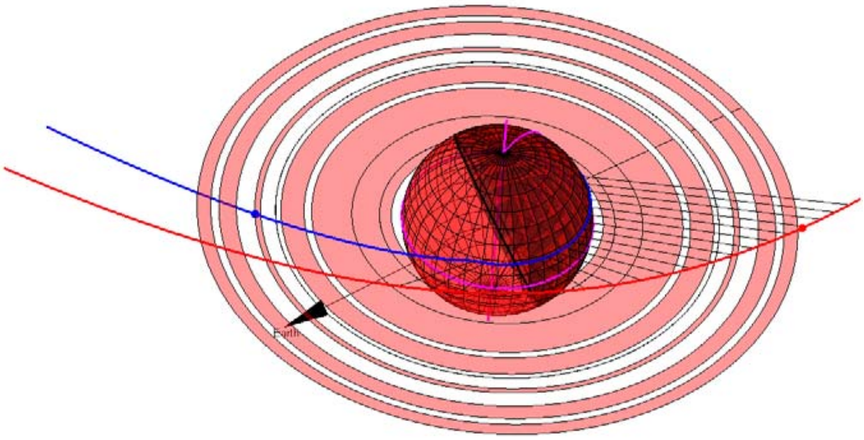
Selection of the Pericentre Radius (Cont'd)

Case 1.1: Carrier out, Probe out



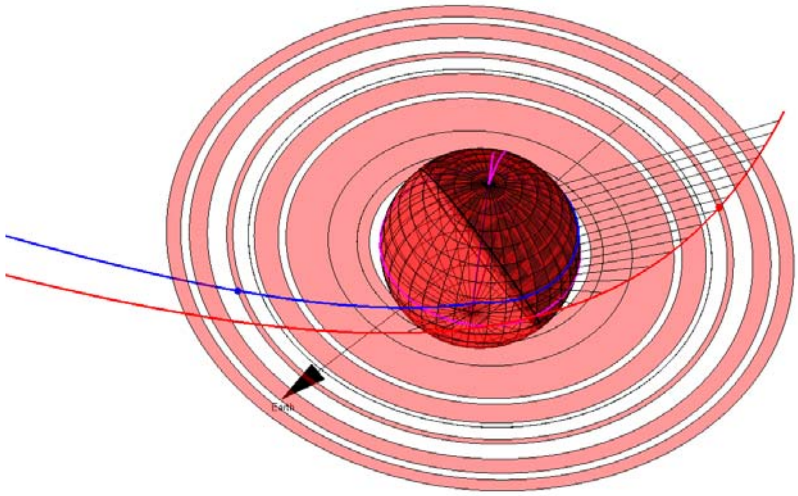
Selection of the Pericentre Radius (Cont'd)

Case 1.2: Carrier out. Probe in



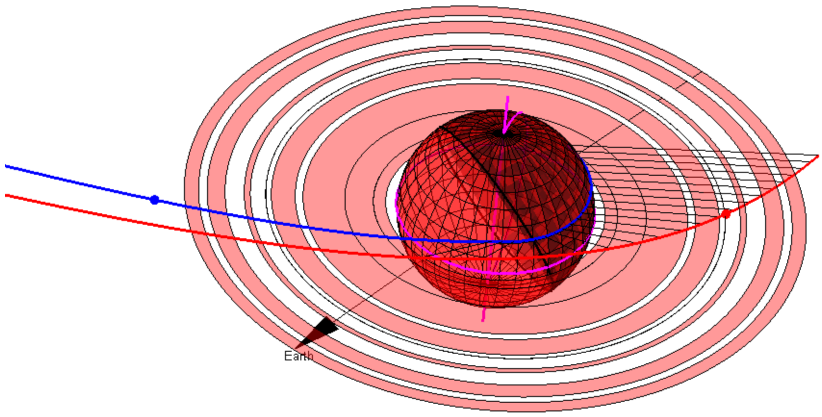
Selection of the Pericentre Radius (Cont'd)

Case 2.1: Carrier in, Probe in



Selection of the Pericentre Radius (Cont'd)

Case 2.2: Carrier in, Probe out



Selection of the Pericentre Radius (Cont'd)

		Carrier	
		In	Out
Probe	In	ODM=50 m/s rp=1.5 Rs	ODM=76 m/s rp=1.8 Rs
	Out	ODM=65 m/s rp=1.7 Rs	ODM=90 m/s rp=2.0 Rs

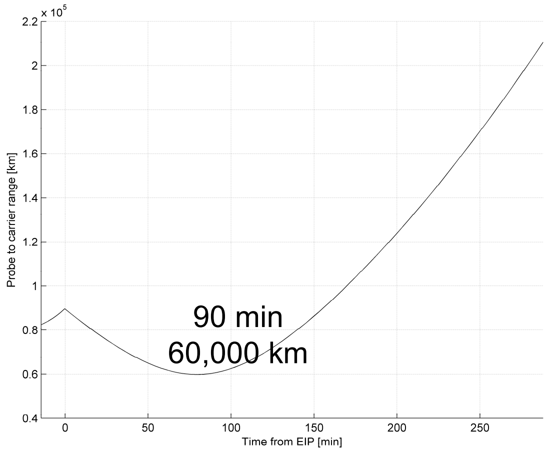
- Minimise risk for carrier
- Allow a good minimum range

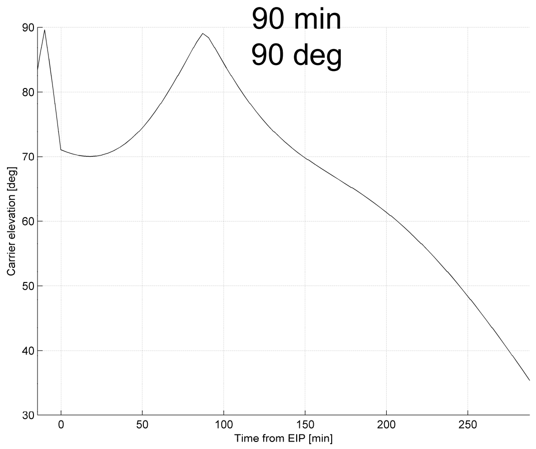
Carrier shall be protected:

- HGA
- Dedicated shield

Delay: 90 min

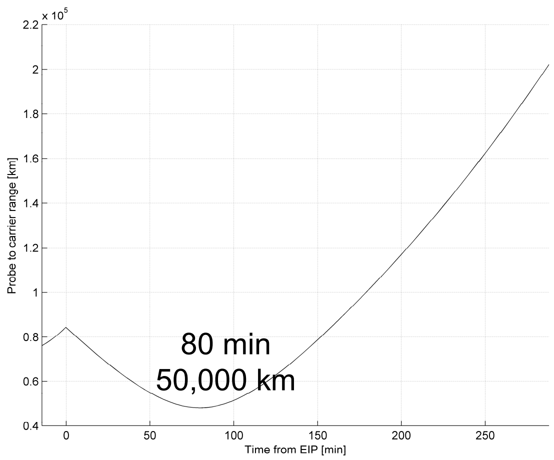
Case 1.1: Carrier out, Probe out

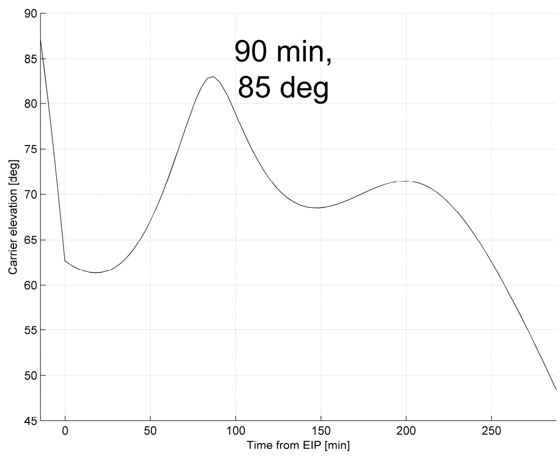




Delay: 90 min

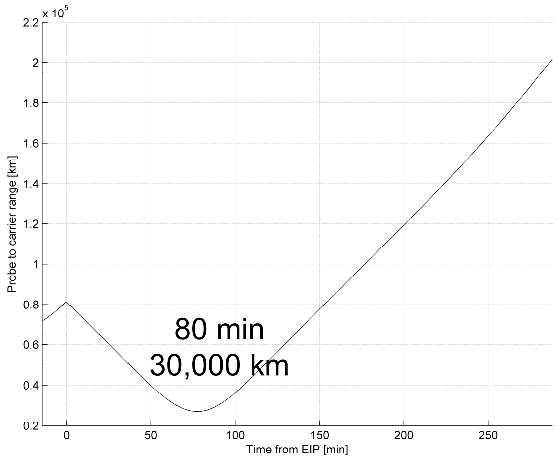
Case 1.2: Carrier out, Probe in

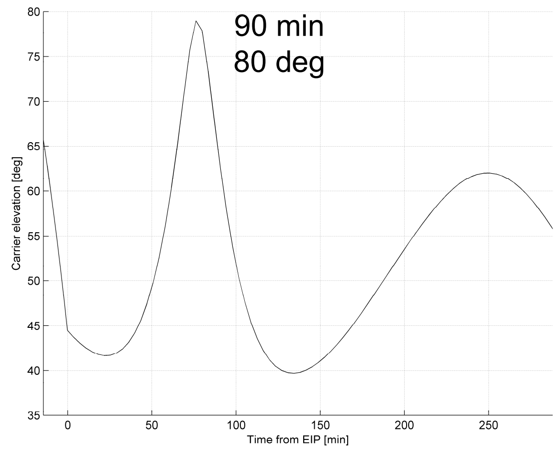




Delay: 90 min

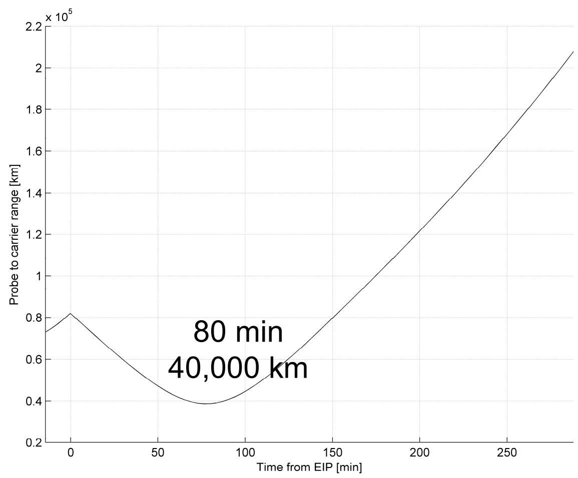
Case 2.1: Carrier in, Probe in

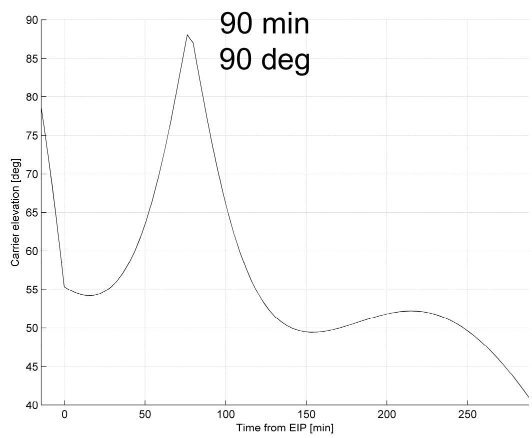




Delay: 90 min

Case 2.2: Carrier in, Probe out

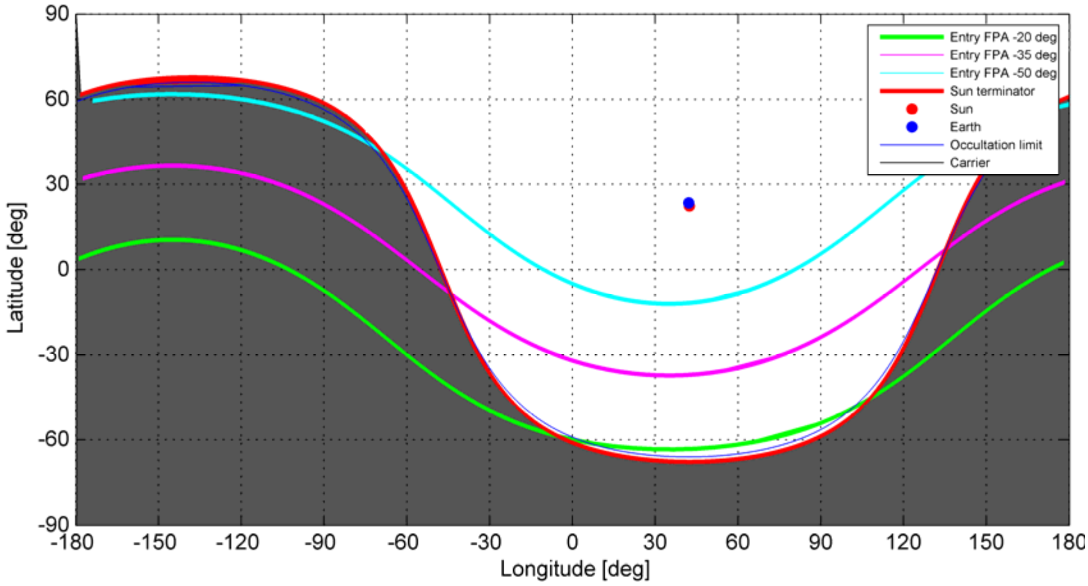




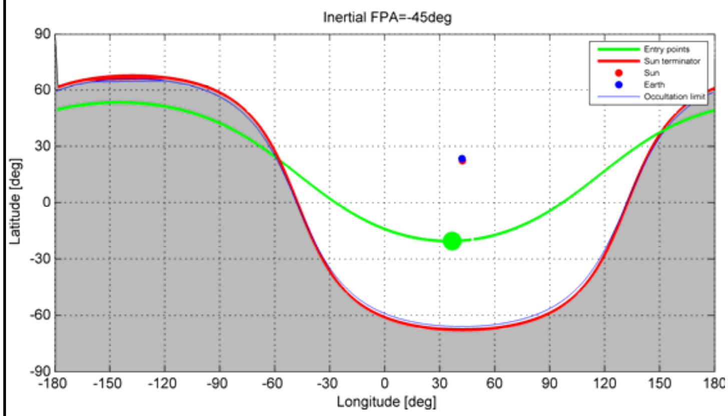
Uranus: Entry

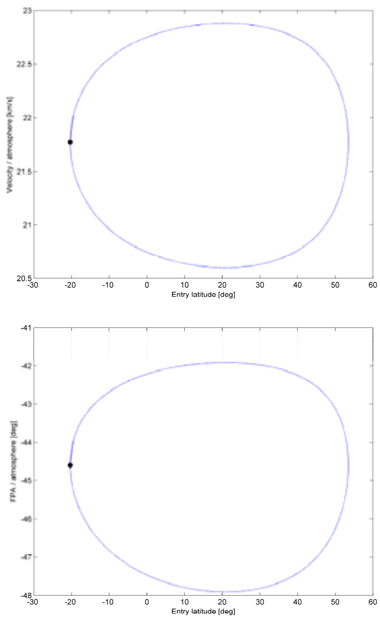
EIP altitude:

700 km



Uranus: Entry with FPA = - 45 deg

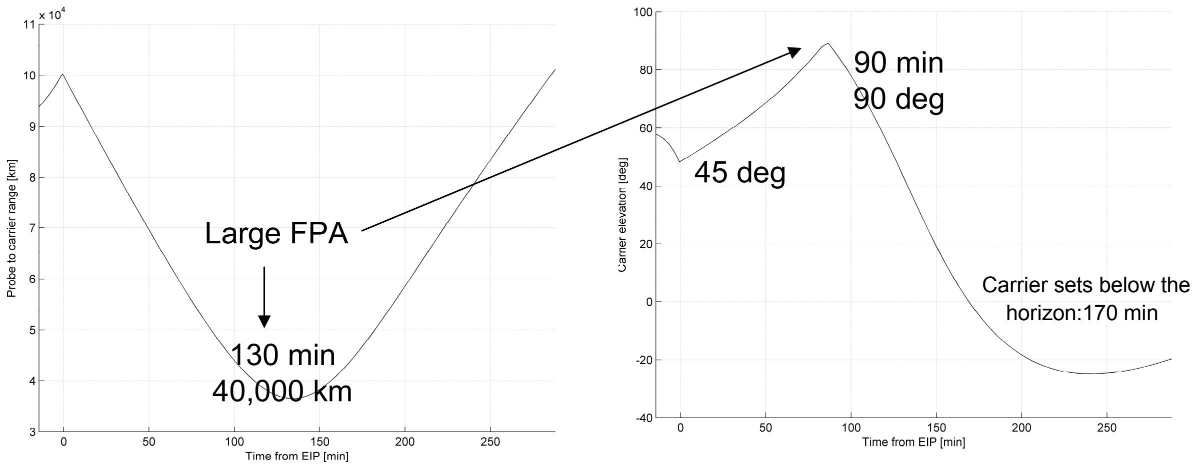




Atmosphere rotation period: 0.71 days

Atmosphere interface velocity: 2.7 km/s

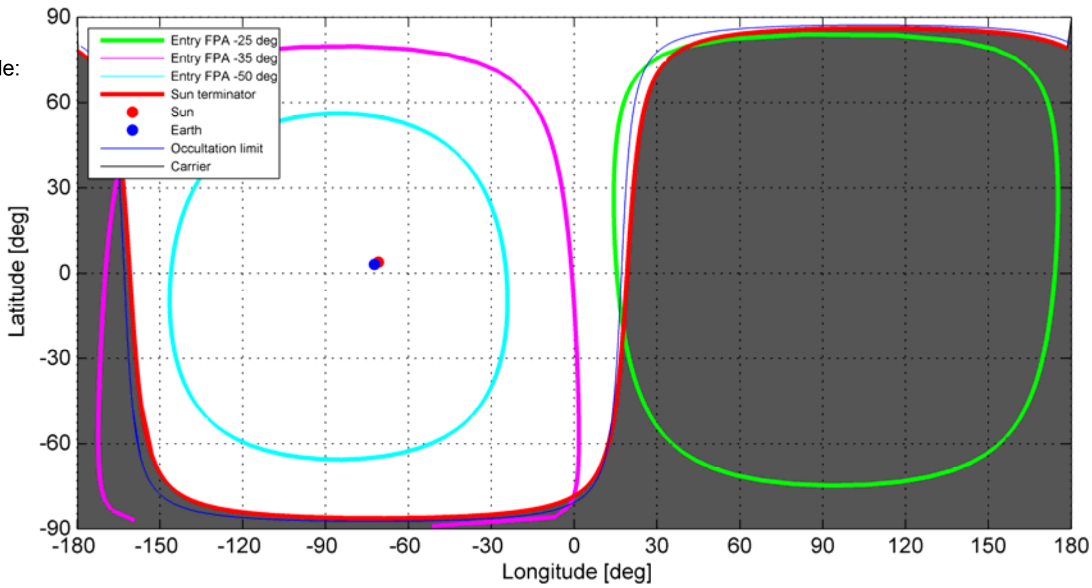
Delay: 90 min



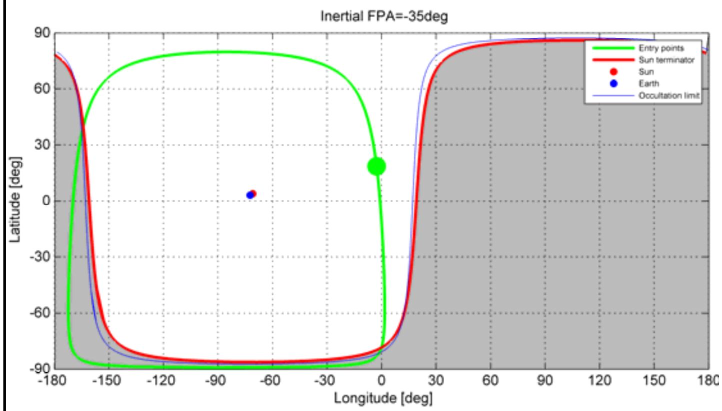
Neptune: Entry

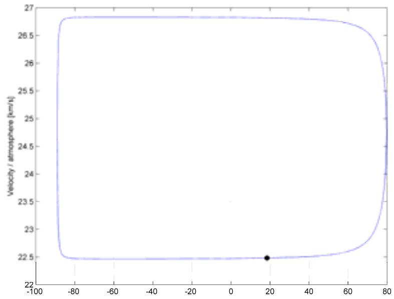
EIP altitude:

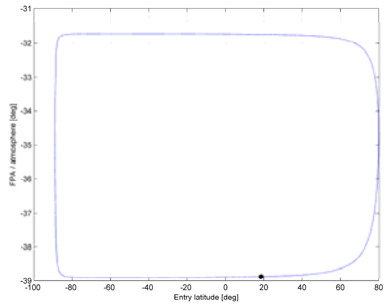
600 km



Neptune: Entry with FPA = - 35 deg



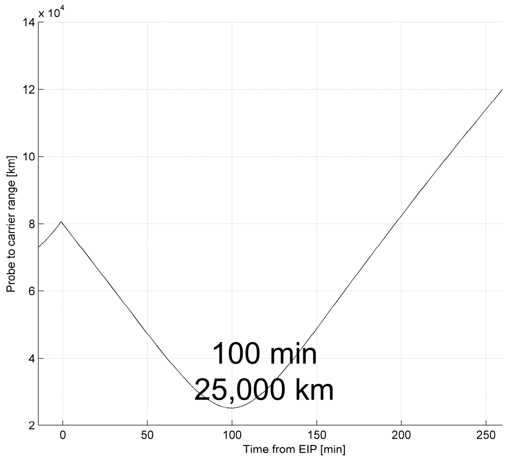


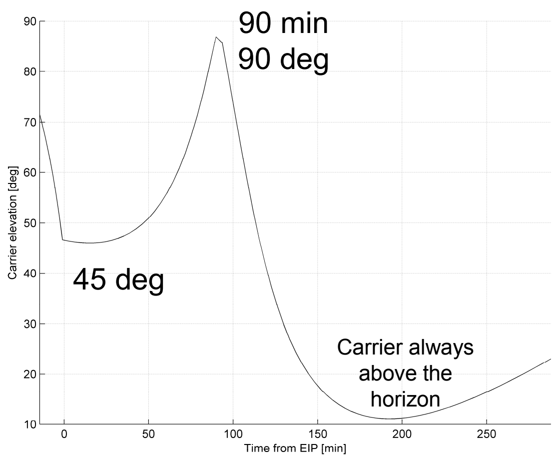


Atmosphere rotation period: 0.67 days

Atmosphere interface velocity: 2.7 km/s

Delay: 90 min





ODM: Operations

- Time for OD after ODM: 2 days
- Time for upload of the TCM1 and implementation: 1 day
- Time for propagation and OD after TCM1: 4 days
- Time for upload of the TCM2 and implementation: 1 day
- Time for potential safe mode: 4 days
- Time before safe mode recovery and probe entry: 4 days

→ A reasonable minimum amount of time between probe separation and probe entry is 20 days for all planets.

A larger amount of time may be needed to decrease the ODM down to an acceptable range. This should be traded against the entry accuracy

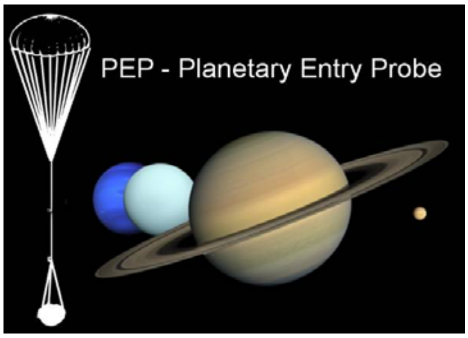
Summary

Planet	Venus1 (1)	Venus2 (1)	Saturn (2)	Uranus	Neptune
Inertial Velocity [km/s]	12	12	35.8	21.7	24.7
Inertial FPA [deg]	-25	-50	-25	-45	-35
Atmosphere Velocity [km/s]	~0	~0	9.9	2.6	2.7
Entry latitude (3) [deg]	20	0	15	20	19
Entry longitude (3) [deg]	-31	-2	176	37	-3
Relative Velocity [km/s]	12	12	27.4	21.9	22.6
Relative FPA [deg]	-25	-50	-33.5	-44.5	-38.9
Velocity azimuth [deg]	-61	-55	79	179	83.2
ODM (4) [m/s]	17	20	76	53	31
Entry FPA Uncertainty [deg]	0.32	0.32	0.13	0.2	0.3
Entry Epoch Uncertainty [s]	7	7	18	20	18

- (1): Release from JGO S/C for a a launch in 2020
- (2): Carrier outside the rings, probe inside the rings
- (3): The choice of entry point affects several parameters: day/night entry, Earth visibility, velocity/atmosphere, FPA/atmosphere. Exception for Saturn: the entry point is fixed because the probe flies through the rings
- (4): All ODM assume a separation 20 days before EIP

PEP
Planetary Entry Probes

Aerothermodynamics



Internal Final Presentation
ESTEC, 30th June 2010

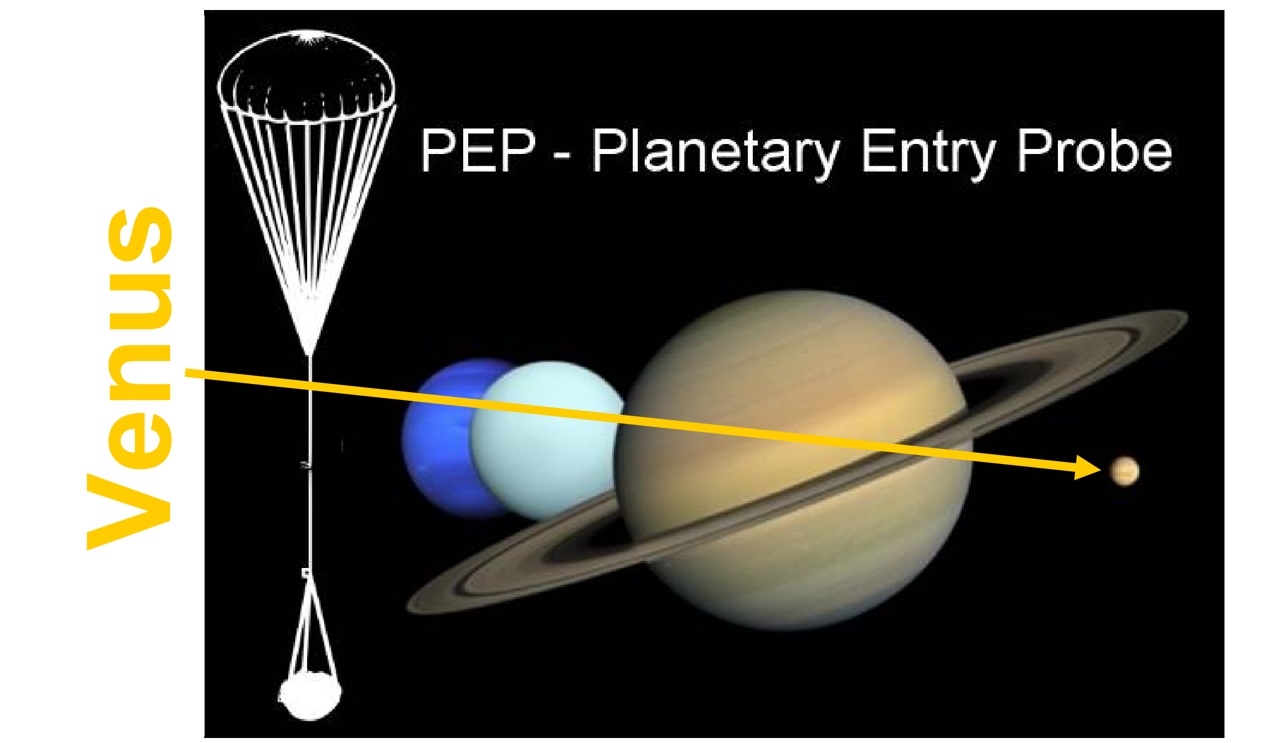
Prepared by the PEP/ CDF* Team

(*) ESTEC Concurrent Design Facility

Scheme

- Venus
- Saturn
- Uranus
- Neptune

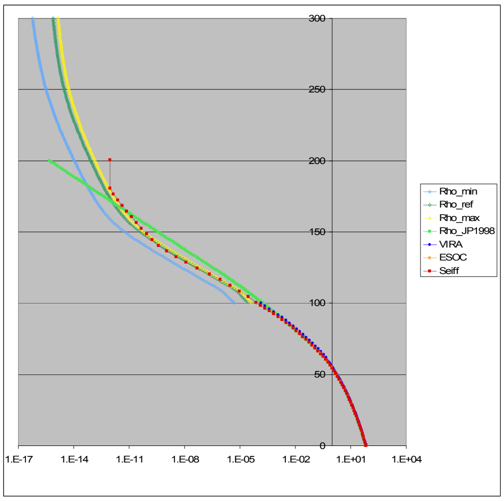
- Assumptions
  - Atmosphere
  - Heat flux correlations
  - Validation
- Entry phase
  - Max heat peak
  - Total heat load
  - Max dynamic pressure
  - Max deceleration
- Descent phase
  - Altitude at drogue chute opening
  - Dynamic pressure at opening
  - Size of parachute to guarantee a requested descent time



Venus Probe Entry assumption: Atmosphere

Different atmosphere available:

- Rho_min (300 – 100 km)
- Rho_ref (300 – 100 km)
- Rho_max (300 – 100 km)
- Rho_JP1998 (200 – 100 km)
- VIRA (100 – 0 km)
- ESOC (100 – 0 km)
- Seiff (200 – 0 km)



Venus: heat flux correlations

- Correlations for the heat fluxes: $q = c \cdot R_n^A \cdot \rho^B \cdot V^C$
- Different correlations for the radiative flux:
  - Florence
  - Tauber and Sutton
  - FGE (A≈0.5, B≈0.5, C=9)
- Different correlations for the convective flux:
  - Zoby
  - Florence (A=-0.5, B=0.5, C=3)

Changing nose radius: scaling the heat fluxes

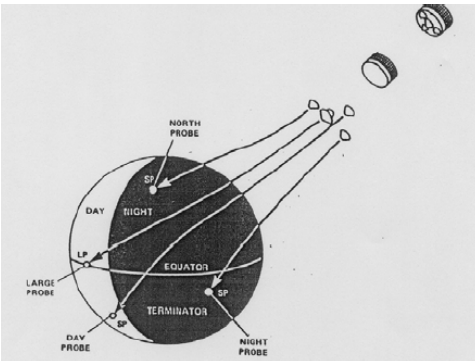
With the chosen correlations

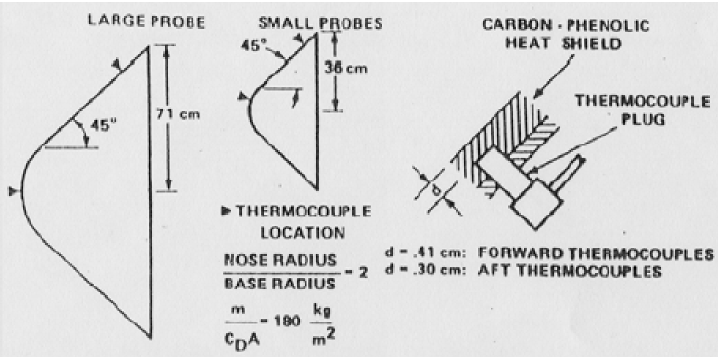
$$\left.\begin{aligned} q_{c1} &= c \cdot R_1^{-0.5} \cdot \rho^{0.5} \cdot V^3 \\ q_{c2} &= c \cdot R_2^{-0.5} \cdot \rho^{0.5} \cdot V^3 \end{aligned}\right\} \quad q_{c1} = q_{c2}\,(R_1/R_2)^{-0.5}$$

$$\left.\begin{aligned} q_{r1} &= c \cdot R_1^{0.5} \cdot \rho^{0.5} \cdot V^9 \\ q_{r2} &= c \cdot R_2^{0.5} \cdot \rho^{0.5} \cdot V^9 \end{aligned}\right\} \quad q_{r1} = q_{r2}\,(R_1/R_2)^{0.5}$$

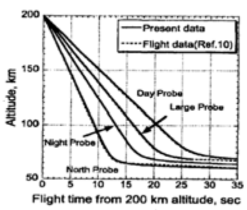
Venus Probe Entry assumption and code validation: reconstructing Pioneer-Venus entry

Probe	Mass	Dimension (base area)	Cd (hyp)	Ball coef	Nose radius	Entry point	Entry Vel	FPA
Large "Sounder"	316.48	1.59	1.07	186	0.36	200	11.54	-32.4
Small "Day"	91	0.46	1.07	185	0.19	200	11.54	-25.4
Small "Night"	91	0.46	1.07	185	0.19	200	11.54	-41.5
Small "North"	91	0.46	1.07	185	0.19	200	11.54	-68.7

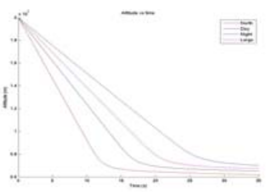




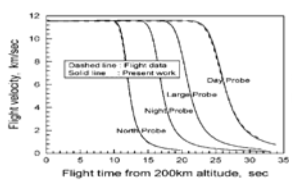
Venus Probe Entry validation: reconstructing Pioneer-Venus entry



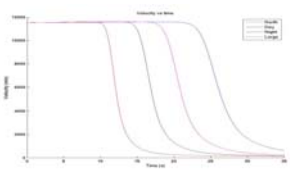
Takahashi, AIAA 2002-0909



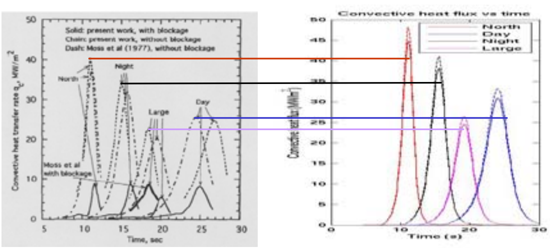
Reconstruction altitude



Ahn, JTHT Vol. 16, No. 3, 2002

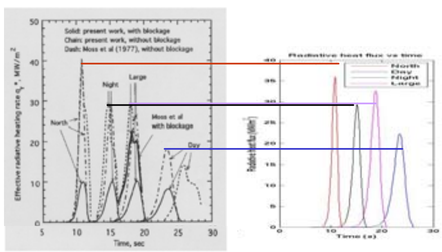


Reconstruction velocity



Park, JTHT Vol. 13,1999

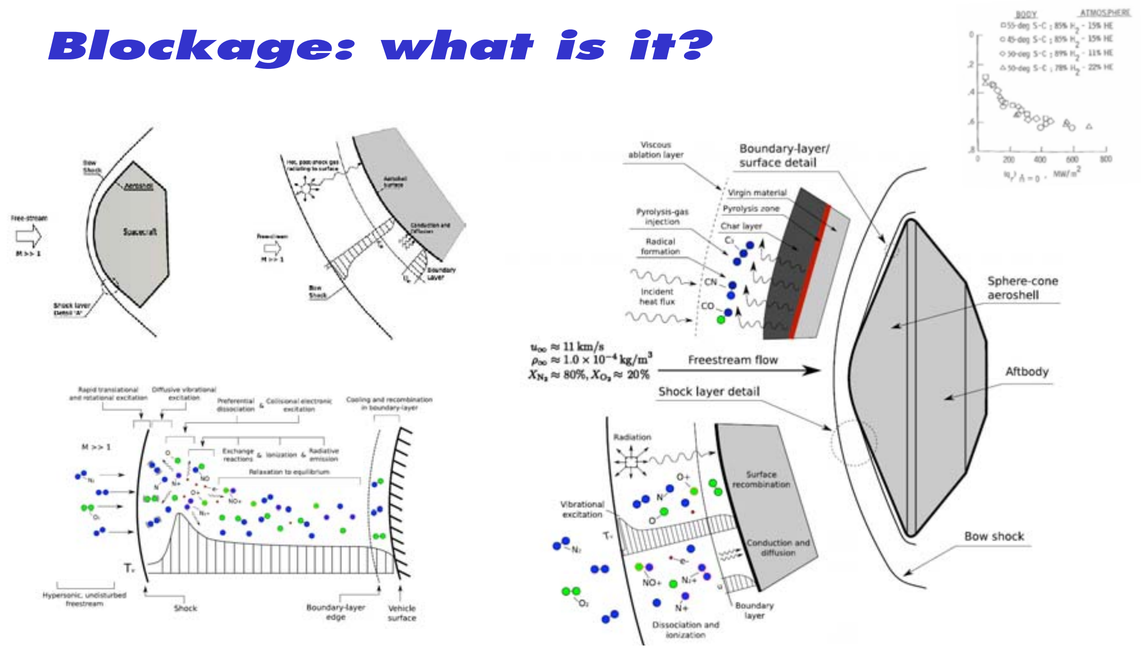
Reconstruction convective heat



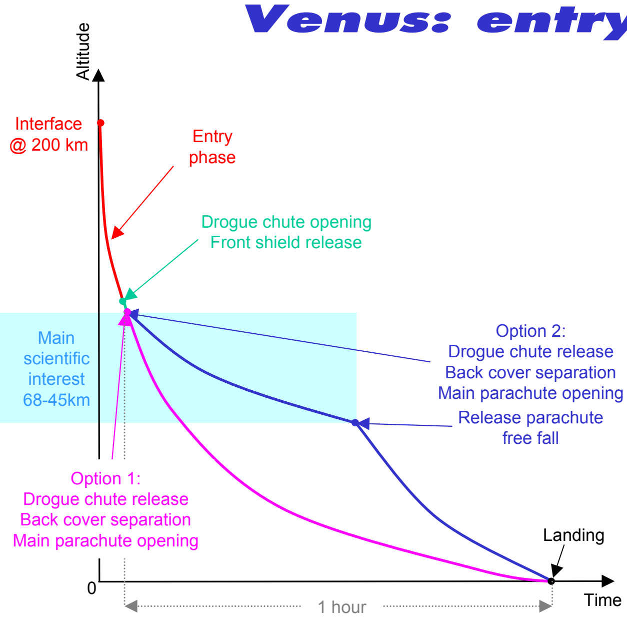
Park, JTHT Vol. 13,1999

Reconstruction radiative heat

Blockage: what is it?



Venus: entry and descent



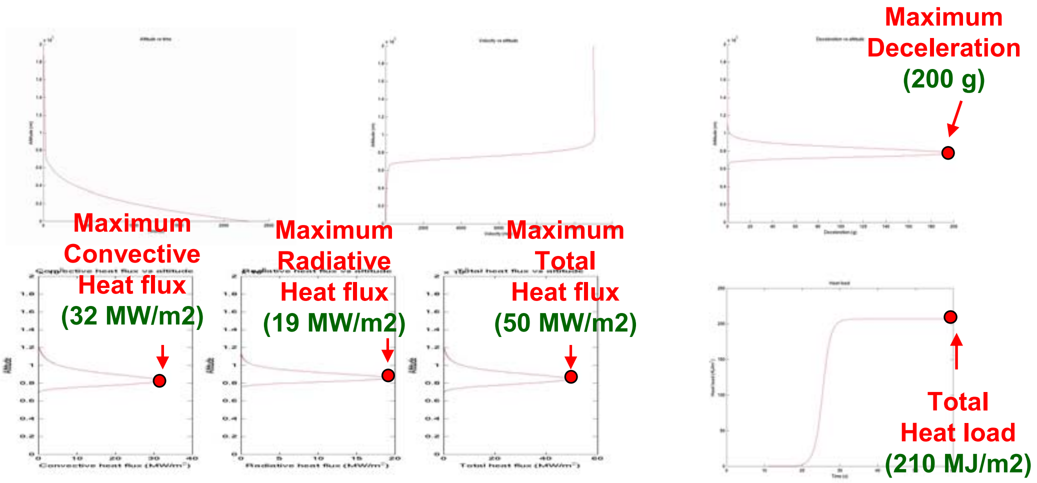
Problem to address and constraints to fulfill

- Max heat flux
- Total heat load
- Max deceleration
- Max dynamic pressure
- Altitude at drogue chute opening
- Dynamic pressure at drogue chute opening
- Guarantee front shield separation at drogue chute opening
- Sizing main parachute: 1 hour descent
- Free fall time (Tf) from 45 km to the surface
- Sizing main parachute: 1h-Tf for 68-45 km

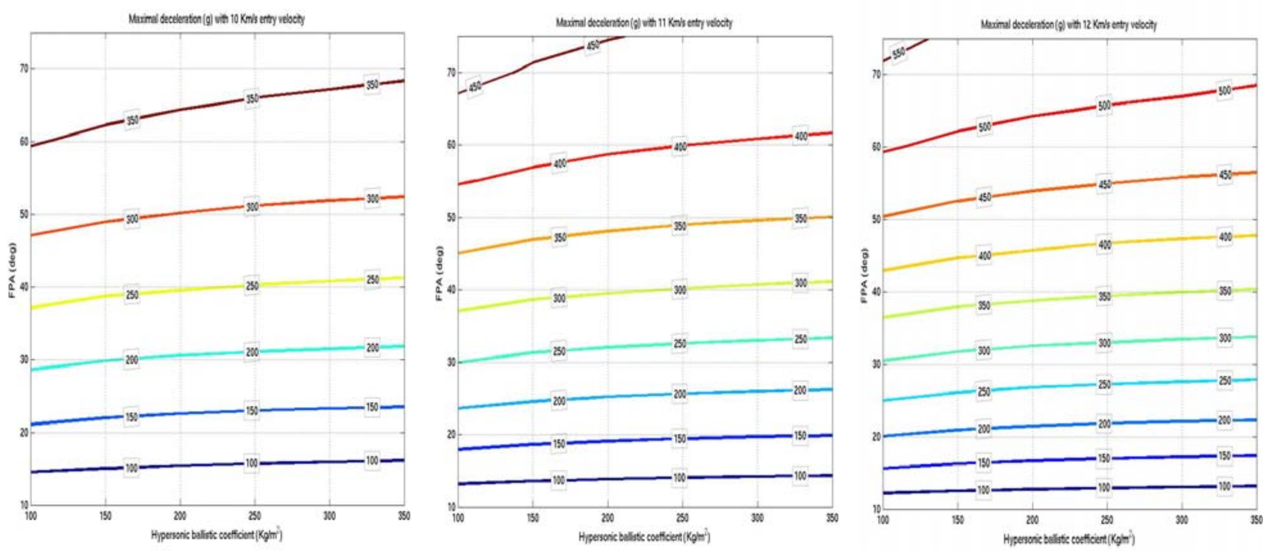
Venus: a parametric analysis for the entry phase

- **Assumptions**
  - Given atmospheres: (Seiff)
  - **Interface at 200 km altitude (entry conditions provided by mission analysis)**
  - Shape is fixed (45 deg half angle blunted cone as Pioneer-Venus/Galileo/JEP..)
  - Cd profile of Galileo is used
  - The nose diameter is fixed (0.36m as Pioneer-Venus but can be rescaled)
  - Chosen correlations (convective flux, radiative flux)
- **Parameters**
  - **Entry velocity (10, 11, 12 Km/s)**
  - Parachute opening (mach = 1, mach = 2)
  - FPA (5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75)
  - (Hypersonic) ballistic coefficient (100, 150, 200, 250, 300, 350)
- **Constraints**
  - Maximal heat flux?
  - Total heat load?
  - Maximal deceleration (at parachute opening)?
  - Altitude at parachute opening?
  - Maximal dynamic (pressure at parachute opening)?

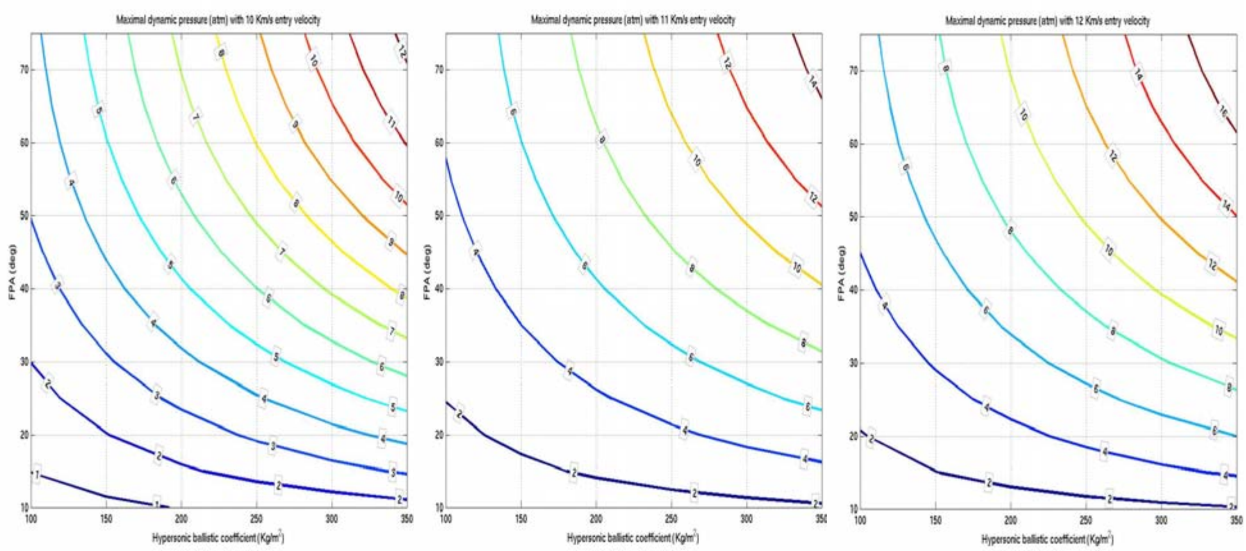
Venus example: Entry=11, Bc=250, FPA=25



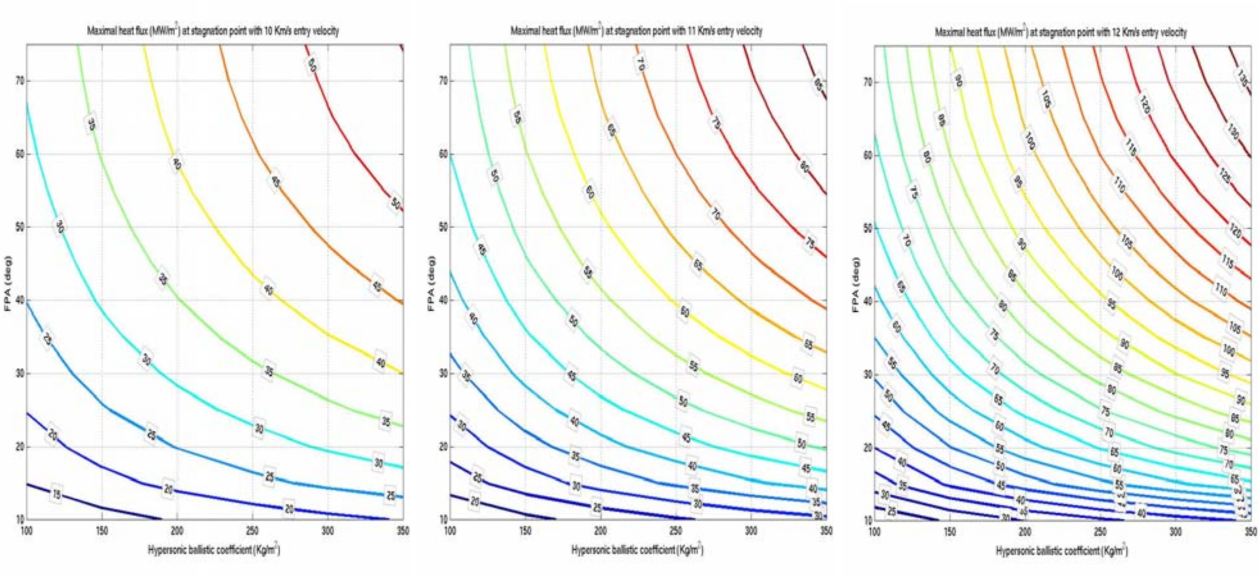
Venus: maximum deceleration



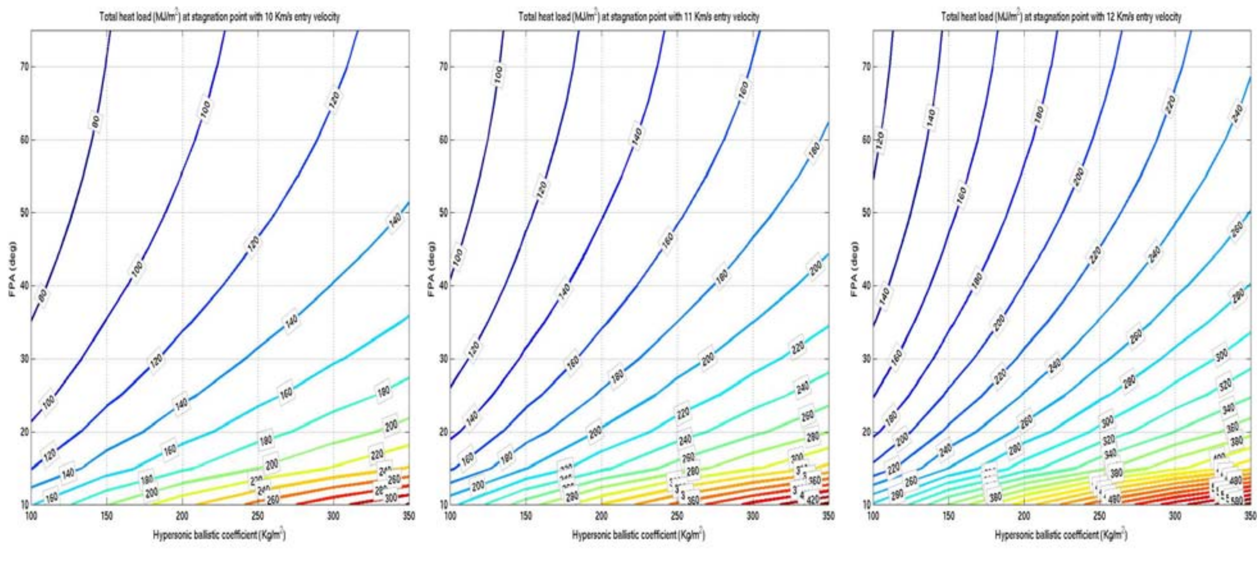
Venus: maximum dynamic pressure



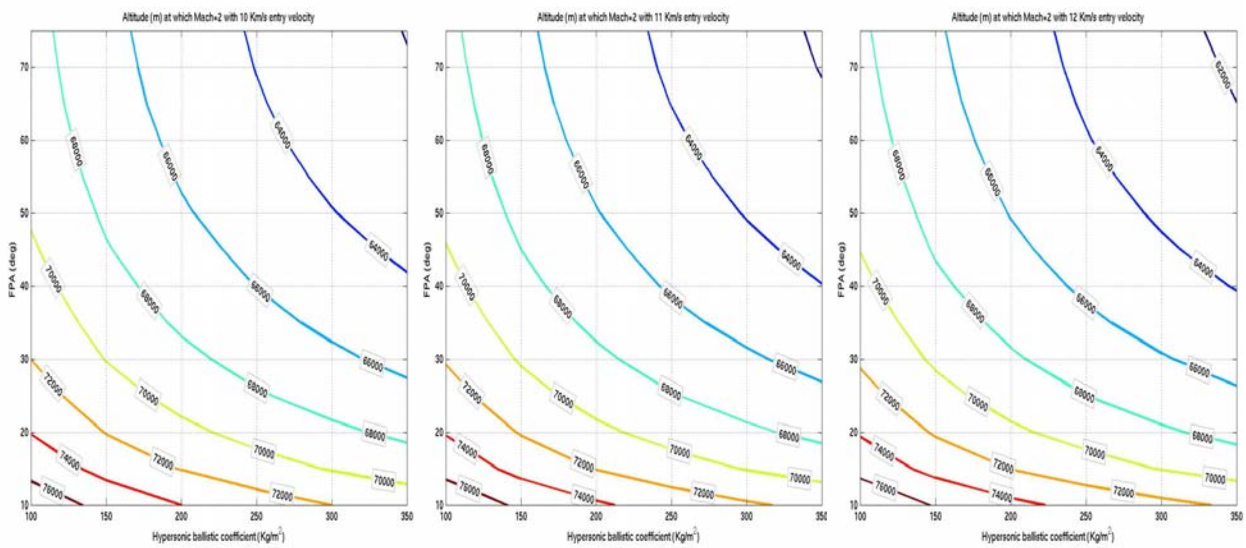
Venus: maximum (total) heat flux



Venus: integrated (total) heat load

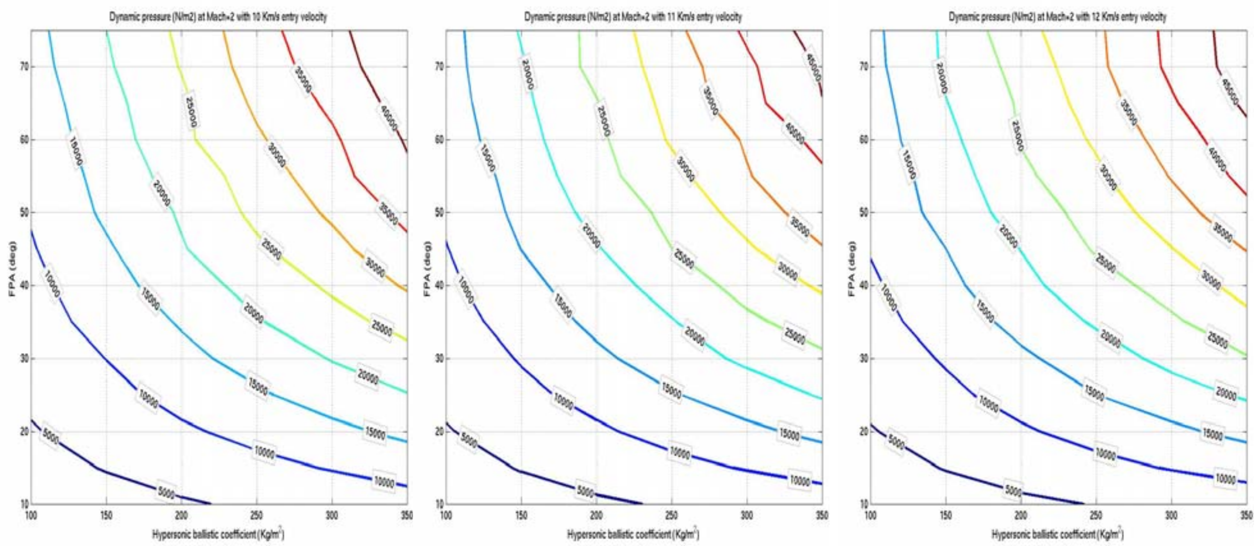


Venus: Altitude @ mach = 2



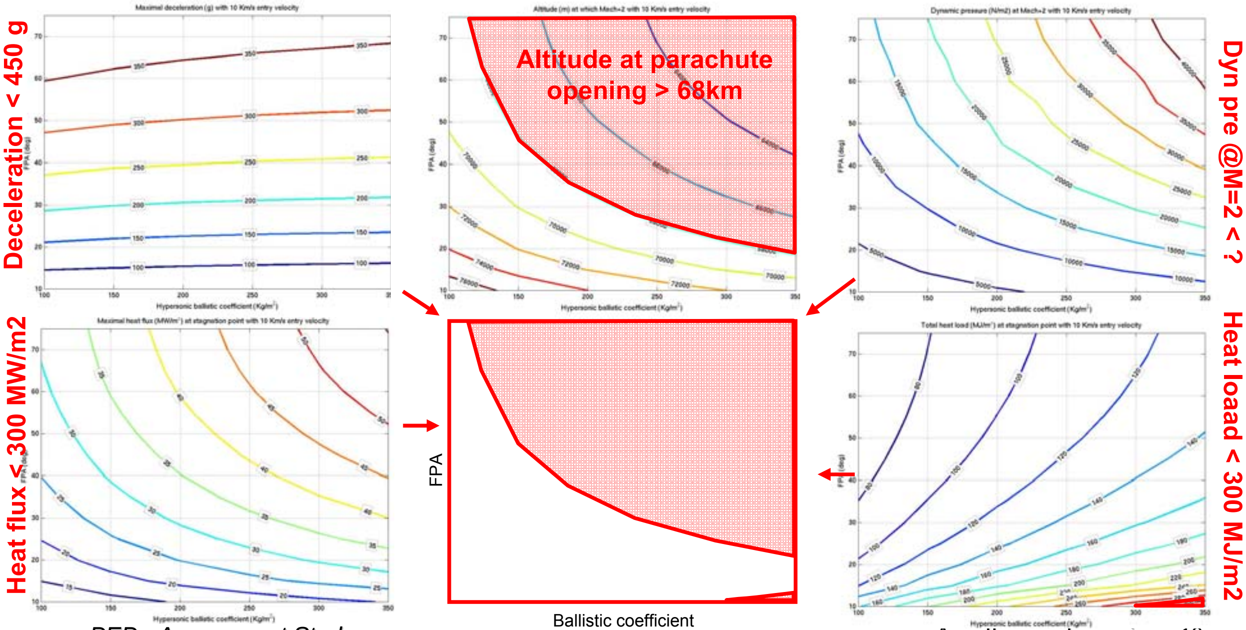
PEP - Assessment Study Aerothermodynamics - 17

Venus: Dynamic pressure @ mach = 2

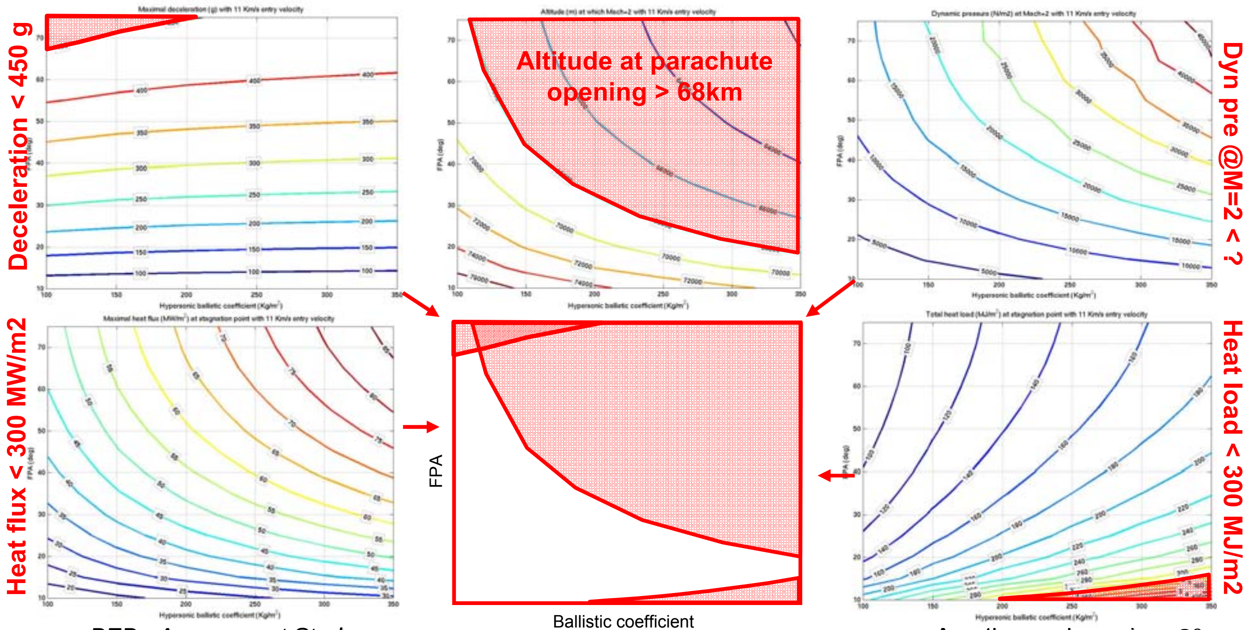


PEP - Assessment Study Aerothermodynamics - 18

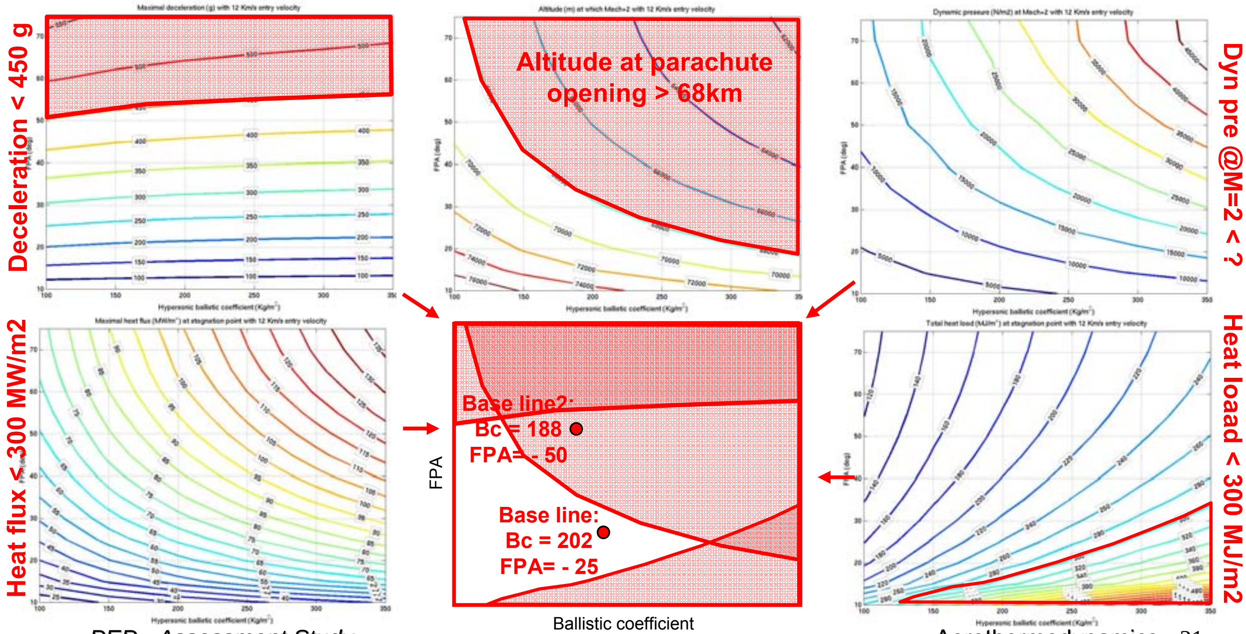
Venus: feasible domain @ 10 KM/s entry



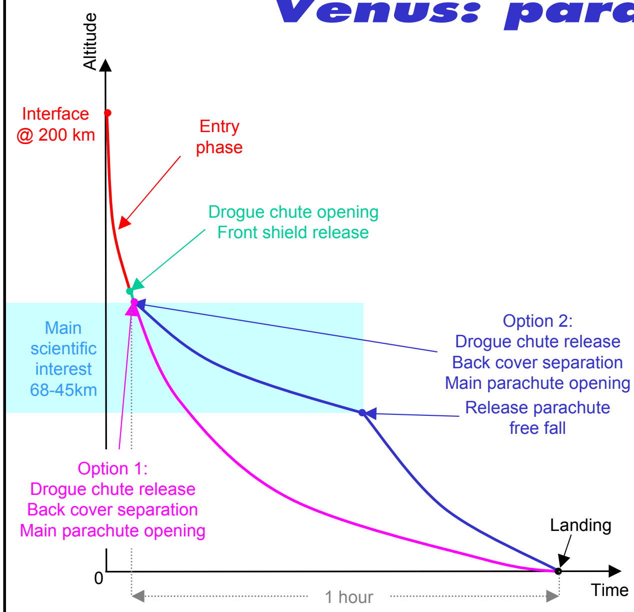
Venus: feasible domain @ 11 KM/s entry



Venus: feasible domain @ 12 KM/s entry

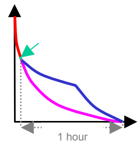


Venus: parachute sizing



- Guarantee front shield separation at drogue chute opening
- Sizing main parachute: 1 hour descent
- Free fall time (Tf) from 45 km to the surface
- Sizing main parachute: 1h-Tf for 68-45 km

Venus: parachute sizing for separation

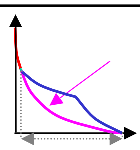


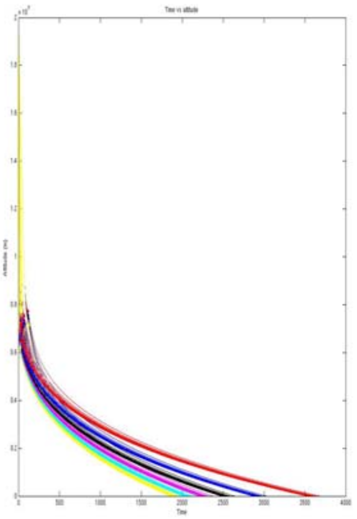
$$B_C^{probe-TPS} \leq 0.7\, B_C^{TPS}$$

$$\frac{M^{probe} - M^{TPS}}{C_D^{drogue} \cdot A^{drogue} + C_D^{sphere} \cdot A^{sphere}} \leq 0.7 \frac{M^{TPS}}{C_D^{TPS} \cdot A^{TPS}}$$

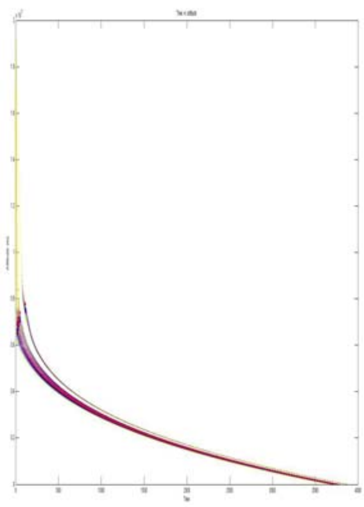
$$A^{drogue} = \frac{1}{0.7} \frac{M^{probe} - M^{TPS}}{M^{TPS}} \frac{C_D^{TPS}}{C_D^{drogue}} A^{TPS} - \cancel{\frac{C_D^{sphere}}{C_D^{drogue}}} A^{sphere}$$

Main parachute opt1: 1h between Mach 2 and landing with a parachute guaranteeing Bc=250

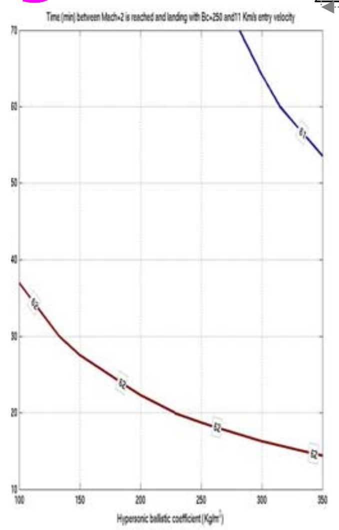




Without parachute

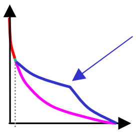


With parachute

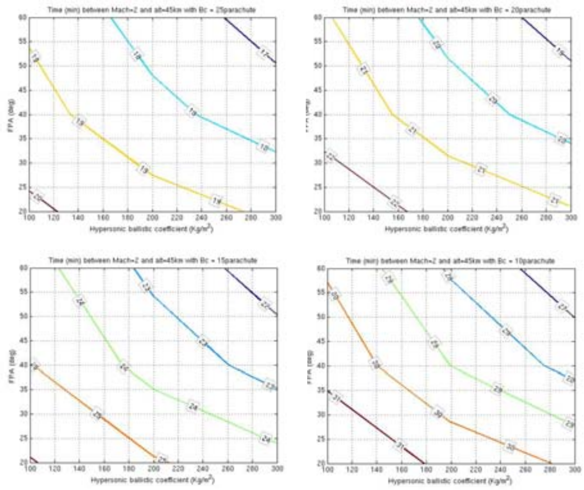


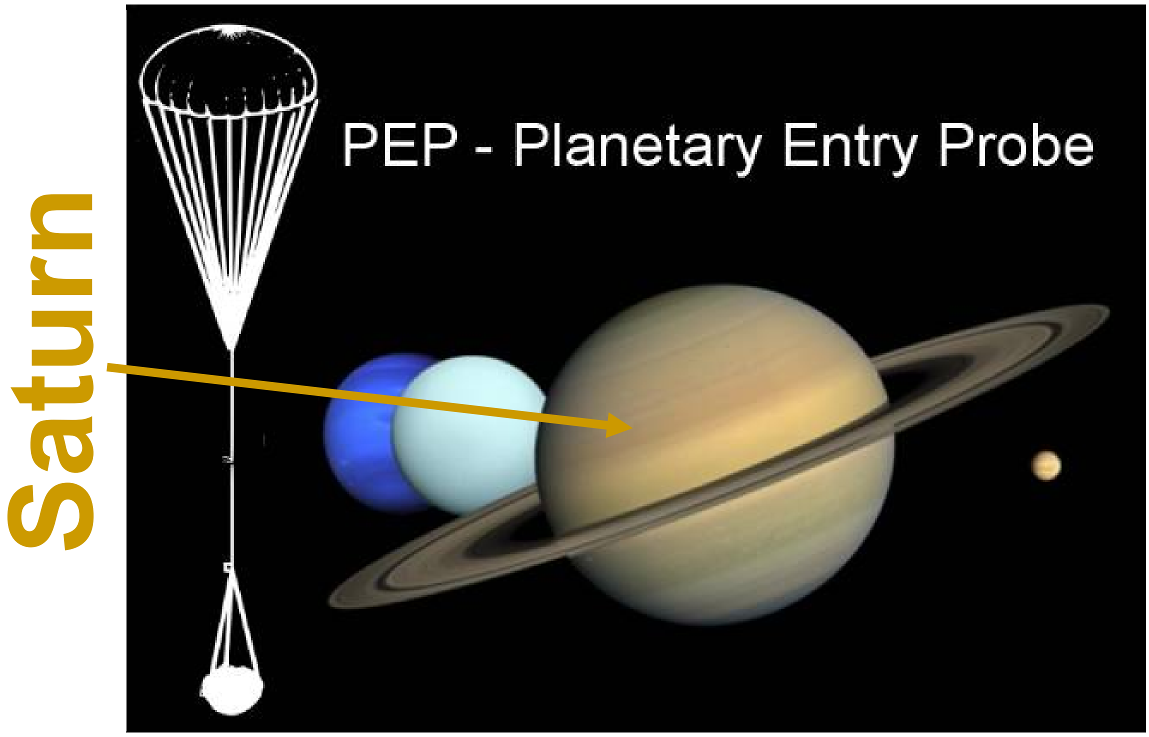
Descent time (with parachute)

Main parachute opt2



- 1 hour available for the descent
- Free fall from 45 km with just the descent module (fixed mass and dimension) takes ≈ 30 min
- 30 min are left for the parachute to descent from 68 to 45
- Increasing the size of the parachute (decrease the ballistic coefficient) to meet the 30 min of descent
- With a parachute guaranteeing a Bc = 10 the descent takes 30 min

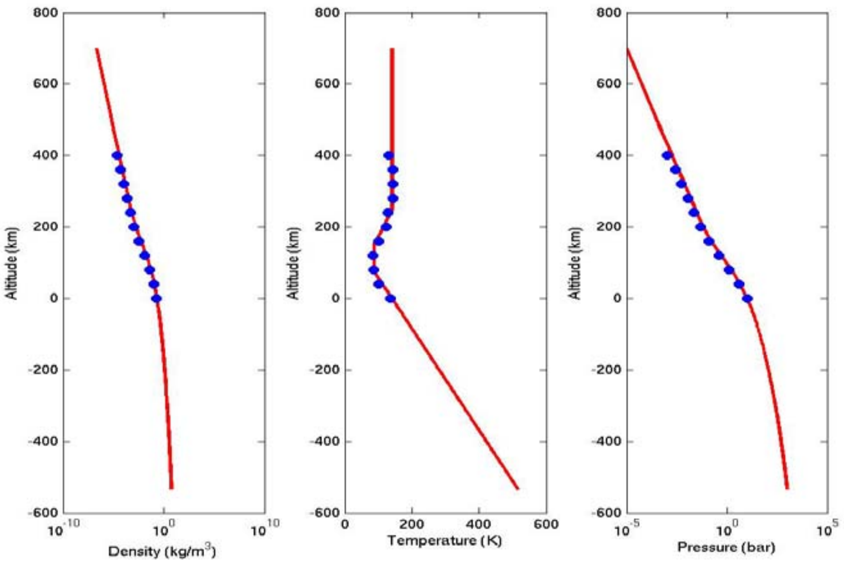




Saturn atmospheric profiles

Different atmosphere models available:

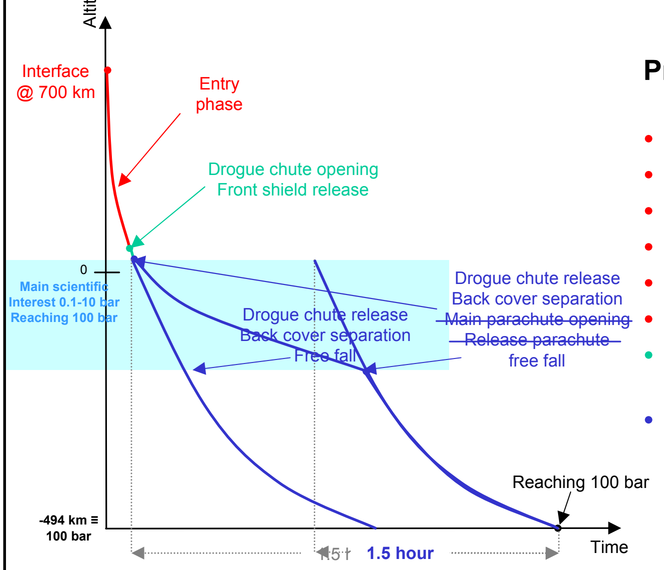
- The Planetary scientist's companion by Lodders, K. Fegley, B.
- Giant Planets of Our Solar System: An Introduction by Patrick Irwin



Saturn assumption: heat flux correlations

- Correlations for the heat fluxes: $\mathbf{q = c \cdot R_n^A \cdot \rho^B \cdot V^C}$
- There are no correlations available in literature for Saturn (Giant planets)
- Due to the close similarity among the Giant planets and a wider literature available for Jupiter, correlations were derived by fitting available (Moss and Simmond AIAA-82-0874) Galileo heat flux data
- Convective: $A = -0.5$, $B \approx 0.43$, $C \approx 3$
- Radiative: $A = 1$, $B \approx 1.33$, $C \approx 6.76$
- Validation against Galileo data (and Saturn) has been performed

Saturn: entry and descent



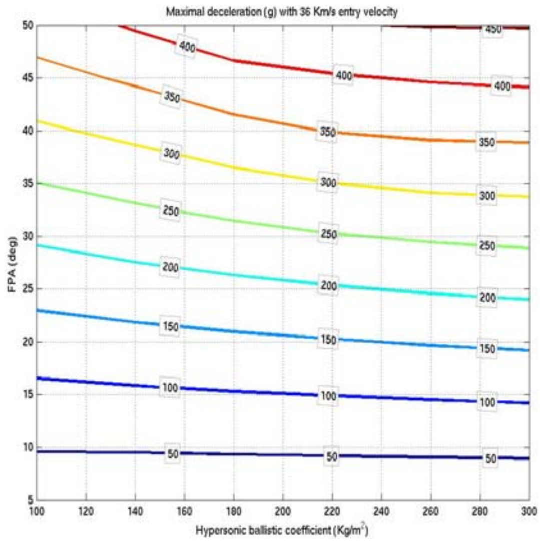
Problem to address and constraints to fulfill

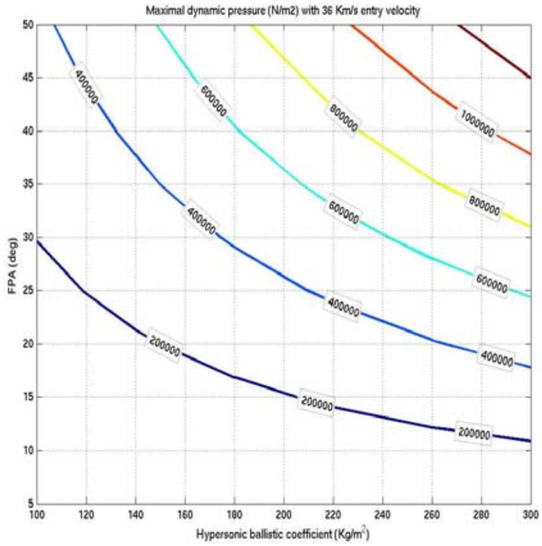
- Max heat flux
- Total heat load
- Max deceleration
- Max dynamic pressure
- Pressure at drogue chute opening
- Dynamic pressure at drogue chute opening
- Guarantee front shield separation at drogue chute opening
- Free fall time from 0.1 bar to 100 bar

Saturn: a parametric analysis for the entry phase

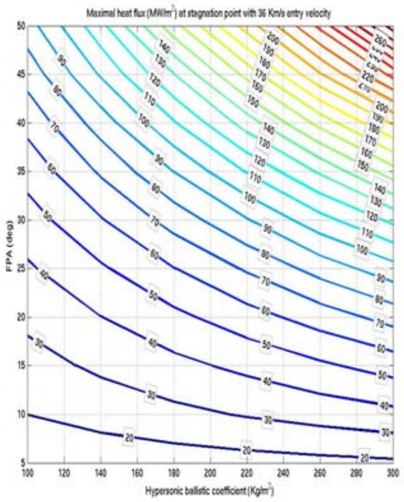
- **Assumptions**
  – Given atmospheres
  – **Interface at 700 km altitude (entry conditions provided by mission analysis)**
  – **Entry velocity (36 Km/s)**
  – Shape is fixed (45 deg half angle blunted cone as Pioneer-Venus/Galileo/JEP..)
  – Cd profile of Galileo is used
  – The nose diameter is fixed (0.512m)
  – Chosen correlations (convective flux, radiative flux)
- **Parameters**
  – Parachute opening (at Mach=1, Mach=2 ?)
  – FPA (5, 10, 15, 20, 25, 30, 35, 40, 45, 50)
  – (Hypersonic) ballistic coefficient (100, 150, 200, 250, 300)
- **Constraints**
  – Maximal heat flux?
  – Total heat load?
  – Maximal deceleration (at parachute opening)?
  – Pressure (altitude) at parachute opening (Mach=1, mach=2)?
  – Maximal dynamic (pressure at parachute opening)?

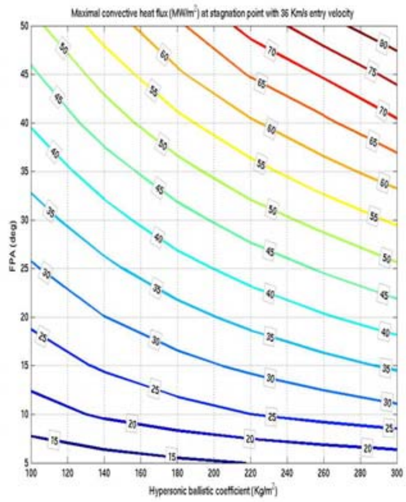
Saturn: maximum deceleration and dynamic pressure

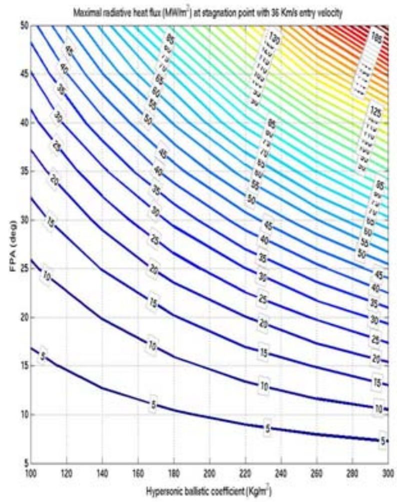




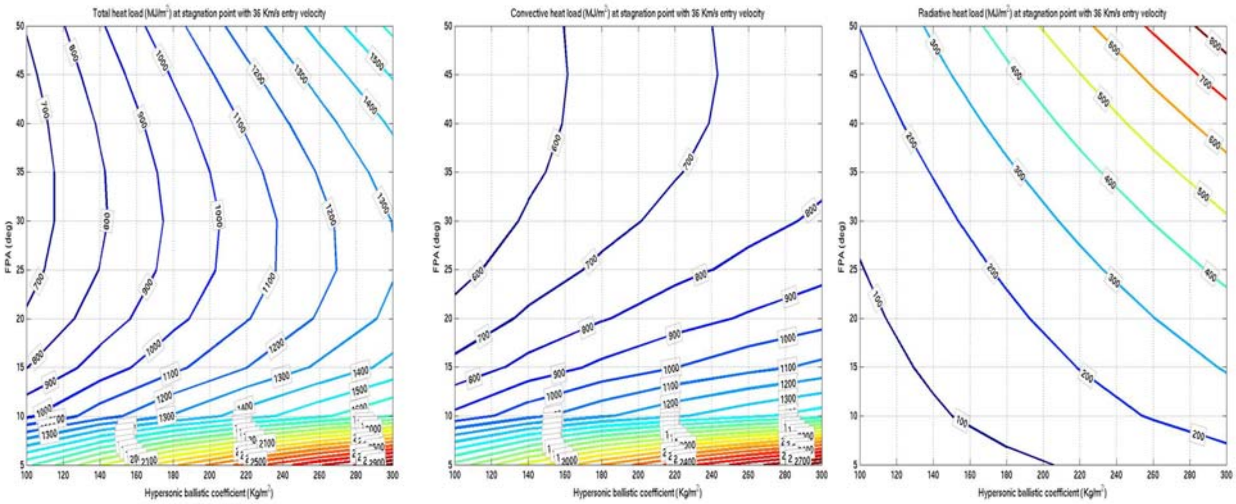
Saturn: maximum heat flux







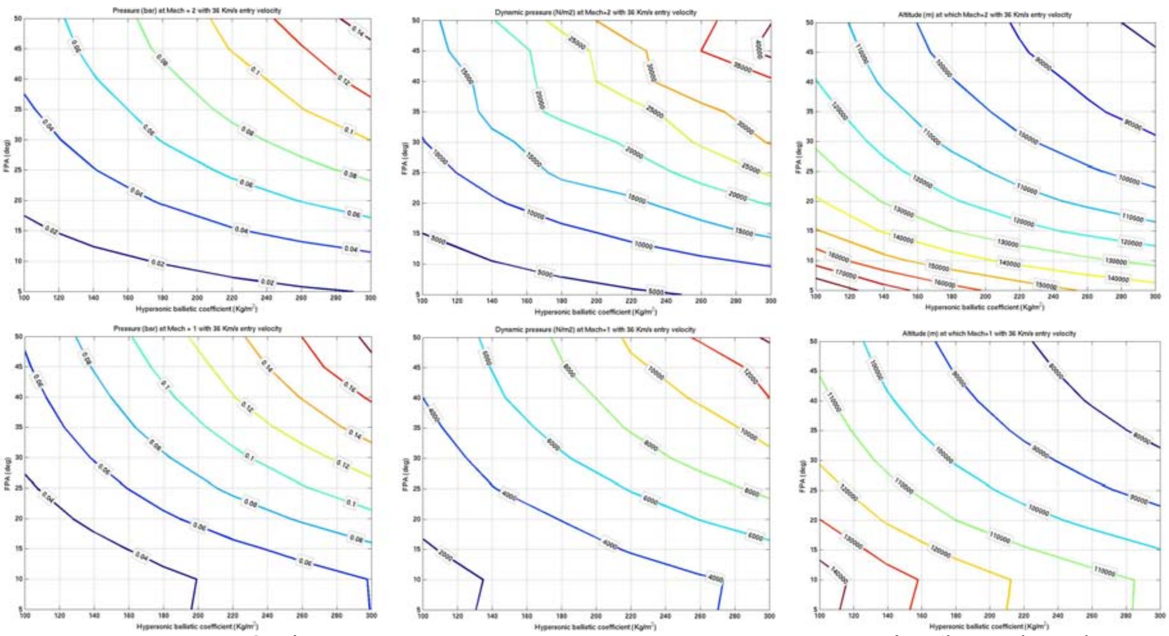
Saturn: total heat load



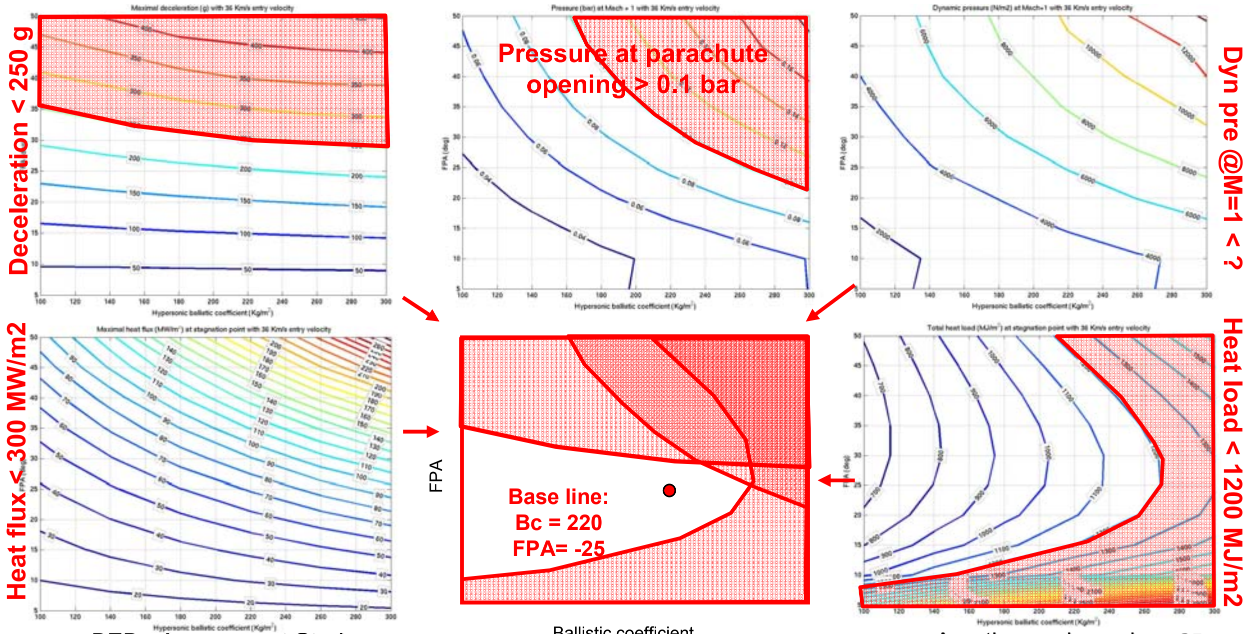
Saturn: Parachute opening: Mach=1,2?

Mach = 2

Mach = 1



Saturn: feasible domain



Saturn: parachute sizing for separation

As for Venus

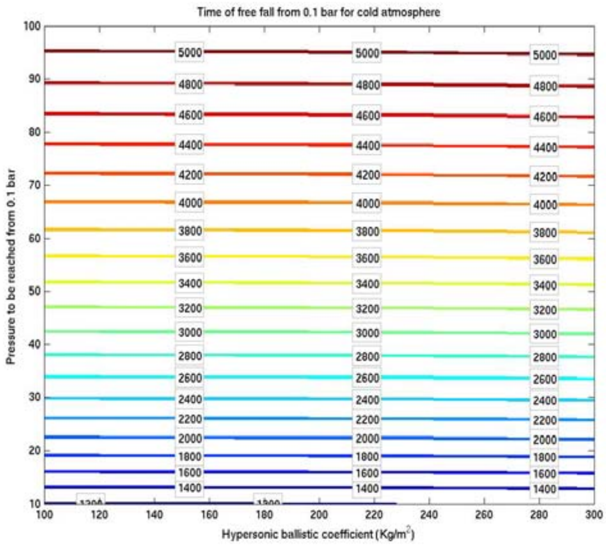
$$B_C^{probe-TPS} \leq 0.7 B_C^{TPS}$$

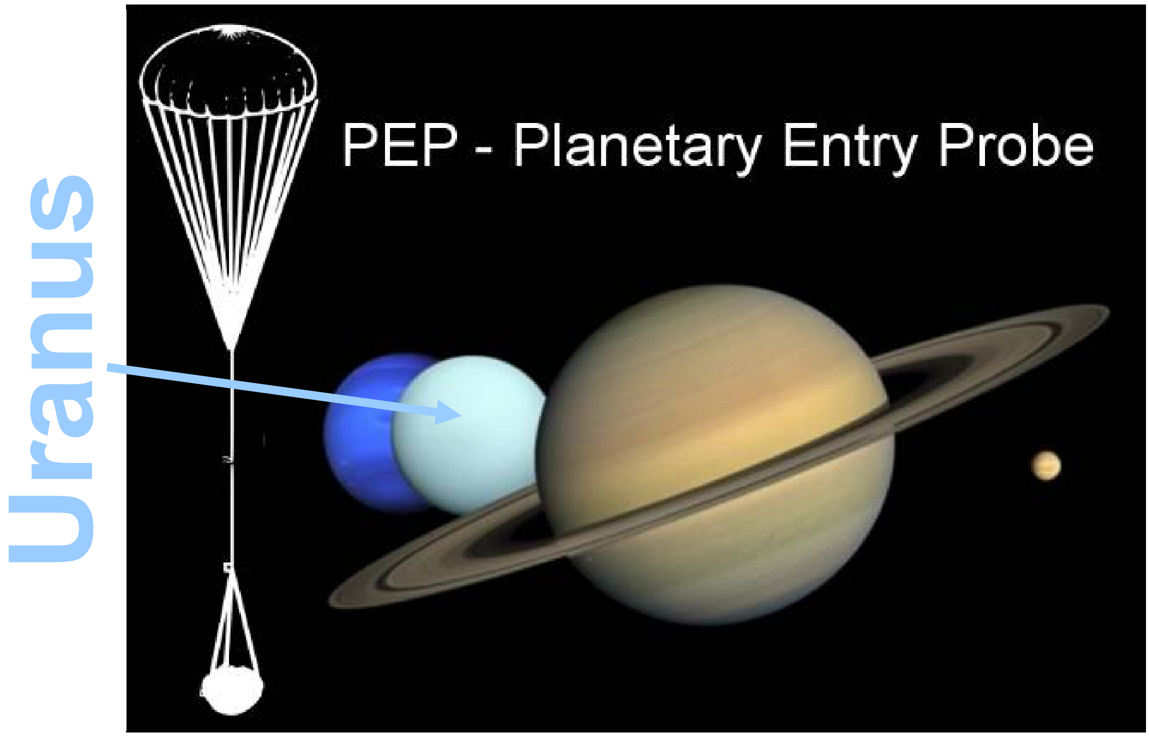
$$\frac{M^{probe} - M^{TPS}}{C_D^{drogue} \cdot A^{drogue} + C_D^{sphere} \cdot A^{sphere}} \leq 0.7 \frac{M^{TPS}}{C_D^{TPS} \cdot A^{TPS}}$$

$$A^{drogue} = \frac{1}{0.7} \frac{M^{probe} - M^{TPS}}{M^{TPS}} \frac{C_D^{TPS}}{C_D^{drogue}} A^{TPS} - \cancel{\frac{C_D^{sphere}}{C_D^{drogue}}} A^{sphere}$$

Saturn: Free fall from pressure = 0.1 bar

- Different entry (hypersonic) ballistic coefficients
- Different FPA
- Fixed ballistic coefficient for the descent phase (pressure vessel mass and dimensions are fixed)





Uranus atmospheric profiles

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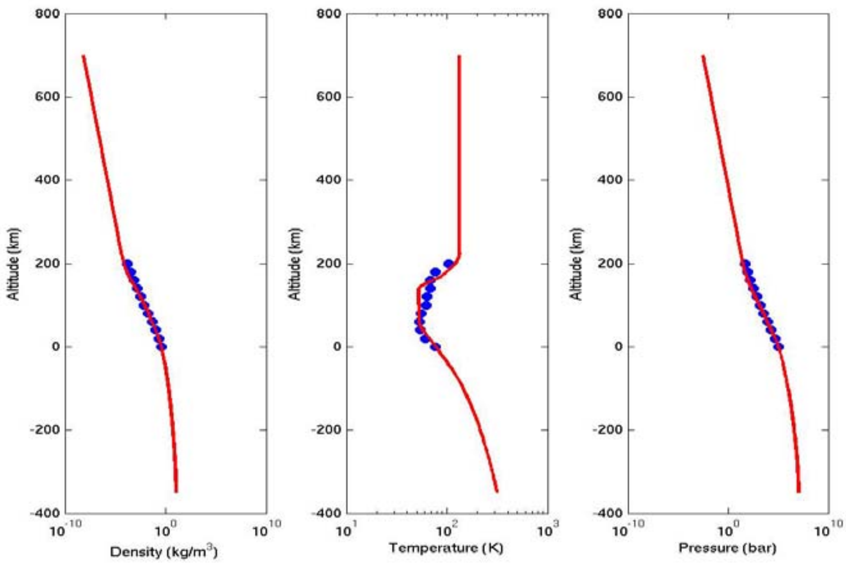
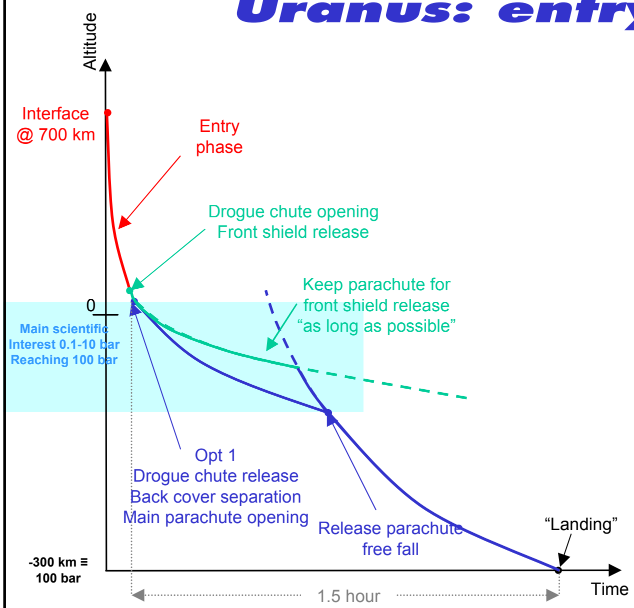
- Giant Planets of Our Solar System: An Introduction by Patrick Irwin



Uranus: entry and descent



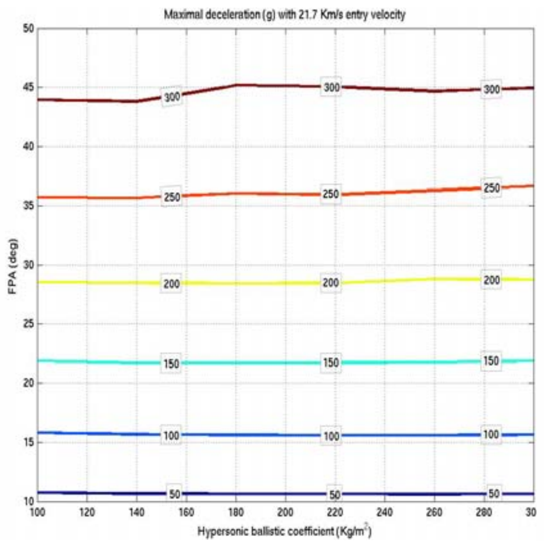
Problem to address and constraints to fulfill

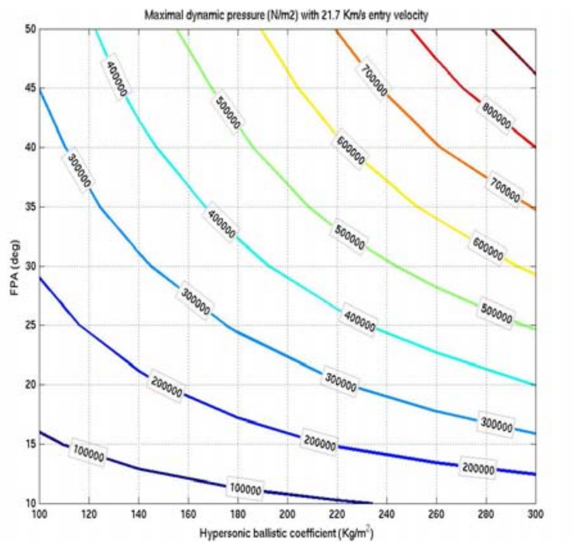
- Max heat flux
- Total heat load
- Max deceleration
- Max dynamic pressure
- Altitude at drogue chute opening
- Dynamic pressure at drogue chute opening
- Guarantee front shield separation at drogue chute opening
- Flight time of drogue parachute
- Free fall time to 100 bar

Uranus: a parametric analysis for the entry phase

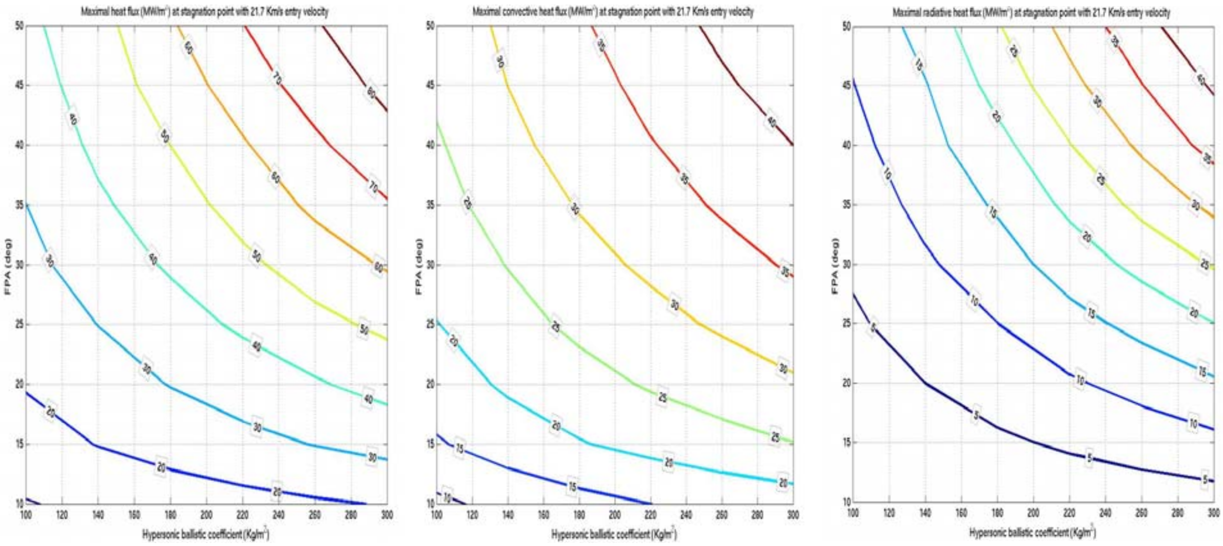
- **Assumptions**
  - Given atmospheres
  - **Interface at 700 km altitude (entry conditions provided by mission analysis)**
  - **Entry velocity (21.7 Km/s)**
  - Shape is fixed (45 deg half angle blunted cone as Pioneer-Venus/Galileo/JEP..)
  - Cd profile of Galileo is used
  - The nose diameter is fixed (0.512m)
  - Chosen correlations (convective flux, radiative flux)
- **Parameters**
  - Parachute opening (at Mach = 1, Mach = 2 ?)
  - FPA (5, 10, 15, 20, 25, 30, 35, 40, 45, 50)
  - (Hypersonic) ballistic coefficient (100, 150, 200, 250, 300)
- **Constraints**
  - Maximal heat flux?
  - Total heat load?
  - Maximal deceleration (at parachute opening)?
  - Pressure (altitude) at parachute opening (Mach = 1, mach = 2)?
  - Maximal dynamic (pressure at parachute opening)?

Uranus: maximum deceleration and dynamic pressure

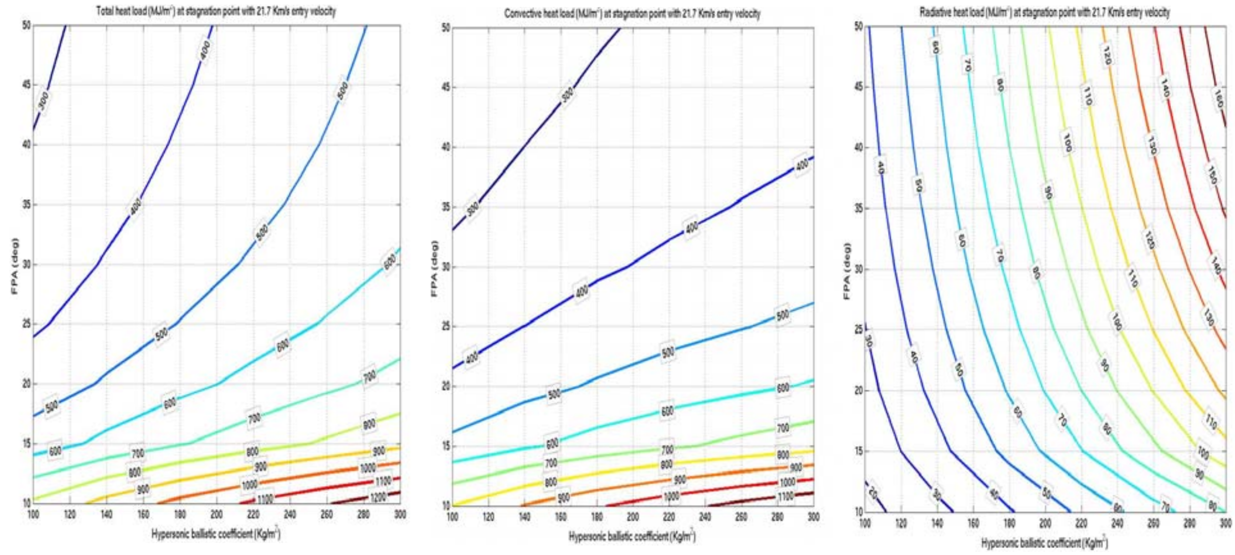




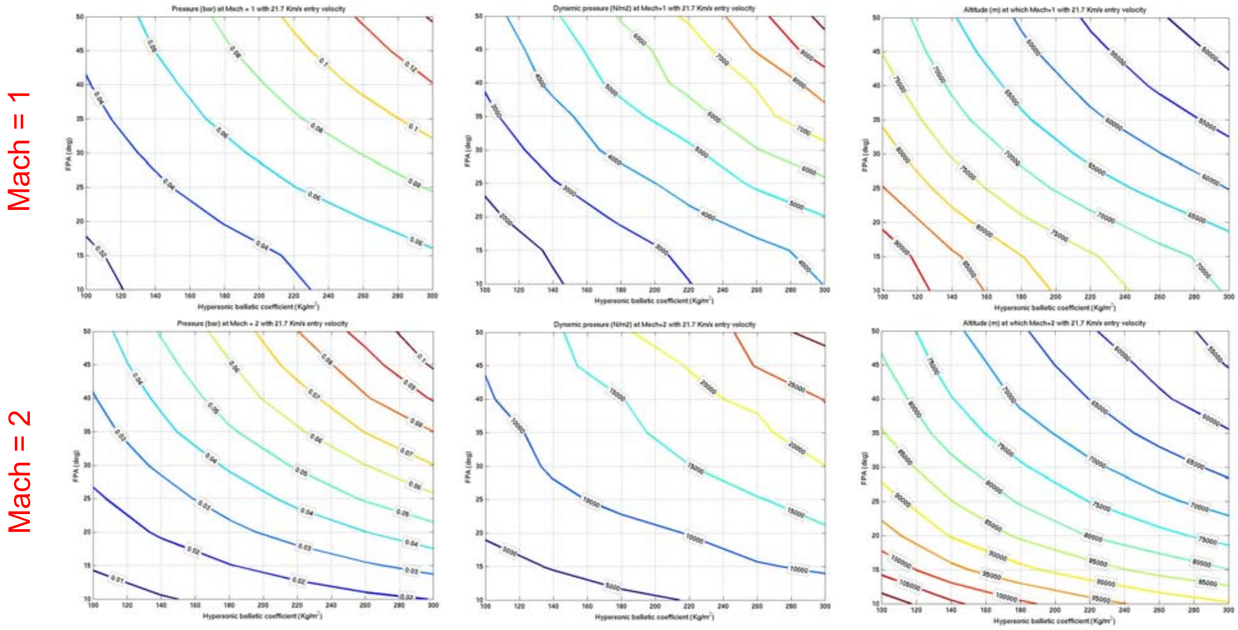
Uranus: maximum heat flux



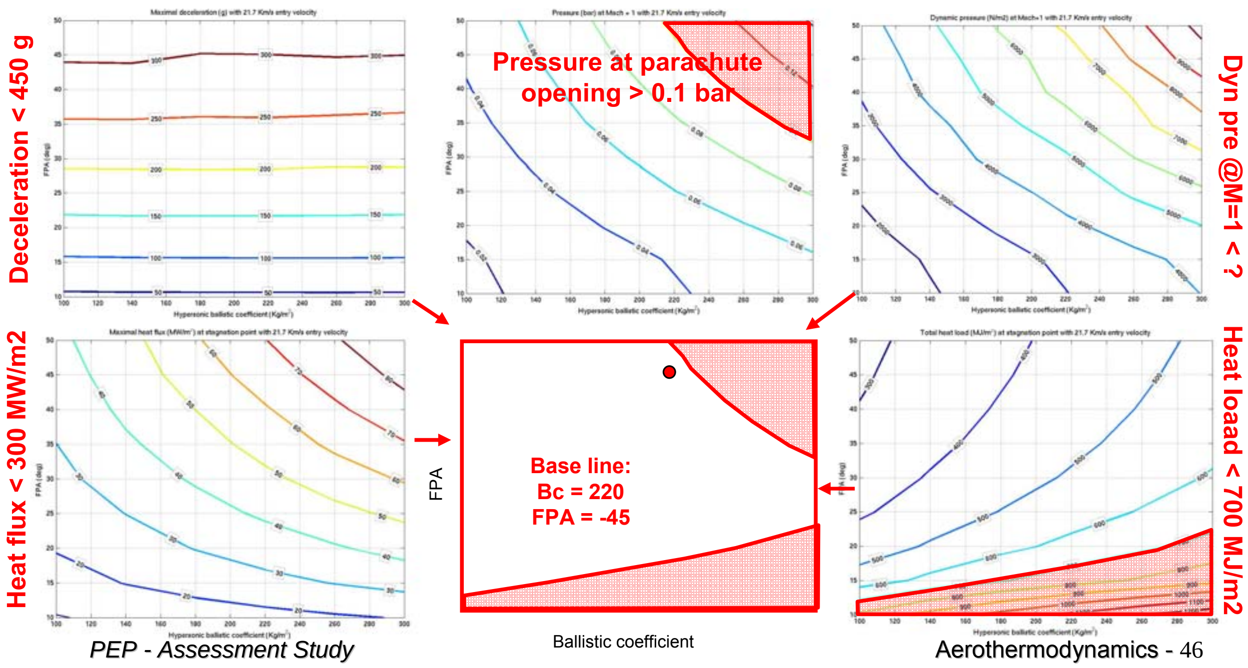
Uranus: total heat load



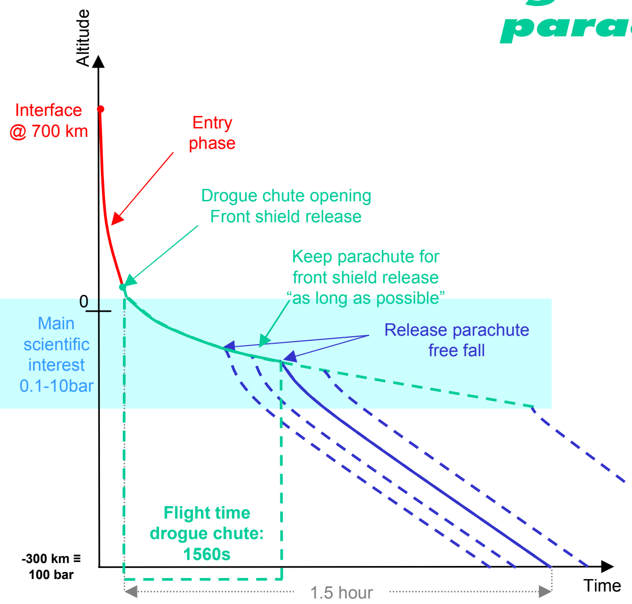
Uranus: Parachute opening: Mach=1,2?

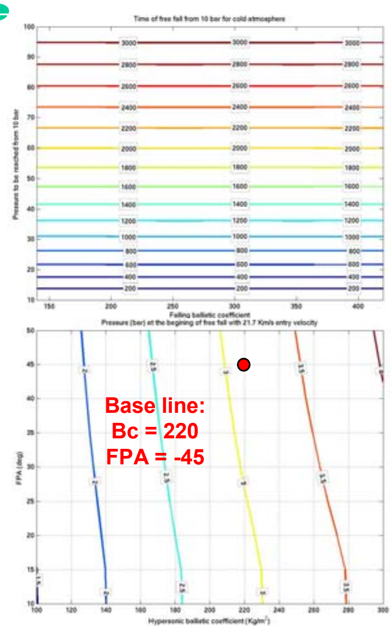


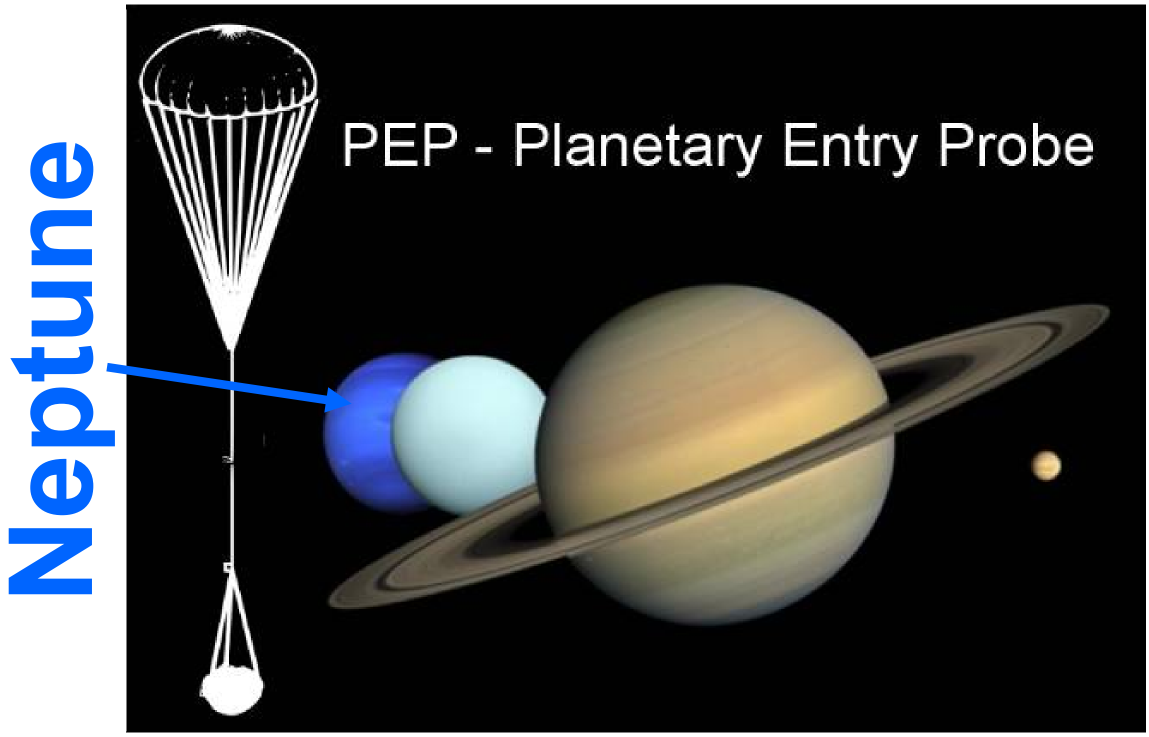
Uranus: feasible domain



Uranus: Flight time of drogue parachute



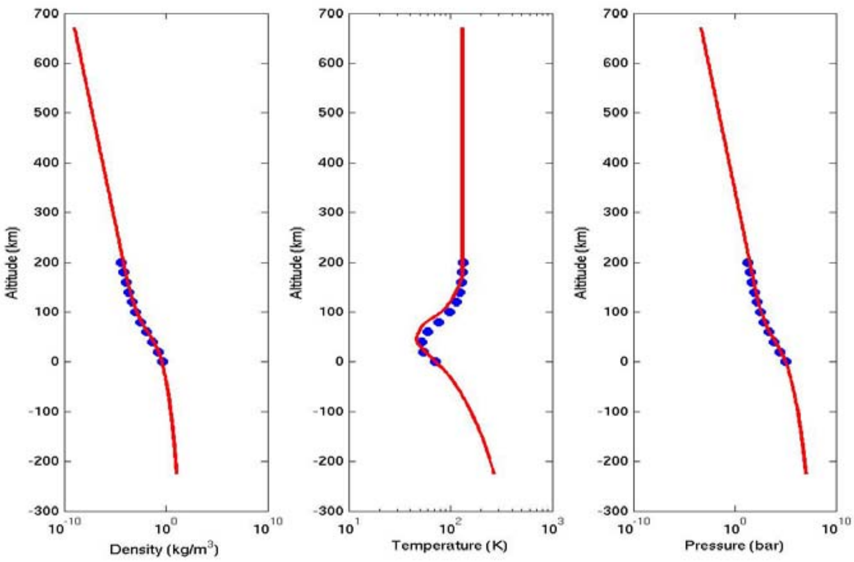




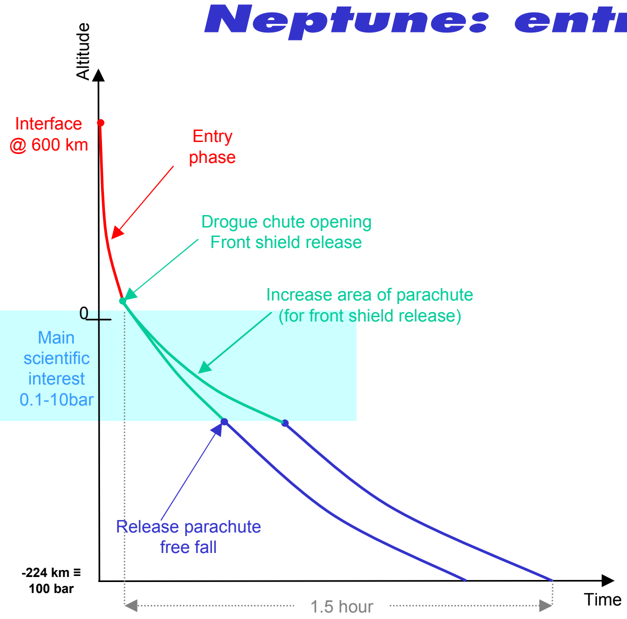
Neptune atmospheric profiles

Different atmosphere models available:

- The Planetary scientist's companion by Lodders, K. Fegley, B.
- Giant Planets of Our Solar System: An Introduction by Patrick Irwin



Neptune: entry and descent



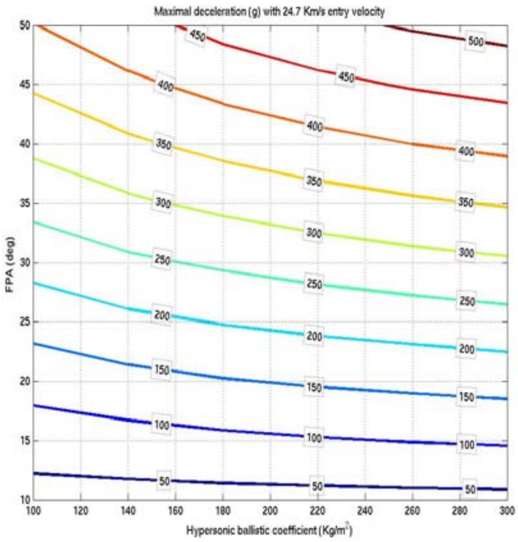
Problem to address and constraints to fulfill

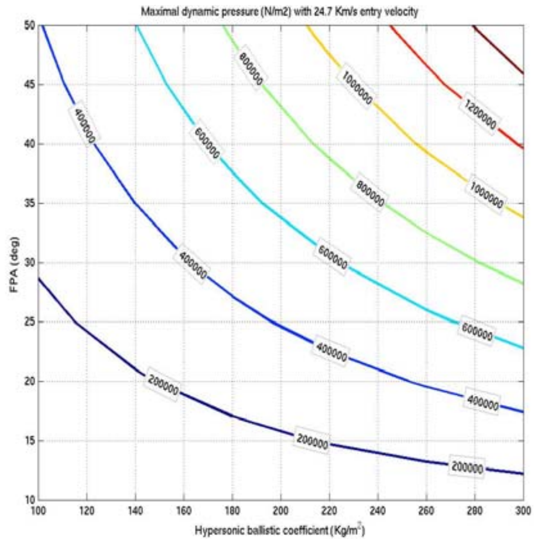
- Max heat flux
- Total heat load
- Max deceleration
- Max dynamic pressure
- Altitude at drogue chute opening
- Dynamic pressure at drogue chute opening
- Guarantee front shield separation at drogue chute opening
- Increasing dimensions of drogue parachute
- Free fall time to 100 bar

Neptune: a parametric analysis for the entry phase

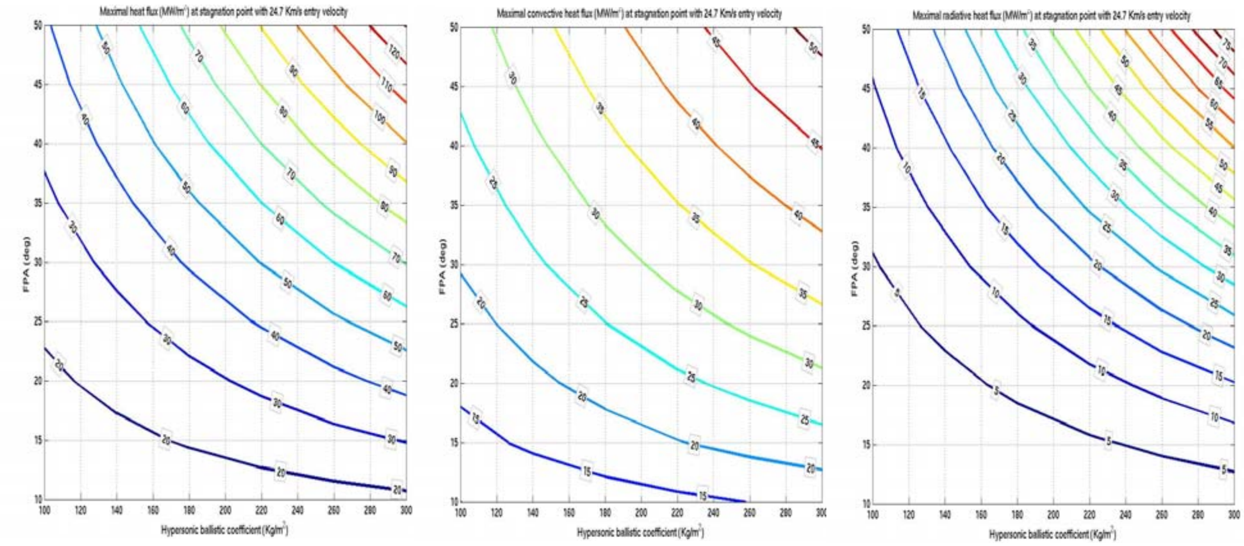
- **Assumptions**
  - Given atmospheres
  - **Interface at 600 km altitude (entry conditions provided by mission analysis)**
  - **Entry velocity (24.7 Km/s)**
  - Shape is fixed (45 deg half angle blunted cone as Pioneer-Venus/Galileo/JEP..)
  - Cd profile of Galileo is used
  - The nose diameter is fixed (0.512m)
  - Chosen correlations (convective flux, radiative flux)
- **Parameters**
  - Parachute opening (at Mach=1, Mach=2 ?)
  - FPA (5, 10, 15, 20, 25, 30, 35, 40, 45, 50)
  - (Hypersonic) ballistic coefficient (100, 150, 200, 250, 300)
- **Constraints**
  - Maximal heat flux?
  - Total heat load?
  - Maximal deceleration (at parachute opening)?
  - Pressure (altitude) at parachute opening (Mach=1, mach=2)?
  - Maximal dynamic (pressure at parachute opening)?

Neptune: maximum deceleration and dynamic pressure

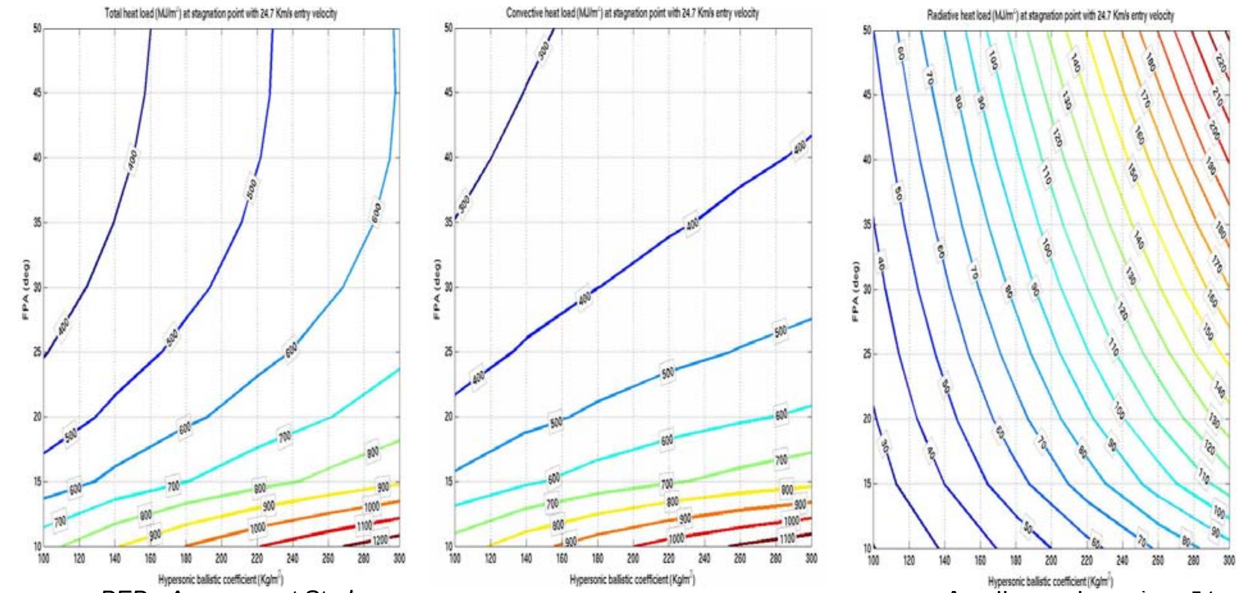




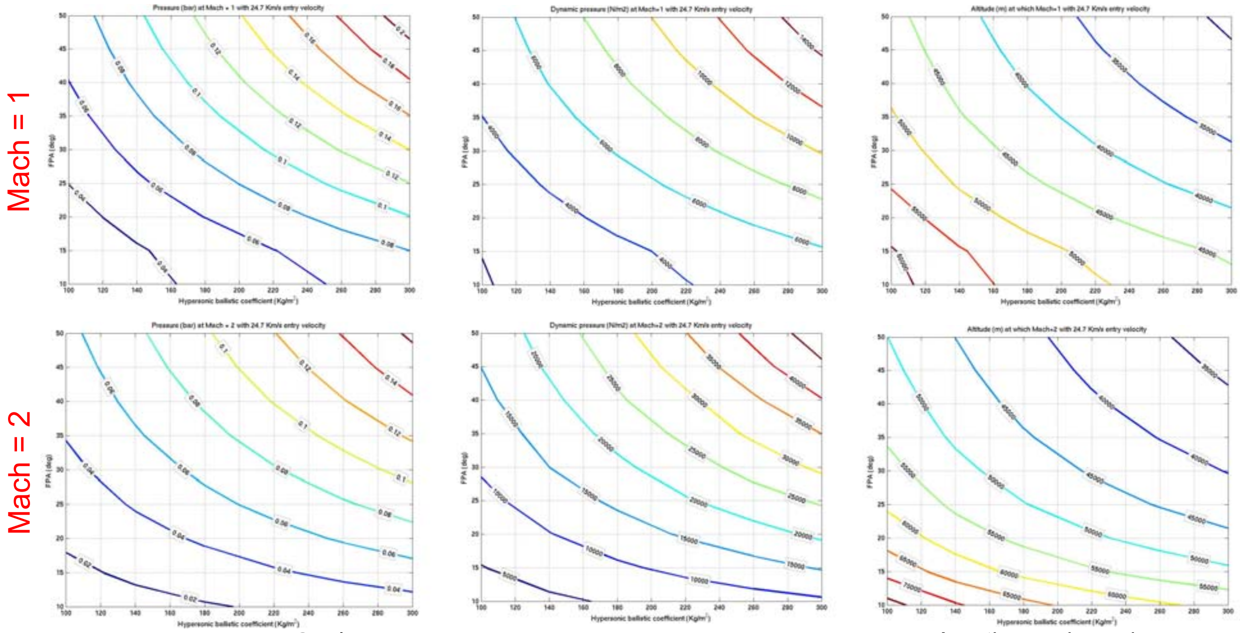
Neptune: maximum heat flux



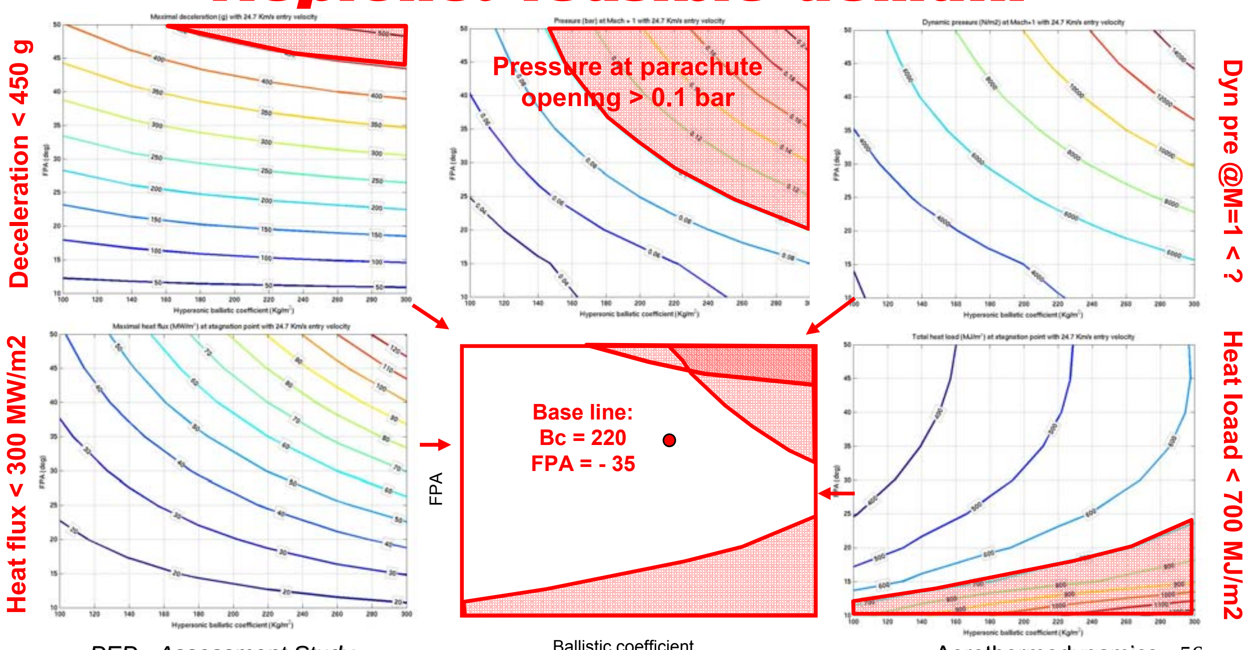
Neptune: total heat load



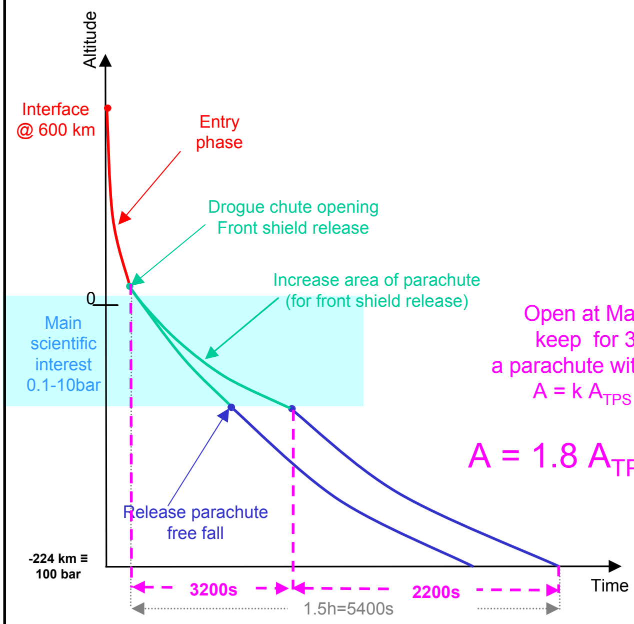
Neptune: Parachute opening: Mach=1,2?



Neptune: feasible domain

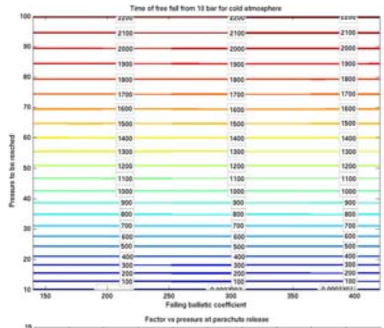


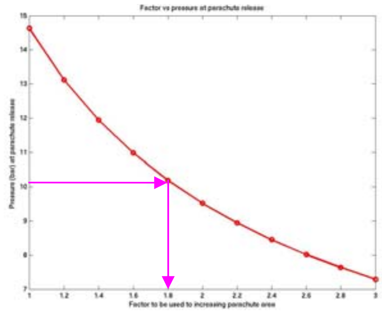
Neptune: sizing the drogue parachute



Open at Mach =1
keep for 3200s
a parachute with an area
$A = k\,A_{TPS\ release}$

$A = 1.8\,A_{TPS\ release}$





Extra material

Venus: Sizing parachute at separation

$$\frac{M^{probe} - M^{TPS}}{C_D^{drogue}\cdot A^{drogue} + C_D^{sphere}\cdot A^{sphere}} \le 0.7 \; \frac{M^{TPS}}{C_D^{TPS}\cdot A^{TPS}}$$

$$\frac{M^{probe} - f_{TPS}\cdot M^{probe}}{C_D^{drogue}\cdot A^{drogue} + C_D^{sphere}\cdot A^{sphere}} \le 0.7 \; \frac{f_{TPS}\cdot M^{probe}}{C_D^{TPS}\cdot A^{TPS}}$$

$$\frac{(1 - f_{TPS})\,\cancel{M^{probe}}}{C_D^{drogue}\cdot A^{drogue} + C_D^{sphere}\cdot A^{sphere}} \le 0.7 \; \frac{f_{TPS}\cdot \cancel{M^{probe}}}{C_D^{TPS}\cdot A^{TPS}}$$

$$A^{drogue} \ge \frac{1}{0.7}\cdot \frac{1-f_{TPS}}{f_{TPS}} \cdot \frac{C_D^{TPS}}{C_D^{drogue}}\cdot A^{TPS} - \frac{C_D^{sphere}\cdot A^{sphere}}{C_D^{drogue}}$$

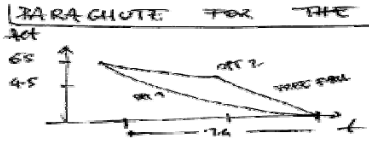
f_{TPS}	$\frac{1-f_{TPS}}{f_{TPS}}$	Area Drogue
0.3	2.3	A^*
0.2	4	$1.7\,A^*$
0.1	9	$3.9\,A^*$

CASE AT HAND

$A^{drogue} \simeq 0.82\,m^2$

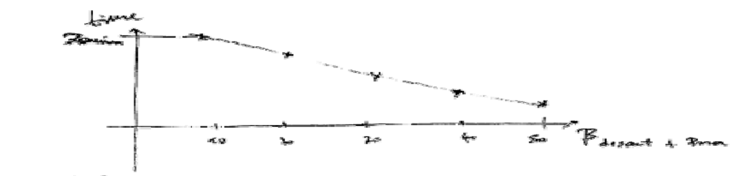
Main parachute opt2

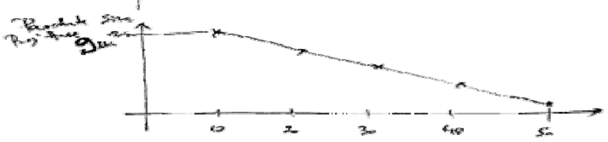
PARACHUTE FOR THE DESCENT



REMARK:
FREE FALL depends on β_c descent sphere (mass and dimensions)

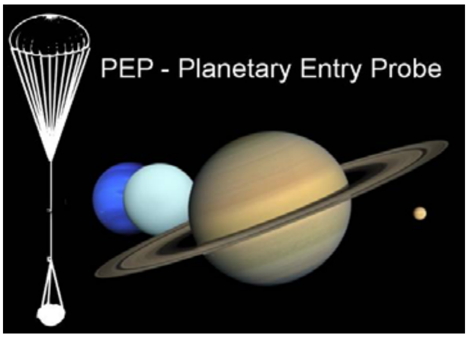
CASE AT HAND
$R_{sphere} \cong 0.6\,m$
$M_{sphere} \cong 125\,kg$ } $\beta_{sphere} \cong 200$
$\Rightarrow t_{FREE\ FALL} \cong 30\,min$





PEP
Planetary Entry Probes

Thermal



IFP

ESTEC, 30th June 2010

Prepared by the PEP/ CDF* Team

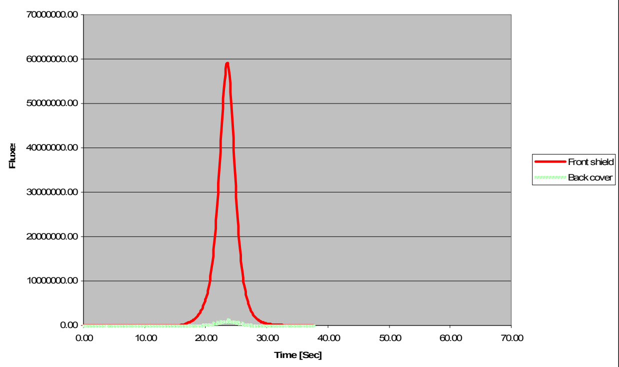
(*) ESTEC Concurrent Design Facility

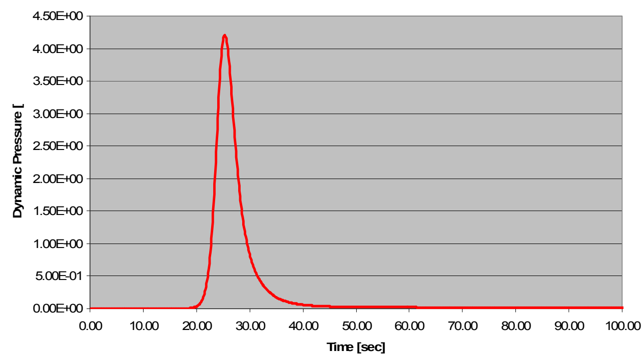
Venus

Assumptions and design drivers

- Two entry cases for TPS sizing:
  - -25 deg entry angle.
  - -50 deg entry angle.
- Coast and descent analysed for case -25 deg entry angle
- Entry and descent environments (Fluxes vs. time, atmospheric temperature vs. time) as provided by aerothermodynamics subsystem.
- Coast environment = Planet environment (no direct solar flux and albedo considered => worst cold case).
- Power dissipations vs. time as provided by Power subsystem.
- Units within –20 / +50 C (possibly –40 / +70 C).
- Three high density ablators traded-off for front shield; one low density ablator considered for back cover.
- ESATAN-Ablat and ThermXL software used for computations

Aerothermal fluxes and Dynamic pressure -25 deg entry

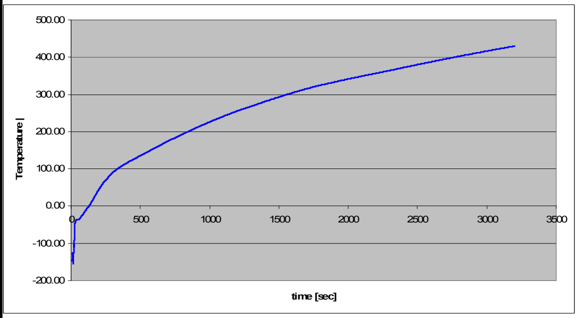


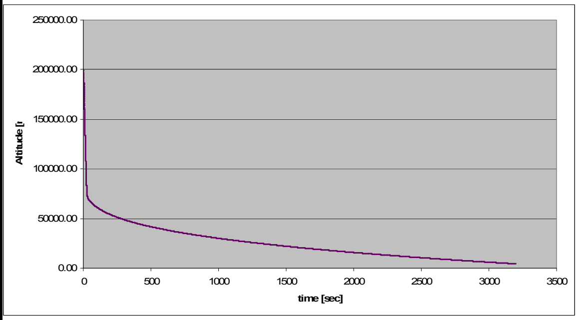


Max Total flux	**59.15 [MW/m2]**	**Max Dynamic pressure**	**4.20 [bar]**
Tot heat load	**2.11E+08 [J/m2]**	**Time max Dynamic pressure**	**25.30 [sec]**

Fluxes to be applied on front shield as from aerothermodynamics data but scaled to the probe nose radius => no margin, no blockage on fluxes.
Fluxes to be applied on back cover calculated as $Q_{tot} = 0.025\ Q_{conv\_front} + 0.01\ Q_{rad\_front}$.

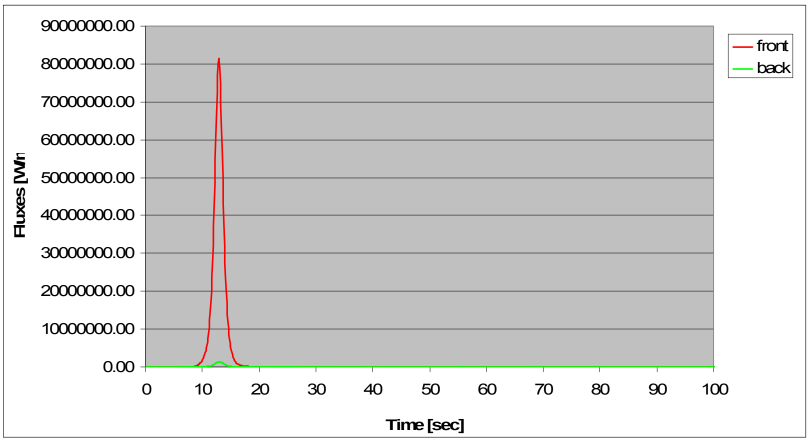
Atmospheric data
-25 deg entry





- Temperature and Altitude during entry phase
- Release of front shield and back cover once Ma ch 2 is reached (back cover after front shield) => this occ urs at an altitude of about 69.5 km and after 3 7 sec from entry.

Aerothermal fluxes
-50 deg entry angle

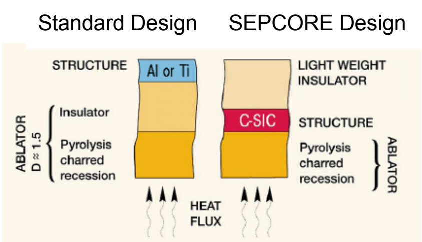


Considerations for TPS dimensioning

- Front shield: both aerothermal fluxes and max dynamic pressure are not in the range of applicabilit y for low density carbon phenolic => hi gh density carbon phenolic needs to be used.
- Back shield: both aerothermal fluxes and dynamic pressure are in the range of applicabil ity for low density carbon phenolic => a PIC A-like material can be used.
- SEPCORE vs. Normal design traded-off; (SEPCORE baselined).
- 50% uncertainty margin to be used on thickness according to requirements plus 20% maturity margin.
- Both High density carbon phenolic and Pica-like ablators have low TRL.

TRL Carbon phenolic	>5 for Launchers <5 for Entry probes	EU
	>5 for Launchers >5 for Entry probes	USA
TRL PICA-like	3-4 end 2010	EU

SEPCORE design vs Normal design



- When high fluxes (above ~ 25 MW) and high dynamic pressure (above ~ 1 bar) occur high density carbon-phenolic materials need to be used.
- In the standard design one kind of material is used; part of it ablates, the rest acts as conductive insulator. Typical cold structure temperature limits are 150 – 180 C (250 C pushing the technology).
- In the SEPCORE design the ablator can be used with a reduced thickness because the hot structure underneath can sustain temperatures of up to 1100 – 1200 C. The light weight insulator (with lower thermal conductivity than high density carbon-phenolic material) at its back acts as conductive insulator permitting the cold structure to stay below 150 – 180 C (250 C pushing the technology).
- The SEPCORE design (ablator + hot structure + light weight insulator) permits to save 20 – 30 % mass compared to the standard design if a high density carbon-phenolic material (~1400 kg/m3) has to be used even if adds complexity to the design.
- It may be convenient also when using low density carbon-phenolic materials.

TPS dimensioning analysis results -25 deg entry

Carbon Phenolic

Front Shield (release at Mach=2)	Thickness [m]	Area[m2]	Density [kg/m3]	Mass TPS [kg]	Mass of IFI+C/SiC [kg]		TOTmass [kg]	
SEPCORE	0.009	1.640	1400.00	31.00	8.11	5 mm IFI	39.11	0.0162 m
	no margin applied yet			50% margin applied on thickness				

Narmco4028

Front Shield (release at Mach=2)	Thickness [m]	Area[m2]	Density [kg/m3]	Mass TPS [kg]	Mass of IFI+C/SiC [kg]		TOTmass [kg]	
SEPCORE	0.0130	1.640	1400	44.77	8.11	5 mm IFI	52.88	0.0234 m
	no margin applied yet			50% margin applied on thickness				

FM5055 Carbon Phenolic

Front Shield (release at Mach=2)	Thickness [m]	Area[m2]	Density [kg/m3]	Mass TPS [kg]	Mass of IFI+C/SiC [kg]		TOTmass [kg]	
SEPCORE	0.0145	1.640	1400	49.94	8.11	5 mm IFI	58.05	0.0261 m
	no margin applied yet			50% margin applied on thickness				Thickness with 50%+20% margin

PICA-Like Carbon Phenolic

SEPCORE DESIGN	Thickness [m]	Area[m2]	Density [kg/m3]	Mass TPS [kg]	Mass of IFI+C/SiC [kg]		TOTmass [kg]	
Back Cover	0.002	1.540	266	1.23	7.62	5 mm IFI	8.85	0.0036 m
	^ II no margin applied yet			^ II 50% margin applied to thickness				Thickness with 50%+20% margin

TPS dimensioning analysis results -50 deg entry

Carbon Phenolic

Front Shield (release at Mach=2)	Thickness [m]	Area[m2]	Density [kg/m3]	Mass TPS [kg]	Mass of IFI+C/SiC [kg]		TOTmass [kg]	
SEPCORE	0.0045	1.640	1400.00	15.50	8.11	5 mm IFI	23.61	0.0081 m
	no margin applied yet			50% margin applied on thickness				

Narmco4028

Front Shield (release at Mach=2)	Thickness [m]	Area[m2]	Density [kg/m3]	Mass TPS [kg]	Mass of IFI+C/SiC [kg]		TOTmass [kg]	
SEPCORE	0.0075	1.640	1400	25.83	8.11	5 mm IFI	33.94	0.0135 m
	no margin applied yet			50% margin applied on thickness				

FM5055 Carbon Phenolic

Front Shield (release at Mach=2)	Thickness [m]	Area[m2]	Density [kg/m3]	Mass TPS [kg]	Mass of IFI+C/SiC [kg]		TOTmass [kg]	
SEPCORE	0.0065	1.640	1400	22.39	8.11	5 mm IFI	30.50	0.0117 m
	no margin applied yet			50% margin applied on thickness				Thickness with 50%+20% margin

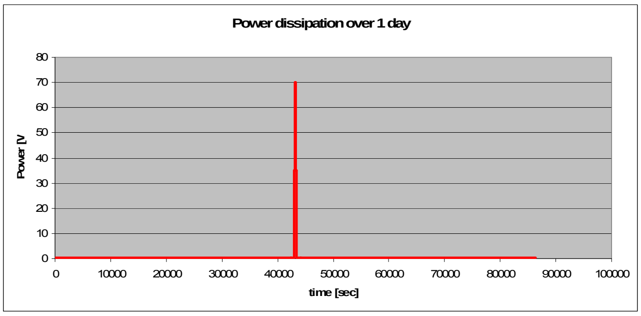
PICA-Like Carbon Phenolic

SEPCORE DESIGN	Thickness [m]	Area[m2]	Density [kg/m3]	Mass TPS [kg]	Mass of IFI+C/SiC [kg]		TOTmass [kg]	
Back Cover	0.002	1.540	266	1.23	7.62	5 mm IFI	8.85	0.0036 m
	^ II no margin applied yet			^ II 50% margin applied to thickness				Thickness with 50%+20% margin

Coast Phase Assumptions

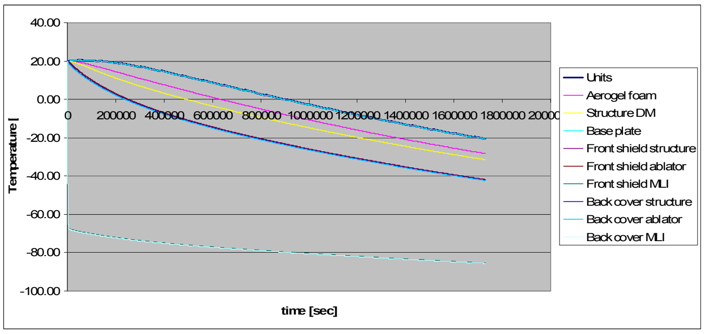
Duration	20 [days]		
	480 [hours]		
	28800 [minutes]		
Power dissipations			
Comms	35 [W]	=>	35 W for 3.6 minutes every day
Duty cycle	0.25% [-]		0 W for the rest of the day
DHS	19.73 [W]	=>	19.672 W for 8.64 minutes every day
Duty cycle	0.60% [-]		0 W for the rest of the day
DHS MTU	0.27 [W]	=>	0.27W the all day
Duty cycle	100% [-]		
GNC	15 [W]	=>	15 W for 8.64 minutes every day
Duty cycle	0.60% [-]		0 W for the rest of the day

IR flux acting on front shield and back cover MLI

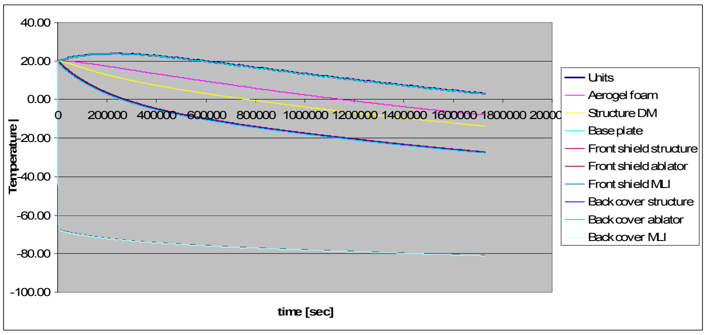


Time	Power dissipation
[sec]	[W]
0	0.27
42336	0.27
42336	0.27
42941	0.27
42941	35
43092	35
43092	70
43308	70
43308	35
43459	35
43459	0.27
44064	0.27
44064	0.27
86400	0.27

Coast Phase - Analysis Results



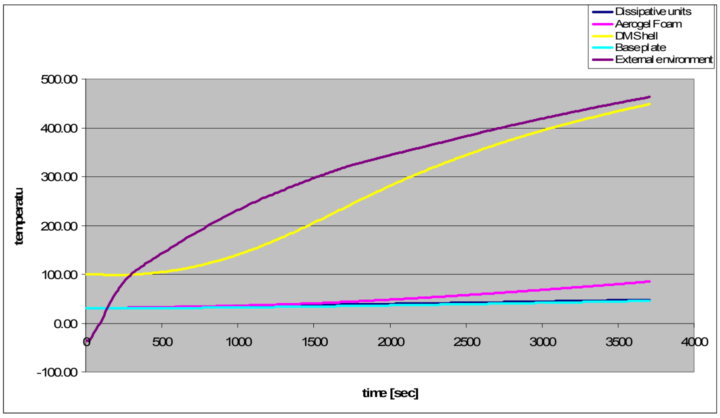
MLI with Low emissivity no Albedo considered



MLI with Low emissivity no Albedo considered, 2 W from RHUs

Descent Phase
Assumptions and Analysis Results

- Total power dissipated = 280 W (100% DC).
- Descent total duration = 1 hour.



TCS and TPS design summary

- DM dissipative units black painted and mounted on the base plate via fillers;
- Base plate finished with one layer Kapton VDA (low emissivity);
- Base plate connected to DM shell with 3 Titanium brackets (low conductive coupling);
- Internal DM s hell in sulated wit h 4 0 mm Aerogel foam finished with one layer Kapton VDA (low emissivity);
- External DM shell white painted;
- DM s hell conne cted t o f ront s hield co ld s tructure wit h 3 Titanium brackets (low conductive coupling);
- Cold structure internal surface fi nished w ith o ne l ayer Kapton V DA (low emissi vity) (both fr ont shield and back cover);
- Front shield TPS: SEPCORE = 16.2 mm (9 mm + 5 0% +20% margins) Carbon phenolic Ablator + 2.4 mm C/SiC hot structure + 5 mm IFI Insulation
- Back cover TPS: SEPCORE = 3.6 mm (2 mm + 50% +20% margins) PICA-like Ablator + 2.4 mm C/SiC hot structure + 5 mm IFI Insulation;
- 15 ablation detectors distributed radially and circumferentially on front shield;
- 20 layer MLI on front shield and back cover used during coasting then burned during entry.

- RHU are not baselined due to the larger temperature range of ba tteries. Temperature will rapidly increase during entry when units will be switched on and high heat fluxes will act on the probe. In case batteries want to be kept above 0 C th en 2 RHU (2 W in total) need to be in stalled on the probe.

Mass Budget Venus (baseline case: -25 deg entry angle)

Element 1	-			MASS [kg]			
Unit	Unit Name Click on button above to **insert new unit**	Part of subsystem	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
1	Front shield ablator (carbon-phenolic)		1	31.00	To be developed	20	37.20
2	Backcover ablator (PICA-like)		1	1.23	To be developed	20	1.47
3	Front shield and back cover insulation (IFI)		1	2.07	To be modified	10	2.27
4	Front shield and back cover hot structure (C/SiC)		1	13.66	To be modified	10	15.03
5	Interface ylindecto DM (C/SiC)		1	1.10	To be modified	10	1.21
6	DM internal insulation (Aerogel)		1	4.34	To be modified	10	4.78
7	1layer VDA between DM and heat shield / back cover		1	0.13	To be modified	10	0.14
8	MLI on front shield and back cover (coast phase)		1	1.27	To be modified	10	1.40
9	Ablation detectors		15	0.10	To be modified	10	1.65
10					To be developed	20	0.00
-	Click on button below to insert new unit			0.00	To be developed	20	0.00
SUBSYSTEM TOTAL			**9**	**56.30**		**15.7**	**65.15**

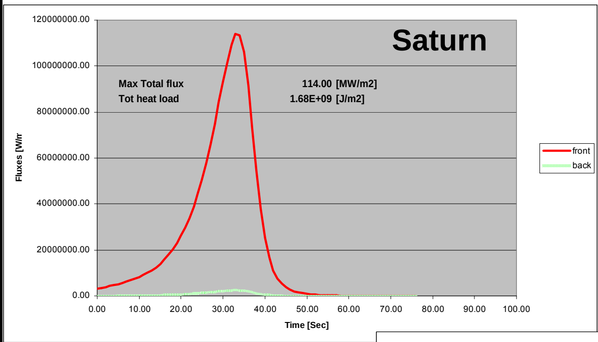
Outer planets

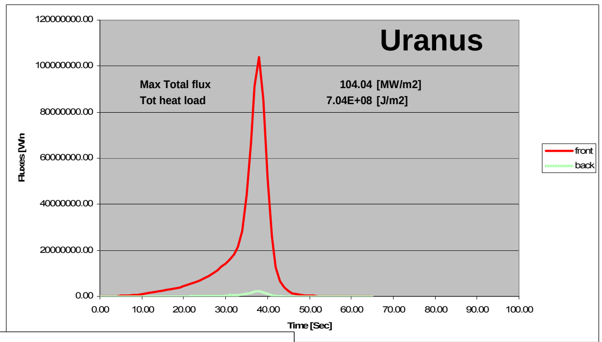
TPS, TCS design

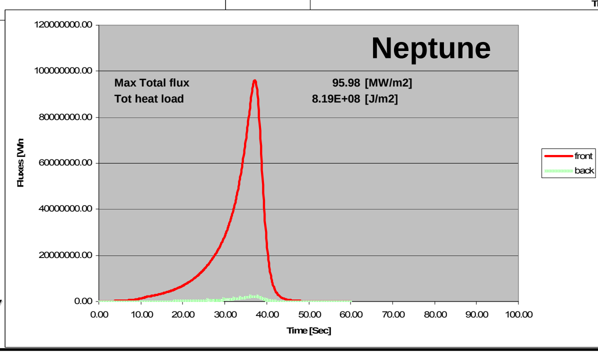
- Same TPS/TCS design principle as per Venus probe.
- Thicknesses of TPS materials differ due to different aerothermodynamics fluxes and shield release timing (Uranus and Neptune probes are identical).
- Aerothermodynamics fluxes: 100% margin + 20% blockage on both convective and radiative fluxes.
- 3 RHUs (3 W in tot) may be required if batteries want to be kept always above 0 C. (currently not baselined)

	Saturn	Uranus	Neptune
Front shield release	Mach = 1 T = 76 sec	Mach = 1 T = 65 sec	Mach =1 T = 60 sec
Back cover release	Mach < 1 T = 106 sec	T = 1625 sec	T = 3260 sec

Aerothermodynamics fluxes







TPS dimensioning Saturn

Carbon Phenolic

Front Shield (release at Mach=1)	Thickness [m]	Area[m2]	Density [kg/m3]	Mass TPS [kg]	Mass of IFI+C/SiC [kg]		TOTmass [kg]	
SEPCORE	0.0205	1.640	1400.00	70.60	8.11	5 mm IFI	78.71	0.0369 m
	no margin applied yet			50% margin applied on thickness				

Narmco4028

Front Shield (release at Mach=1)	Thickness [m]	Area[m2]	Density [kg/m3]	Mass TPS [kg]	Mass of IFI+C/SiC [kg]		TOTmass [kg]	
SEPCORE	0.0275	1.640	1400	94.71	8.11	5 mm IFI	102.82	0.0495 m
	no margin applied yet			50% margin applied on thickness				

FM5055 Carbon Phenolic

Front Shield (release at Mach=1)	Thickness [m]	Area[m2]	Density [kg/m3]	Mass TPS [kg]	Mass of IFI+C/SiC [kg]		TOTmass [kg]	
SEPCORE	0.0305	1.640	1400	105.04	8.11	5 mm IFI	113.15	0.0549 m
	no margin applied yet			50% margin applied on thickness				50%+20% margin

PICA-Like Carbon Phenolic

SEPCORE DESIGN	Thickness [m]	Area[m2]	Density [kg/m3]	Mass TPS [kg]	Mass of IFI+C/SiC [kg]		TOTmass [kg]	
Back Cover	0.005	1.540	266	3.07	8.62	10 mm IFI	11.69	0.009 m
	^ II no margin applied yet			^ II 50% margin applied to thickness				50%+20% margin

TPS dimensioning Uranus/Neptune

Carbon Phenolic

Front Shield (release at Mach=1)	Thickness [m]	Area[m2]	Density [kg/m3]	Mass TPS [kg]	Mass of IFI+C/SiC [kg]		TOTmass [kg]	
SEPCORE	0.0155	1.640	1400.00	53.38	8.11	5 mm IFI	61.49	0.0279 m
	no margin applied yet			50% margin applied on thickness				

Narmco4028

Front Shield (release at Mach=1)	Thickness [m]	Area[m2]	Density [kg/m3]	Mass TPS [kg]	Mass of IFI+C/SiC [kg]		TOTmass [kg]	
SEPCORE	0.0215	1.640	1400	74.05	8.11	5 mm IFI	82.16	0.0387 m
	no margin applied yet			50% margin applied on thickness				

FM5055 Carbon Phenolic

Front Shield (release at Mach=1)	Thickness [m]	Area[m2]	Density [kg/m3]	Mass TPS [kg]	Mass of IFI+C/SiC [kg]		TOTmass [kg]	
SEPCORE	0.0235	1.640	1400	80.93	8.11	5 mm IFI	89.05	0.0423 m
	no margin applied yet			50% margin applied on thickness				50%+20% margin

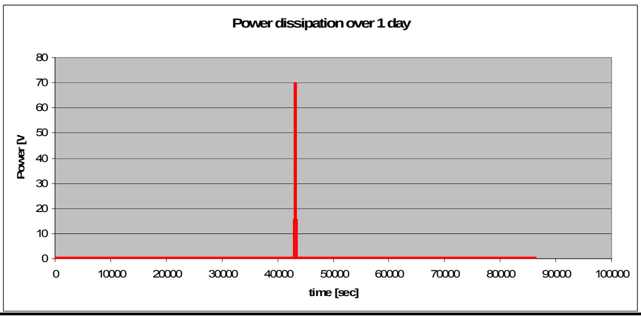
PICA-Like Carbon Phenolic

SEPCORE DESIGN	Thickness [m]	Area[m2]	Density [kg/m3]	Mass TPS [kg]	Mass of IFI+C/SiC [kg]		TOTmass [kg]	
Back Cover	0.005	1.540	266	3.07	10.62	20 mm IFI	13.69	0.009 m
	^ II no margin applied yet			^ II 50% margin applied to thickness				50%+20% margin

Coast phase assumptions (common to the 3 outer planets)

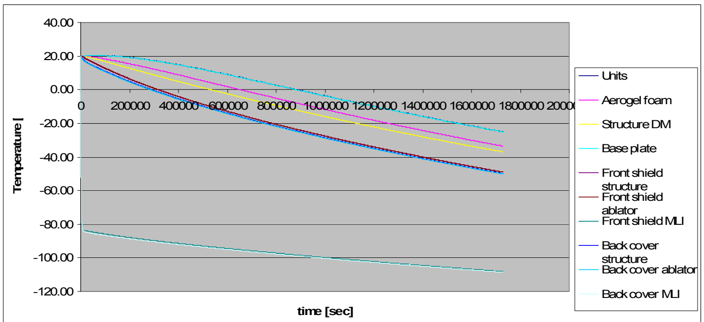
Duration	20	[days]		
	480	[hours]		
	28800	[minutes]		
Power dissipations				
Comms	35	[W]	=>	35 W for 3.024 minutes every day
Duty cycle	0.21%	[-]		0 W for the rest of the day
DHS	19.4	[W]	=>	19.4 W for 3.024 minutes every day
Duty cycle	0.21%	[-]		0 W for the rest of the day
DHS MTU	0.272	[W]	=>	0.272W the all day
Duty cycle	100%	[-]		
GNC	15	[W]	=>	15 W for 8.64 minutes every day
Duty cycle	0.60%	[-]		0 W for the rest of the day

IR flux acting on front shield and back cover MLI

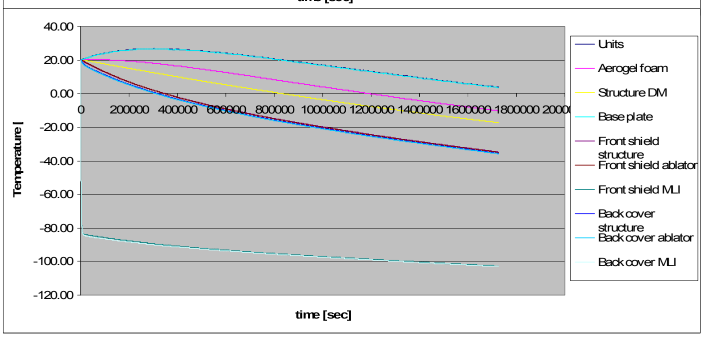


Time [sec]	Power dissipation [W]
0	0.272
42336	0.272
42336	0.272
42941	0.272
42941	15.272
43109	15.272
43109	69.672
43291	69.672
43291	15.272
43459	15.272
43459	0.272
44064	0.272
44064	0.272
86400	0.272

Coast phase Saturn

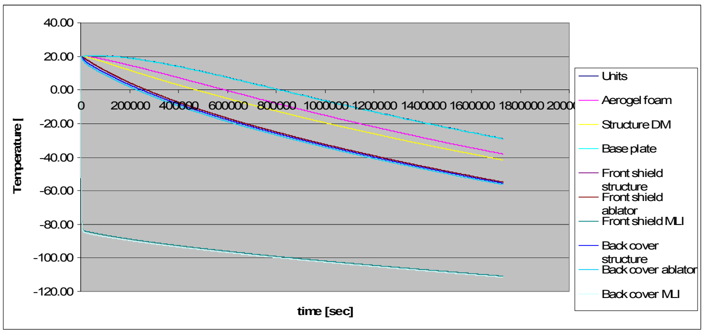


Low emissivity MLI, No albedo

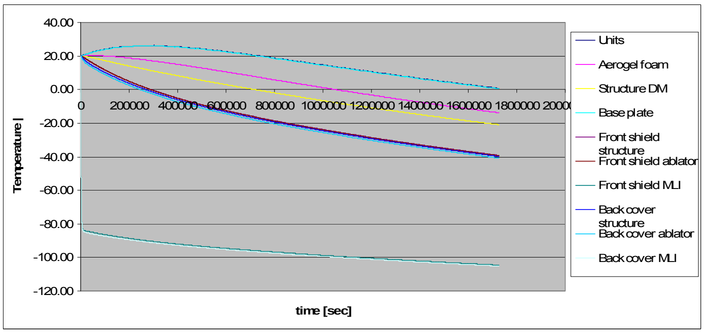


Low emissivity MLI, No albedo, 3W heating from RHUs

Coast phase Uranus

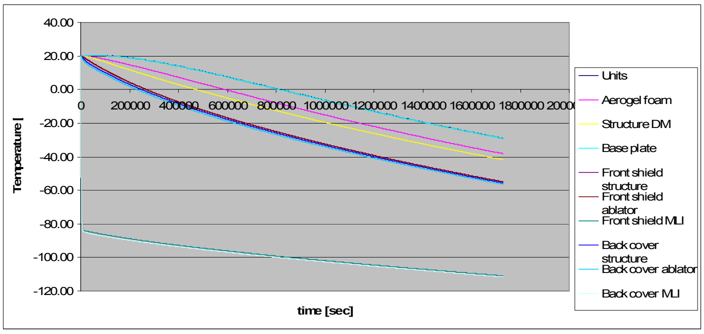


Low emissivity MLI, No albedo

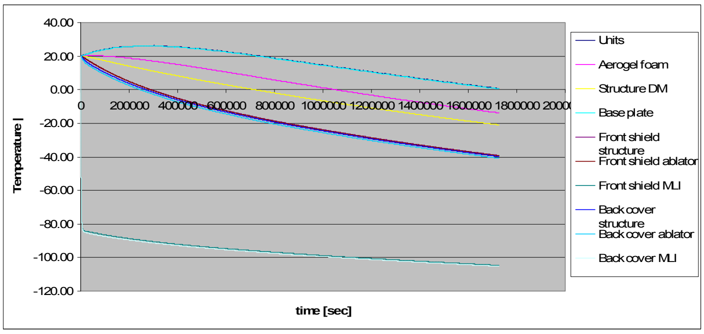


Low emissivity MLI, No albedo, 3W heating from RHUs

Coast phase Neptune



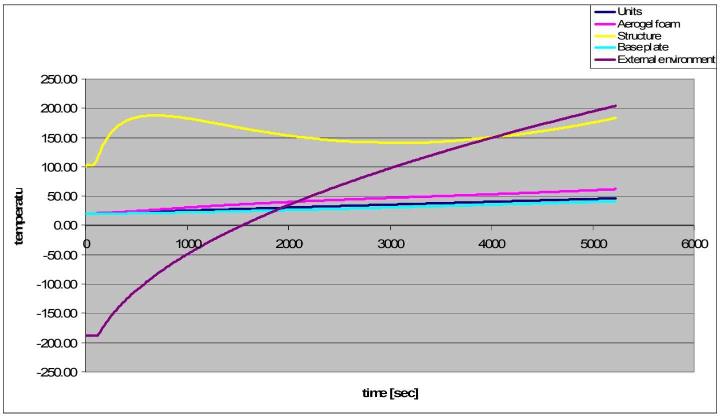
Low emissivity MLI, No albedo



Low emissivity MLI, No albedo, 3W heating from RHUs

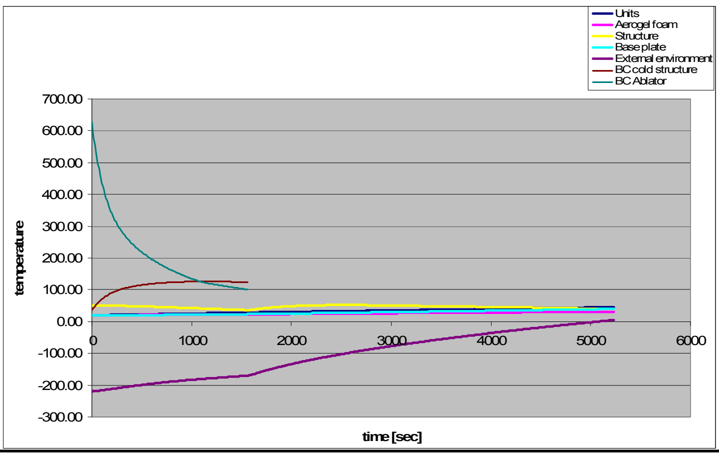
Descent phase Saturn

- Total power dissipated = 310 W (100% DC).
- Descent total duration = 1.5 hour.



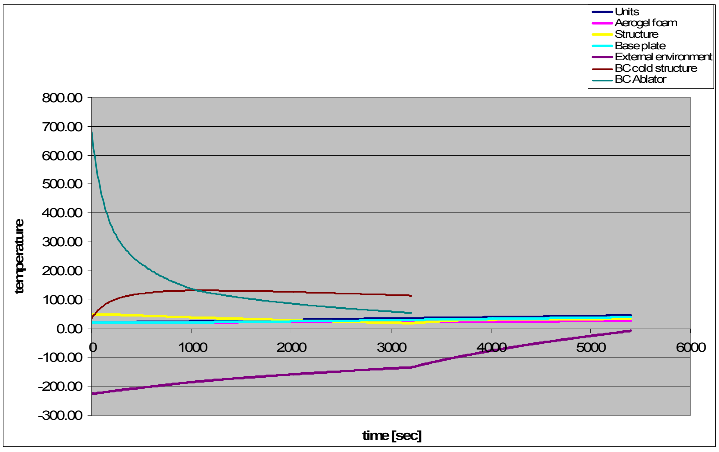
Descent phase Uranus

- Total power dissipated = 310 W (100% DC).
- Descent total duration = 1.5 hour.
- Back cover kept attached for 1560 sec after front shield release.



Descent phase Neptune

- Total power dissipated = 310 W (100% DC).
- Descent total duration = 1.5 hour.
- Back cover kept attached for 3200 sec after front shield release.



Mass budget Saturn

Element 1	0			MASS [kg]			
Unit	Unit Name Click on button above to **insert new unit**	Part of subsystem	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
1	Front shield ablator (carbon-phenolic)		1	70.60	To be developed	20	84.72
2	Backcover ablator (PICA-like)		1	3.07	To be developed	20	3.69
3	Front shield and back cover insulation (IFI)		1	3.07	To be modified	10	3.37
4	Front shield and back cover hot structure (C/SiC)		1	13.66	To be modified	10	15.03
5	Interface ylindec to DM (C/SiC)		1	1.10	To be modified	10	1.21
6	DM internal insulation (Aerogel)		1	5.10	To be modified	10	5.61
7	1layer VDA between DM and heat shield / back cover		1	0.13	To be modified	10	0.14
8	MLI on front shield and back cover (coast phase)		1	1.27	To be modified	10	1.40
9	Ablation detectors		15	0.10	To be modified	10	1.65
10					To be developed	20	0.00
-	Click on button below to insert new unit			0.00	To be developed	20	0.00
SUBSYSTEM TOTAL			9	99.50		17.4	116.82

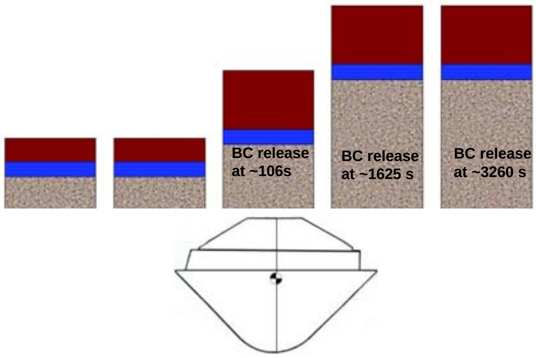
Mass Budget Uranus/Neptune

Element 1	0			MASS [kg]			
Unit	Unit Name Click on button above to **insert new unit**	Part of subsystem	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
1	Front shield ablator (carbon-phenolic)		1	53.38	To be developed	20	64.06
2	Backcover ablator (PICA-like)		1	3.07	To be developed	20	3.69
3	Front shield and back cover insulation (IFI)		1	5.07	To be modified	10	5.58
4	Front shield and back cover hot structure (C/SiC)		1	13.66	To be modified	10	15.03
5	Interface ylindec to DM (C/SiC)		1	1.10	To be modified	10	1.21
6	DM internal insulation (Aerogel)		1	5.10	To be modified	10	5.61
7	1layer VDA between DM and heat shield / back cover		1	0.13	To be modified	10	0.14
8	MLI on front shield and back cover (coast phase)		1	1.27	To be modified	10	1.40
9	Ablation detectors		15	0.10	To be modified	10	1.65
10					To be developed	20	0.00
-	Click on button below to insert new unit			0.00	To be developed	20	0.00
	SUBSYSTEM TOTAL		**9**	**84.28**		**16.7**	**98.36**

TPS Design Summary

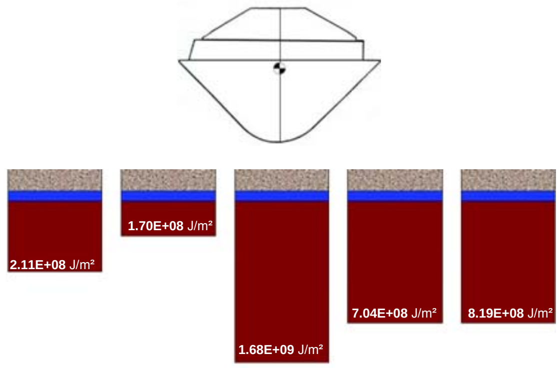
	Venus FPA = -25°	Venus FPA = -50°	Saturn FPA = -25°	Uranus FPA = -45°	Neptune FPA = -35°
THICKNESS					
Front Shield Ablator	CP **16.2mm** (31.0kg) Narmco4028 **23.4mm** (44.77kg) FM5055 **26.1mm** (49.94)	CP **8.1mm** (15.5kg) Narmco4028 **13.5**mm (25.83kg) FM5055 **11.7mm** (22.39kg)	CP **36.9mm** (70.6kg) Narmco4028 **49.5**mm (94.71 kg) FM5055 **54.9mm** (105.04 kg)	CP **27.9mm** (53.38kg) Narmco4028 **38.7** mm (74.05 kg) FM5055 **42.3** (80.93 kg)	CP **27.9mm** (53.38kg) Narmco4028 **38.7** mm (74.05 kg) FM5055 **42.3** (80.93 kg)
Front Shield C/SiC	2.4 mm	2.4 mm	2.4 mm	2.4 mm	2.4 mm
Front Shield IFI	5 mm	5 mm	5 mm	5 mm	5 mm
Back Cover Ablator	3.6 mm	3.6 mm	9 mm	9 mm (3.07 kg)	9 mm (3.07 kg)
Back Cover C/SiC	2.4 mm	2.4 mm	2.4 mm	2.4 mm	2.4 mm
Back Cover IFI	5 mm	5 mm	10 mm	20 mm	20 mm
MASS					
Front Shield C/SiC+IFI	8.11 kg	8.11 kg	8.11 kg	8.11 kg	8.11 kg
Back Cover C/SiC+IFI	7.62 kg	7.62 kg	8.62 kg	10.62 kg	10.62 kg
Total Front Shield (Ablator+C/SiC+IFI)	CP 16.2mm (**39.11kg**) Narmco4028 23.4mm (**52.88kg**) FM5055 26.1mm (**58.05kg**)	CP 8.1mm (**23.61kg**) Narmco4028 13.5mm (**33.94kg**) FM5055 11.7mm (**30.5kg**)	CP 36.9mm (**78.71kg**) Narmco4028 49.5mm (**102.82kg**) FM5055 54.9 (**113.15 kg**)	CP 27.9mm (**61.49kg**) Narmco4028 38.7 mm (**82.16kg**) FM5055 42.3 (**89.05 kg**)	CP 27.9mm (**61.49kg**) Narmco4028 38.7 mm (**82.16kg**) FM5055 42.3 (**89.05 kg**)
Total Back Cover (Ablator+C/SiC+IFI)	PICA-likeCP 3.6mm (**8.85kg**)	PICA-likeCP 3.6mm (**8.85 kg**)	PICA-likeCP 9mm (**11.69kg**)	PICA-likeCP 9mm (**13.69kg**)	PICA-likeCP 9mm (**13.69kg**)

Back cover

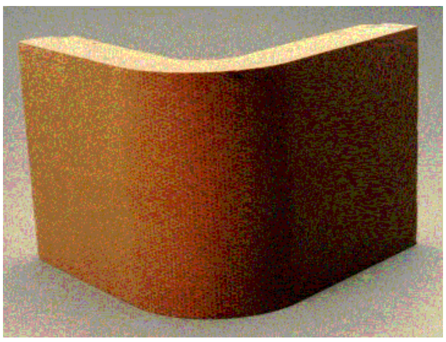


	Venus (FPA -25)	Venus (FPA -50)	Saturn	Uranus	Neptune
Ablator	3.6 mm	3.6 mm	9.0 mm	9.0 mm	9.0 mm
C/SiC	2.4 mm	2.4 mm	2.4 mm	2.4 mm	2.4 mm
IFI	5.0 mm	5.0 mm	10.0 mm	20.0 mm	20.0 mm

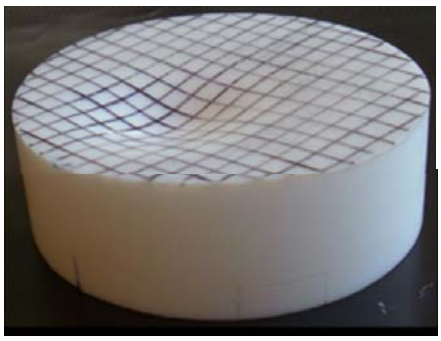
Front shield



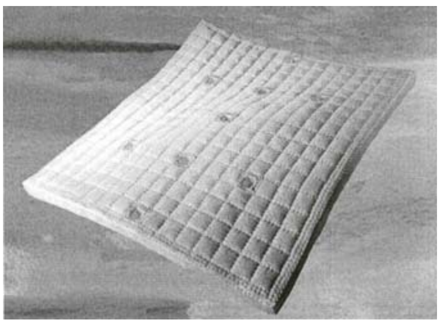
	Venus (FPA -25)	Venus (FPA -50)	Saturn	Uranus	Neptune
Ablator	16.2 mm	8.1 mm	36.9 mm	27.9 mm	27.9 mm
C/SiC	2.4 mm	2.4 mm	2.4 mm	2.4 mm	2.4 mm
IFI	5.0 mm	5.0 mm	5.0 mm	5.0 mm	5.0 mm



High density Carbon-Phenolic Ablator



Low density Carbon-Phenolic Ablator: PICA



IFI: Internal Flexible Insulation

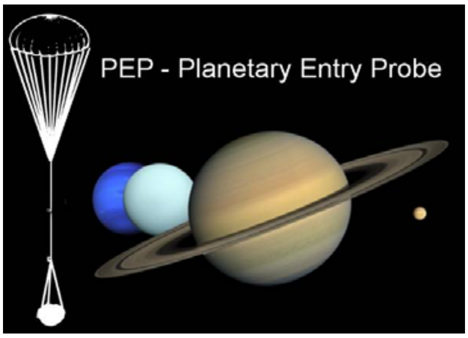
Made by Al_2O_3-based ceramic microfiber fleeces

PEP

EDLS

IFP

ESTEC, 30-06 2010

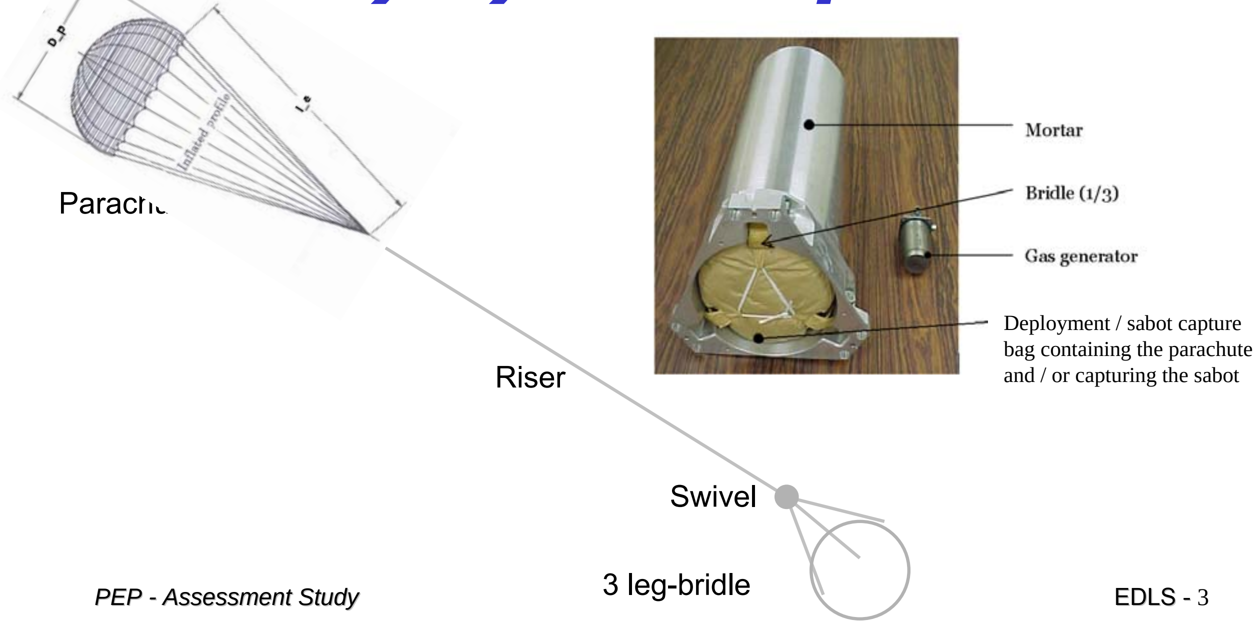


Prepared by the PEP/ CDF* Team

(*) ESTEC Concurrent Design Facility

Theory: System Components

Theory: System components

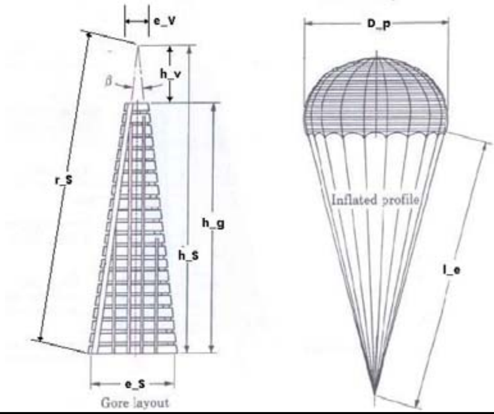


Theory: Parachute types

Theory: Parachute types

Conical ribbon parachute:

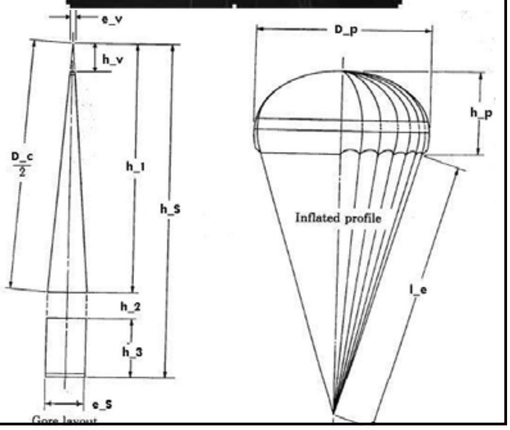
- Primarily used as drogue or pilot parachutes in space missions
- Excellent supersonic inflation
- Good stability (typical oscillation < 5◦)
- Good performance at high dynamic pressures
- High structural integrity
- Deployable above Mach = 2
- Moderate drag
- Very difficult to build scale models



Theory: Parachute types

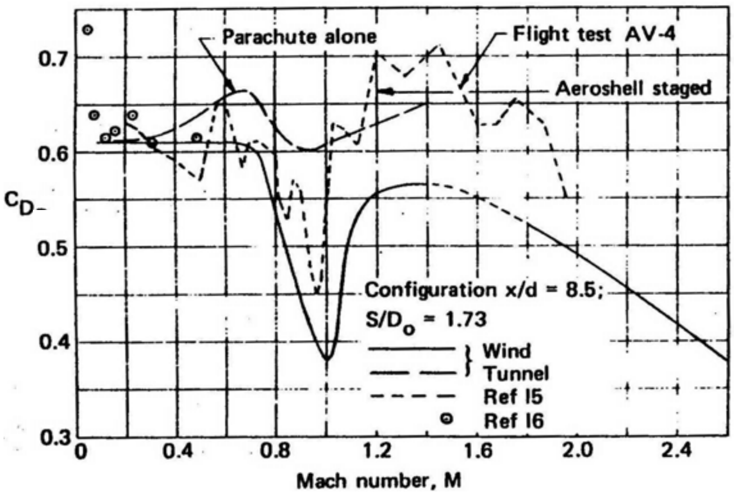
Disc Gap Band parachute:

- Used frequently for Mars missions to decelerate probes before landing or to control descent speed (Huygens).
- Good supersonic, low dynamic pressure inflation
- Easy to build small scale models
- Deployable above Mach = 2 possible
- Higher drag coefficient than Conical Ribbon parachute
- Less stable than Conical Ribbon parachute (typical oscillation < 10◦)
- Better performance at low dynamic pressures



Theory: Parachute C_{Dp}

Theory: Parachute C_{Dp}



Type	Constructed Shape: Planform Uninflated Flat View (Top)	Profile View Uninflated (Side)	Nominal Diameter D_c/D_o	Projected Diameter D_p/D_o	Drag Coefficient C_{D_o}(1) Range	Opening Force C_X (Inf. Mass)	Average Angle of Oscillation	General Application Remarks
Annular			1.04	.94	.95 to 1.00	~1.4	<±6°	Descent
Cross			1.15 to 1.19	.66 to .72	.60 to .78	~1.2	0° to ±3°	Descent Deceleration See Patent 3,331,573

SLOTTED TEXTILE PARACHUTES

Type	Constructed Shape: Planform Uninflated Flat View (Top)	Profile View Uninflated (Side)	Nominal Diameter D_c/D_o	Projected Diameter D_p/D_o	Drag Coefficient C_{D_o}(1) Range	Opening Force C_X (Inf. Mass)	Average Angle of Oscillation	General Application Remarks
Flat Ribbon			1.00	.67	.45 to .50	~1.05	0° to ±3°	Drogue, Descent, Deceleration
Conical Ribbon			.95 to .97	.70	.50 to .55	~1.05	0° to ±3°	Descent, Deceleration
Conical Ribbon (Varied Porosity)			.97	.70	.55 to .65	1.05 to 1.30	0° to ±3°	Drogue, Descent, Deceleration
Ribbon (Hemisflo)			.62	.62	.30* to .46	1.00 to 1.30	±2°	Supersonic Drogue
Ringslot			1.00	.67 to .70	.56 to .65	~1.05	0° to ±5°	Extraction, Deceleration
Ringsail			1.16	.69	.75 to .90	~1.10	±5° to ±10°	Descent
Disc-Gap-Band			.73	.65	.52 to .58	~1.30	±10° to ±15°	Descent

*Supersonic

$$C_{D_{projected}} = \frac{S_0}{S_{projected}} C_{D_0} \text{ where } S_0 = \frac{1}{4}\pi D_0^2 \text{ and } S_{projected} = \frac{1}{4}\pi D_{projected}^2$$

Theory: Parachute C_{Dp}

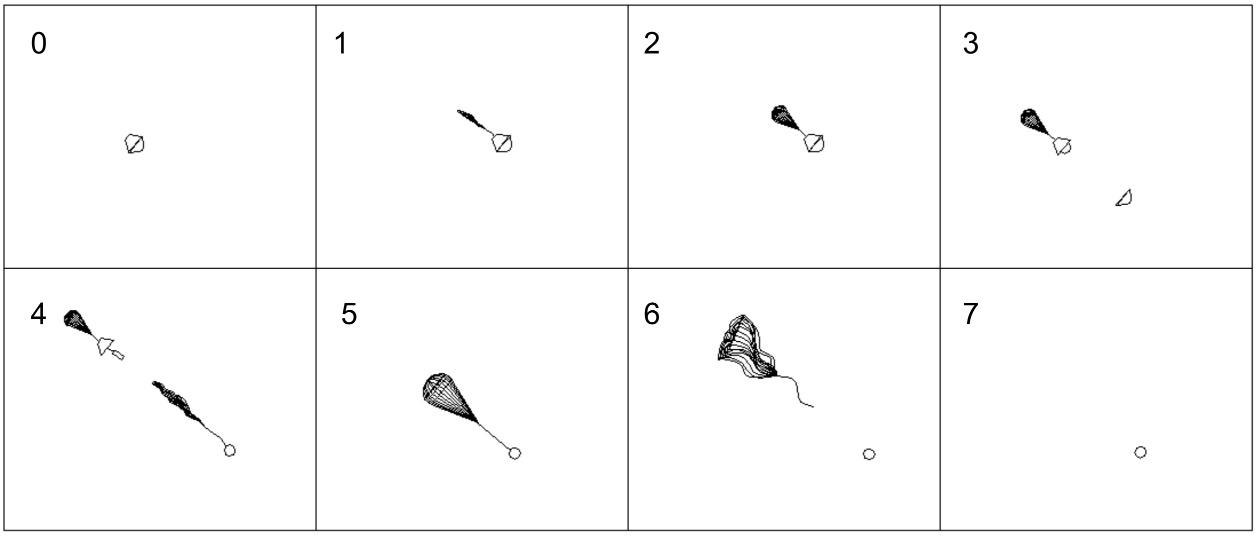
	Conical Ribbon	Disc Gap Band
Subsonic C_{D_0}	0.5-0.55	0.52-0.58
Subsonic $C_{D_{projected}}$	1.12	1.37
Supersonic $C_{D_{projected}}$	1.02	1.23

$$\beta_i = \frac{\sum_j m_{ij}}{\sum_j (C_d S)_{ij}} \qquad \beta = 0.7\beta$$

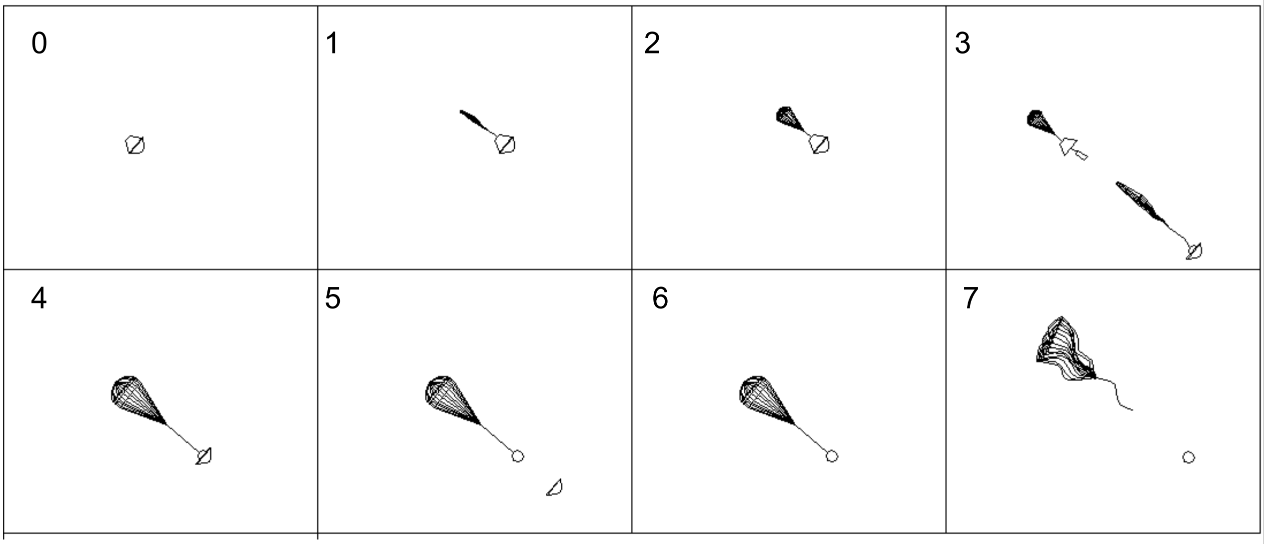
Ballistic coefficient and separation requirement

Theory: EDLS options

EDLS sequence Option 1



EDLS sequence Option 2



VENUS

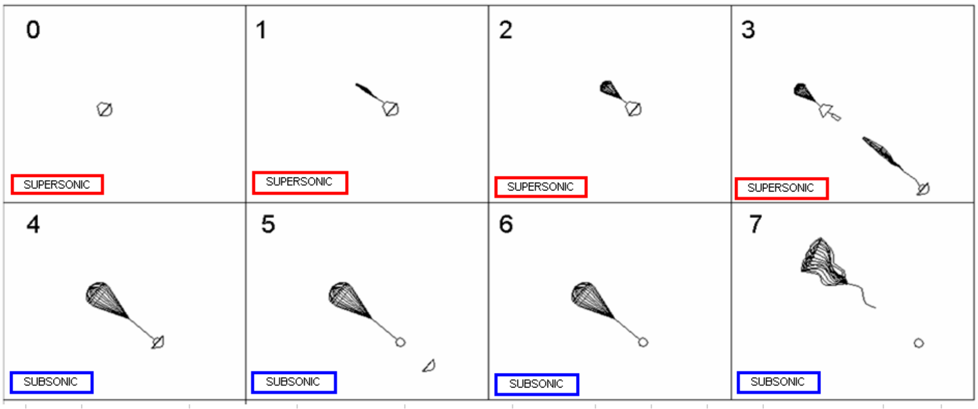
VENUS

- Verification of EDLS sequence option 1 and 2
- EDLS options verified for correct ballistic coefficients (proper separation, not flying back into items that were just separated etc.).
- The above is done for:
  - a small parachute that is kept all the way to the Venus surface
  - a large parachute that is jettisoned at about 45 km altitude

    This measurement range and duration of the free fall in combination with the total available time sizes the large parachute.
  - Now it is shown that with this large jettisonable parachute EDLS option 2 is feasible again and turns out to be the best option, since only a small parachute has to be ejected with the mortar and not a large parachute.

VENUS

Small main parachute, kept all the way to Venus surface, EDLS option 2

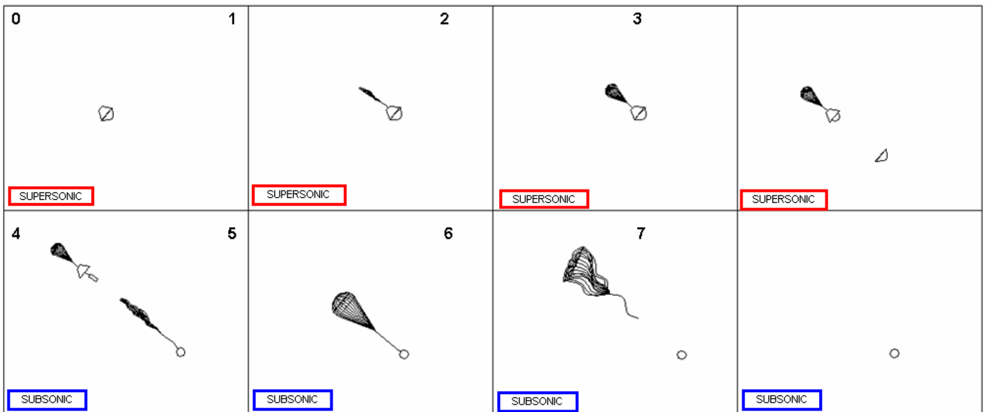


INPUT DATA		
Masses		
Front shield	[kg]	67.89
Back cover	[kg]	31.63
Sphere	[kg]	167.83
Total	[kg]	267.35
Dimensions		
Front shield	[m]	1.251
Back cover	[m]	0.99
Sphere	[m]	0.65
Drogue parachute	[m]	0.6
Main parachute	[m]	0.6
SUPERsonic drag coefficients		
Whole probe	[-]	1.26
Front shield	[-]	1.26
Back cover	[-]	1.26
Sphere	[-]	-
Drogue parachute	[-]	1.02
Main parachute	[-]	1.23
SUBsonic drag coefficients		
Whole probe	[-]	0.47
Front shield	[-]	0.47
Back cover	[-]	0.47
Sphere	[-]	0.5
Drogue parachute	[-]	1.12
Main parachute	[-]	1.37

CONCLUSION of the above: No separation since ballistic coefficient of heat shield is smaller than the ballistic coefficient of the sphere– parachute combination.
→ Change to EDLS option 1

VENUS

Small main parachute, kept all the way to Venus surface, EDLS option 1

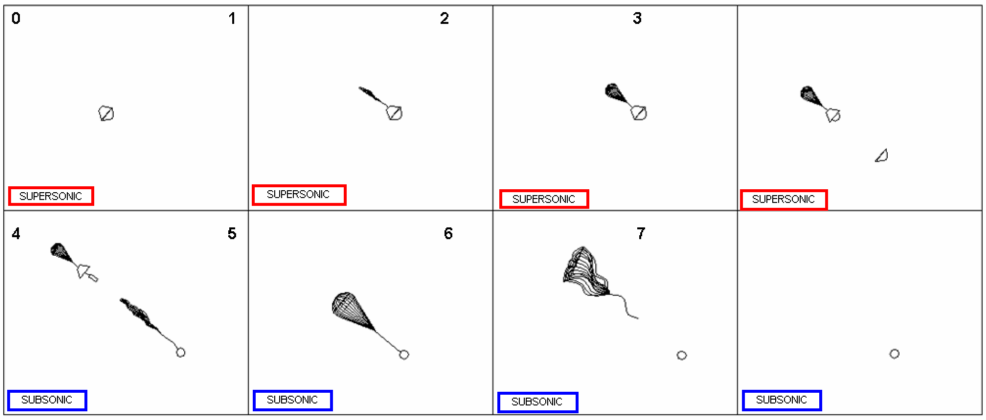


INPUT DATA		
Masses		
Front shield	[kg]	67.89
Back cover	[kg]	31.63
Sphere	[kg]	167.83
Total	[kg]	267.35
Dimensions		
Front shield	[m]	1.251
Back cover	[m]	0.99
Sphere	[m]	0.65
Drogue parachute	[m]	2.63
Main parachute	[m]	0.6
SUPERsonic drag coefficients		
Whole probe	[-]	1.26
Front shield	[-]	1.26
Back cover	[-]	1.26
Sphere	[-]	-
Drogue parachute	[-]	1.02
Main parachute	[-]	1.23
SUBsonic drag coefficients		
Whole probe	[-]	0.47
Front shield	[-]	0.47
Back cover	[-]	0.47
Sphere	[-]	0.5
Drogue parachute	[-]	1.12
Main parachute	[-]	1.37

CONCLUSION of the above: With EDLS option 1and drogue parachute dimensioned for heat shield separation.

VENUS

Large jettisonable main parachute, then free fall to the surface EDLS option1

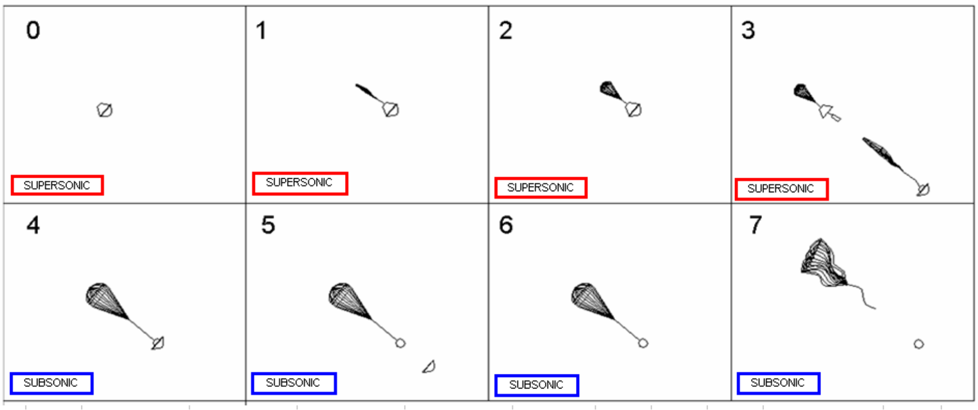


INPUT DATA		
Masses		
Front shield	[kg]	67.89
Back cover	[kg]	31.63
Sphere	[kg]	167.83
Total	[kg]	267.35
Dimensions		
Front shield	[m]	1.251
Back cover	[m]	0.99
Sphere	[m]	0.65
Drogue parachute	[m]	2.63
Main parachute	[m]	3.3
SUPERsonic drag coefficients		
Whole probe	[-]	1.26
Front shield	[-]	1.26
Back cover	[-]	1.26
Sphere	[-]	-
Drogue parachute	[-]	1.02
Main parachute	[-]	1.23
SUBsonic drag coefficients		
Whole probe	[-]	0.47
Front shield	[-]	0.47
Back cover	[-]	0.47
Sphere	[-]	0.5
Drogue parachute	[-]	1.12
Main parachute	[-]	1.37

CONCLUSION of the above: With EDLS option 1as well a large drogue parachute dimensioned for heat shield separation as well as a large main parachute for maintaining height altitude are required. → Change back to EDLS option 2?

VENUS

Large jettisonable main parachute, then free fall to the surface EDLS option2



INPUT DATA		
Masses		
Front shield	[kg]	67.89
Back cover	[kg]	31.63
Sphere	[kg]	167.83
Total	[kg]	267.35
Dimensions		
Front shield	[m]	1.251
Back cover	[m]	0.99
Sphere	[m]	0.65
Drogue parachute	[m]	0.6
Main parachute	[m]	3.3
SUPERsonic drag coefficients		
Whole probe	[-]	1.26
Front shield	[-]	1.26
Back cover	[-]	1.26
Sphere	[-]	-
Drogue parachute	[-]	1.02
Main parachute	[-]	1.23
SUBsonic drag coefficients		
Whole probe	[-]	0.47
Front shield	[-]	0.47
Back cover	[-]	0.47
Sphere	[-]	0.5
Drogue parachute	[-]	1.12
Main parachute	[-]	1.37

CONCLUSION of the above: It is possible to change back to EDLS option 2. The ballistic coefficients differ sufficiently and the drogue parachute that shall be jettisoned with the mortar is small. Mortar dimensions fit in this case the current configuration design.

VENUS (and other planets)

- Note: Although not base-lined, a small drag-generating drogue parachute is recommended for stabilization during final free fall.
  – This applies for all free falling probes of the study (Venus, Saturn, Uranus and Neptune)
  – Drogue parachutes are widely and commonly used and are very reliable. Even if they would not properly deploy, the mission has still a large potential to be successful.
- Landing gear

VENUS (1)

Unit	Element 1 Unit Name Click on button below to **insert new unit**	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
1	Drogue parachute canopy fabric	1	1.11	To be modified	10	1.2
2	Drogue parachute lines (split 50-50 with	1	0.35	To be modified	10	0.4
3	Drogue parachute riser (split 50-50 with	1	0.35	To be developed	20	0.4
4	Drogue parachute bridle	1	0.10	To be developed	20	0.1
5	Drogue parachute deployment bag	1	0.10	To be developed	20	0.1
6	Drogue parachute mortar	1	3.92	To be modified	10	4.3
7	Main parachute canopy fabric	1	0.10	To be developed	20	0.1
8	Main parachute lines (split 50-50 with ri	1	0.20	To be developed	20	0.2
9	Main parachute riser (split 50-50 with lir	1	0.20	To be developed	20	0.2
10	Main parachute bridle (riser-back shell)	1	0.1000	To be developed	20	0.1
11	Main parachute deployment bag	1	0.1000	Fully developed	5	0.1
12	Mass reservation for aerodynamic fins and other stabilisation means	1	1.0000	To be developed	20	1.2
13				To be developed	20	0.0
14	Parachute release mechanism (cutters)	0	0.0000	To be modified	10	0.0
15	Heat shield separation mechanism	0	0.0000	To be developed	20	0.0
16	Heat shield instrumentation	0	0.0000	To be developed	20	0.0
17	Bioseal	0	0.0000	To be developed	20	0.0
18	Clevises	0	0.0000	To be developed	20	0.0
19	MLI	0	0.00	Fully developed	5	0.0
20	Miscellaneous	0	0.00	To be developed	20	0.0
-	Click on button below to insert new unit		0.0	To be developed	20	0.0
ELEMENT 1 SUBSYSTEM TOTAL		**12**	**7.6**		**12.8**	**8.6**

VENUS (2)

Unit	Element 1 Unit Name Click on button below to **insert new unit**	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
1	Drogue parachute canopy fabric	1	0.06	To be developed	20	0.1
2	Drogue parachute lines (split 50-50 with	1	0.15	To be developed	20	0.2
3	Drogue parachute riser (split 50-50 with	1	0.15	To be developed	20	0.2
4	Drogue parachute bridle (riser-back she	1	0.10	To be developed	20	0.1
5	Drogue parachute deployment bag	1	0.10	To be developed	20	0.1
6	Drogue parachute mortar	1	2.57	To be developed	20	3.1
7	Main parachute canopy fabric	1	2.58	To be developed	20	3.1
8	Main parachute lines (split 50-50 with ris	1	0.80	To be developed	20	1.0
9	Main parachute riser (split 50-50 with lin	1	0.80	To be developed	20	1.0
10	Main parachute bridle (riser-back shell)	1	0.1000	To be developed	20	0.1
11	Main parachute deployment bag	1	0.2000	To be developed	20	0.2
12	Mass reservation for aerodynamic fins and other stabilisation means	1	1.0000	To be developed	20	1.2
13				To be developed	20	0.0
14	Parachute release mechanism (cutters)	0	0.0000	To be modified	10	0.0
15	Heat shield separation mechanism	0	0.0000	To be developed	20	0.0
16	Heat shield instrumentation	0	0.0000	To be developed	20	0.0
17	Bioseal	0	0.0000	To be developed	20	0.0
18	Clevises	0	0.0000	To be developed	20	0.0
19	MLI	0	0.00	Fully developed	5	0.0
20	Miscellaneous	0	0.00	To be developed	20	0.0
-	Click on button below to insert new unit		0.0	To be developed	20	0.0
ELEMENT 1 SUBSYSTEM TOTAL		**12**	**8.6**		**20.0**	**10.3**

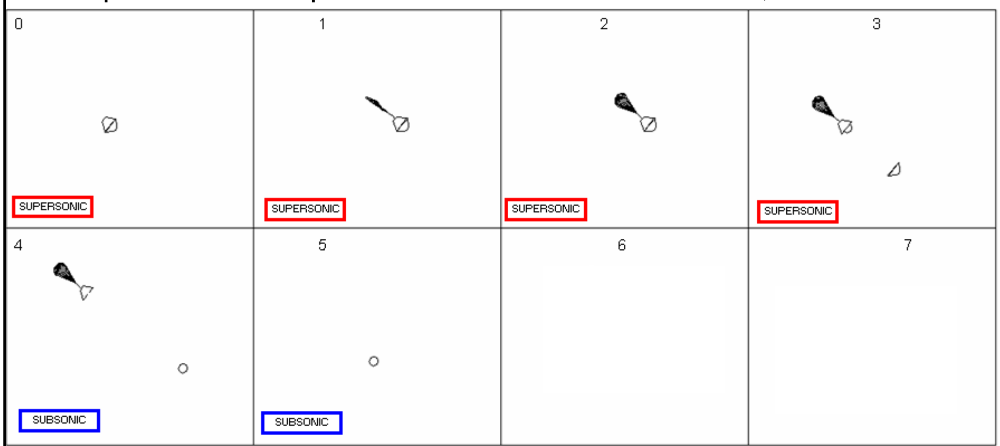
SATURN

SATURN

- Sizing of parachute to separate the front shield
- Free fall of sphere without parachute from the back cover deeper into the Saturn atmosphere.
- Small aerodynamic means to maintain proper attitude are foreseen in the mass budget but no parachute is foreseen for this free fall, since any drag generating device would shorten the free fall an then the penetration dept into Saturn would be less than desirable (1.5 hours is available and it takes 1.5 hours to achieve a depth where the pressure is 100 bar)
- As a NON-BASELINE it might be interesting describe how much a very small parachute would actually “eat up” of the penetration depth. This way, penetration depth (science) is exchanged for greater reliability of the system.)

SATURN

Small parachute to separate heat shield and back cover, then free fall.



INPUT DATA			
Masses			
Front shield	[kg]		116.25
Back cover	[kg]		34.68
Sphere	[kg]		169.95
Total	[kg]		320.88
Dimensions			
Front shield	[m]		1.251
Back cover	[m]		0.99
Sphere	[m]		0.85
Drogue parachute	[m]		1.91
Main parachute	[m]	-	
SUPERsonic drag coefficients			
Whole probe	[-]		1.26
Front shield	[-]		1.26
Back cover	[-]		1.26
Sphere	[-]	-	
Drogue parachute	[-]		1.02
Main parachute	[-]		1.23
SUBsonic drag coefficients			
Whole probe	[-]		0.47
Front shield	[-]		0.47
Back cover	[-]		0.47
Sphere	[-]		0.5
Drogue parachute	[-]		1.12
Main parachute	[-]		1.37

Conclusion: 1.9 m (projected diameter) Conical Ribbon parachute

SATURN

Unit	Element 1 Unit Name Click on button below to **insert new unit**	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
1	Drogue parachute canopy fabric	1	0.40	To be developed	20	0.7
2	Drogue parachute lines (split 50-50 with riser)	1	0.24	To be developed	20	0.5
3	Drogue parachute riser (split 50-50 with lines)	1	0.24	To be developed	20	0.5
4	Drogue parachute bridle (riser-back shell)	1	0.10	To be developed	20	0.1
5	Drogue parachute deployment bag	1	0.10	To be developed	20	0.1
6	Drogue parachute mortar	1	3.92	To be developed	20	4.7
7	Main parachute canopy fabric	1	0.00	To be developed	20	0.0
8	Main parachute lines (split 50-50 with riser)	1	0.00	To be developed	20	0.0
9	Main parachute riser (split 50-50 with lines)	1	0.00	To be developed	20	0.0
10	Main parachute bridle (riser-back shell)	1	0.0000	To be developed	20	0.0
11	Main parachute deployment bag	1	0.0000	Fully developed	5	0.0
12	Reservation for aerodynamic fins and other stabilization means	1	1.0000	To be developed	20	1.2
13		0	0.0000	To be developed	20	0.0
14	Parachute release mechanism (cutters)	0	0.0000	To be modified	10	0.0
15	Heat shield separation mechanism	0	0.0000	To be developed	20	0.0
16	Heat shield instrumentation	0	0.0000	To be developed	20	0.0
17	Bioseal	0	0.0000	To be developed	20	0.0
18	Clevises	0	0.0000	To be developed	20	0.0
19	MLI	0	0.00	Fully developed	5	0.0
20	Miscellaneous	0	0.00	To be developed	20	0.0
-	Click on button below to insert new unit		0.0	To be developed	20	0.0
	ELEMENT 1 SUBSYSTEM TOTAL	**12**	**6.5**		**20.0**	**7.8**

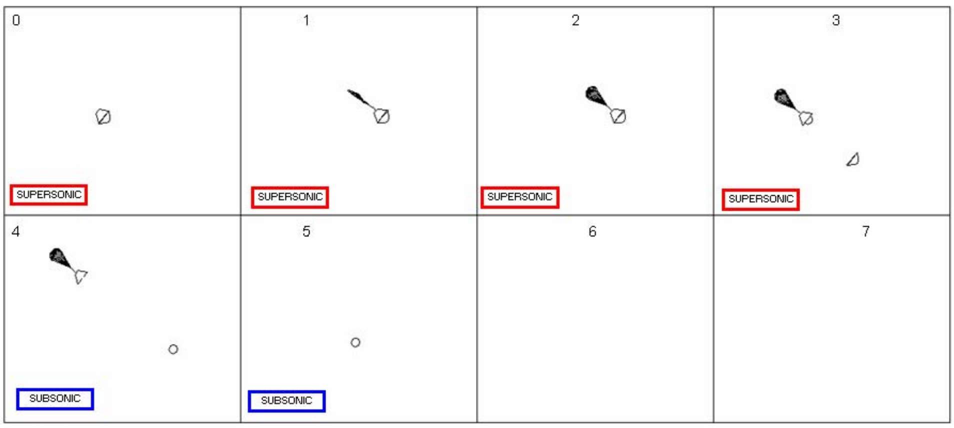
URANUS

URANUS

- Sizing of parachute to separate the front shield
- Back cover is kept and the probe descents on the parachute and back cover till 10 bar would be reached.
- Since this parachute is too large to reach 10 bars in time, the sphere / probe is released and the following options exist:
  - Option 1 second small parachute (not worked out in detail)
  - Option 2 Keep the too large parachute for less time (hence descent only to approximately 4 bar and free fall from there)

URANUS

Small main parachute, to separate front shield (keep back cover) then free fall.



INPUT DATA			
Masses			
Front shield	[kg]		95.67
Back cover	[kg]		36.63
Sphere	[kg]		170.35
Total	[kg]		302.65
Dimensions			
Front shield	[m]		1.251
Back cover	[m]		0.99
Sphere	[m]		0.65
Drogue parachute	[m]		2.18
Main parachute	[m]	-	
SUPERsonic drag coefficients			
Whole probe	[-]		1.26
Front shield	[-]		1.26
Back cover	[-]		1.26
Sphere	[-]	-	
Drogue parachute	[-]		1.02
Main parachute	[-]		1.23
SUBsonic drag coefficients			
Whole probe	[-]		0.47
Front shield	[-]		0.47
Back cover	[-]		0.47
Sphere	[-]		0.5
Drogue parachute	[-]		1.12
Main parachute	[-]		1.37

URANUS

Unit	Element 1 Unit Name Click on button below to **insert new unit**	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
1	Drogue parachute canopy fabric	1	0.80	To be modified	10	0.9
2	Drogue parachute lines (split 50-50 with riser)	1	0.28	To be modified	10	0.3
3	Drogue parachute riser (split 50-50 with lines)	1	0.28	To be developed	20	0.3
4	Drogue parachute bridle (riser-back shell)	1	0.10	To be developed	20	0.1
5	Drogue parachute deployment bag	1	0.10	To be developed	20	0.1
6	Drogue parachute mortar	1	3.92	To be developed	20	4.7
7	Main parachute canopy fabric	1	0.00	To be developed	20	0.0
8	Main parachute lines (split 50-50 with riser)	1	0.00	To be developed	20	0.0
9	Main parachute riser (split 50-50 with lines)	1	0.00	To be developed	20	0.0
10	Main parachute bridle (riser-back shell)	1	0.0000	To be developed	20	0.0
11	Main parachute deployment bag	1	0.0000	Fully developed	5	0.0
12	Reservation for aerodynamic fins and other sta	1	1.0000	To be developed	20	1.2
13		0	0.0000	To be developed	20	0.0
14	Parachute release mechanism (cutters)	0	0.0000	To be modified	10	0.0
15	Heat shield separation mechanism	0	0.0000	To be developed	20	0.0
16	Heat shield instrumentation	0	0.0000	To be developed	20	0.0
17	Bioseal	0	0.0000	To be developed	20	0.0
18	Clevises	0	0.0000	To be developed	20	0.0
19	MLI	0	0.00	Fully developed	5	0.0
20	Miscellaneous	0	0.00	To be developed	20	0.0
-	Click on button below to insert new unit		0.0	To be developed	20	0.0
	ELEMENT 1 SUBSYSTEM TOTAL	**12**	**6.5**		**18.3**	**7.7**

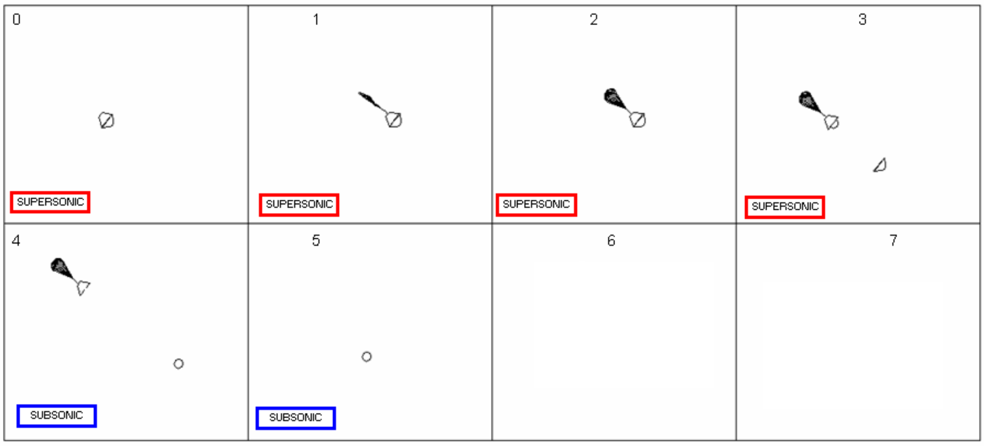
NEPTUNE

NEPTUNE

- Size parachute required to separate the front shield AND to increase the stay at the upper layers of the atmosphere
- The parachute size actually required for the descent through the atmosphere is therefore a certain factor greater. The parachute AREA is multiplied by a factor 1.8
- The back cover is kept and the probe descents on the drogue parachute from 0.1 bar to 10 bar for ~ 60 minutes, and is then jettisoned.
- Perhaps (not the baseline) a stabilising drogue would be required for the free fall.

NEPTUNE

Oversized (1.8 x projected area) drogue parachute to separate front shield (keep back cover) and to maintain longer in the upper atmosphere, then free fall.



INPUT DATA			
Masses			
Front shield	[kg]		95.67
Back cover	[kg]		36.63
Sphere	[kg]		170.35
Total	[kg]		302.65
Dimensions			
Front shield	[m]		1.251
Back cover	[m]		0.99
Sphere	[m]		[illegible]
Drogue parachute	[m]		2.92
Main parachute	[m]	-	
SUPERsonic drag coefficients			
Whole probe	[-]		1.26
Front shield	[-]		1.26
Back cover	[-]		1.26
Sphere	[-]	-	
Drogue parachute	[-]		1.02
Main parachute	[-]		1.23
SUBsonic drag coefficients			
Whole probe	[-]		0.47
Front shield	[-]		0.47
Back cover	[-]		0.47
Sphere	[-]		0.5
Drogue parachute	[-]		1.12
Main parachute	[-]		1.37

NEPTUNE

Unit	Element 1 Unit Name Click on button below to **insert new unit**	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
1	Drogue parachute canopy fabric	1	1.35	To be modified	10	1.5
2	Drogue parachute lines (split 50-50 with riser)	1	0.35	To be modified	10	0.4
3	Drogue parachute riser (split 50-50 with lines)	1	0.35	To be developed	20	0.4
4	Drogue parachute bridle (riser-back shell)	1	0.10	To be developed	20	0.1
5	Drogue parachute deployment bag	1	0.10	To be developed	20	0.1
6	Drogue parachute mortar	1	3.92	To be developed	20	4.7
7	Main parachute canopy fabric	1	0.00	To be developed	20	0.0
8	Main parachute lines (split 50-50 with riser)	1	0.00	To be developed	20	0.0
9	Main parachute riser (split 50-50 with lines)	1	0.00	To be developed	20	0.0
10	Main parachute bridle (riser-back shell)	1	0.0000	To be developed	20	0.0
11	Main parachute deployment bag	1	0.0000	Fully developed	5	0.0
12	Reservation for aerodynamic fins and other sta	1	1.0000	To be developed	20	1.2
13		0	0.0000	To be developed	20	0.0
14	Parachute release mechanism (cutters)	0	0.0000	To be modified	10	0.0
15	Heat shield separation mechanism	0	0.0000	To be developed	20	0.0
16	Heat shield instrumentation	0	0.0000	To be developed	20	0.0
17	Bioseal	0	0.0000	To be developed	20	0.0
18	Clevises	0	0.0000	To be developed	20	0.0
19	MLI	0	0.00	Fully developed	5	0.0
20	Miscellaneous	0	0.00	To be developed	20	0.0
-	Click on button below to insert new unit		0.0	To be developed	20	0.0
	ELEMENT 1 SUBSYSTEM TOTAL	**12**	**7.2**		**17.6**	**8.4**

The payload complement of the entry probe study for Venus and outer planets PEP

Jens Romstedt

Håkan Svedhem

Jonan Larrañaga

Scientific commonalities for (atmospheric) entry probes

- **Structure, dynamics and meteorology**
  - Temperature, pressure, density, electric field
  - Winds
- **Chemical composition** **(abundances & isotopes)**
  - main gases
  - trace gases
  - noble gases
  - aerosols
- **Optical properties and features**
  - Surface and atmosphere

Model P/L approach

- ❑ **Model payload selection is based on scientific themes using payload elements from precursor missions or mission studies**
  - Huygens (mission)
  - Venus Express (mission)
  - Jupiter Entry Probes, *JEP*, (study)
  - Venus Entry Probes, *VEP*, (study)
  - Tandem (gondola), (study)
- ❑ **However, the selected P/L is a generic placeholder only providing the resource requirements to the probe and mission design.**
- ❑ **One fits all (Venus, Saturn, Uranus, Neptune)**
- ❑ **Individual P/L elements can be replaced or modified e.g.**
  - additional sensors can be added or replaced in the environmental sensor package
  - the chemical analyser can be specifically designed to address relevant chemical species of the respective atmosphere.
  - The imager can be tuned onto the desired wavelength range or replaced by a spectrometer, radiometer, nephelometer etc.

P/L resource budgets

- ❑ **Realistic resource budgets:**
  - Mass, size, power consumption, data volume/rate, operating temperature
  - Duty cycle and accommodation (top level)
- ❑ **Mass target is ~10kg**
- ❑ **Uniformly a 20% margin is applied, that corresponds to a "to be developed instrument".**
- ❑ **some resources are reserved for a centralised power supply and DPU**
- ❑ **Uniform operational and non-operational temperatures applied**
  - Operational temperature: +50/-40 °C Non-ops. +60/-50 °C
  - Exception: pressure and temperature sensor outside the probe

Comparison of P/L elements

	Venus Entry Probe Aerobot (study)	TANDEM * gondola (study)	TANDEM * wet lander (study)	Huygens (mission)	Jupiter Entry Probe
GC/MS	0.8	6.0	23	17.3	5.0
Imager	- -	2.0	1	8.1	- -
Imaging spec.	- -	3.0	- -	- -	- -
Aerosol analysis	0.3	- -	- -	6.3	- -
Solar & IR flux	0.2	- -	- -	part of imager	0.3
Atmosph. Struc.	0.05	1.0	1.5	6.3	0.7
Inertial package	0.05	- -	- -	- -	- -
Radar altimeter	1.0	8.0	- -	- -	- -
E-environ.	- -	1.0	- -	in atm. struc	- -
Magnetometer	- -	0.5	- -	- -	- -
Radio science	- -	- -	- -	1.9	0.5
Nephelometer	0.2	- -	- -	- -	0.2
Surface science	- -	- -	1.5	9.0	- -
Speed of sound	- -	- -	- -	- -	1
DPU	0.1	- -	- -	- -	0.5
Structure	0.3	- -	- -	- -	- -
TOTAL	3.0	21.5	27 *Payload Definition Doc., Nov. 2001, Iss.1 rev. 2-1	48.90	8.2

P/L elements PEP

- **Atmospheric Structure**
  - ASI/MET (Tandem) — 1.25 kg
- **Chemical composition and isotopes**
  - MS (Tandem) — 5.00 kg
- **Position and Drift**
  - Doppler Wind (Huygens) — 1.50 kg
- **Camera incl. UV/VIS/IR photometer**
  - VEx & Huygens — 1.50 kg
- **Data, Control and power**
  - this study — 1.00 kg

TOTAL — ***10.25 kg***

incl. 20% margin — *12.30 kg*

ASI/MET (multisensor package)

- density, pressure and temperature profile, atmos. electr., acoustic noise, optical depth
- a variety of sensors that needs access through the hull to the environment
  - short studs, valves or other inlets, windows
- Current design relies on central electronics and DPU
- ASI-ACC: 3-axis accelerometer, atmospheric density
- ASI-TEM: Pt-wire resistance thermometer
- ASI-PPI: Kiel probe, pressure measurements
- Other sensors as required (accounted for in resource budget)

Mass Spectrometer (MS)

- aerosol analyzer, chemical composition of minor atmosphere constituents, noble gas abundances and chemical composition
- quadrupole ion trap mass spectrometer with aerosol inlet and pyrolyser
- mass range 10-600 amu
- resolution $M/\Delta M = 600$
- noble gases concentration ppm range (no concentrator)
- 1 inlet each for atmosphere and aerosol samples
- 10 minutes per analysis

Doppler Wind

- ❑ measures wind induced motion and spin rate
- ❑ precision better than 1 m/s
- ❑ makes use of the probe-carrier S/C radio link
- ❑ 2 USOs, one on probe - one on orbiter
- ❑ account for same mass etc. on orbiter

Camera & photometer

- ❑ surface observation (Venus!), atmospheric phenomena, optical density
- ❑ e.g. Venus Monitoring Camera (VMC) downward looking
  - 1kx1k CCD
  - split into 4 sectors for observation from UV up to IR
  - compression; 12 bit => 8 bit, factor 8 (approach on Huygens)
- ❑ in principle the camera could be replaced by a IR spectrometer providing similar resource budgets
- ❑ UV or VIS or IR photometer upward looking
  - the optical unit and sensor is separated, other subsystems are shared.
  - final selection of wavelength range depends on selected science objectives
  - photo diode

Data, Control and Power

- ❑ **External unit to support payload elements**
- ❑ **SCOC 3 (spacecraft controller on-a-chip)**
  - Current ESA development
  - LEON 3 processor
  - variety of interfaces; SpaceWire, CAN,1553 MIL and other
- ❑ **Custom designed power conditioner is assumed to part of this unit**

P/L resource budget summary

	Mass [kg] w/o margin	X*Y*X [mm]	Power [W]	Data rate [kb/s]	Data vol. [kb]	Duty cycle in 1 h
ASI/MET	1.25	TEM, PPI 205x30Ø (outside) ACC 79x58x68 50x50x50 other	1 sby. 5 ave. 10 max.	0.16 CANbus	5900/h 590 compressed	cont.
MS	5.0	250x200x100	4 sby. 8 ave. 10 max.	0.13 CANbus	4800/h (6 samples) 480 compressed	1/10′
Doppler Wind	1.5	150x150x118	2 sby. 10 ave. 18 max.	-	-	cont.
Camera	1.2	100x100x200	4 sby. 8 ave. 10 max.	1.747 Spacewire	75.5 Mb/h 6290 kbit comp.	1/10′
Photometer	0.3	30x30x80	1 sby. 1 ave. 2 max.	0.00026	16 bit/minute 0.96 kbit/h	cont.
DPU and power conv.	1.0	50x50x100	3	-	-	cont
Σ	10.25		35 ave.	2.037	7360.5 comp.	

P/L accommodation I

	ACOOMMODATION REQUIREMENTS	
ASI/MET	ACC	Close to the center of mass
	TEM	Combined with PPI in one external stud
	PPI	See above
MS	2 INLETS	
Doppler Wind	NONE	
Camera	Downward looking, 15° field of view	
Photometer	Upward looking, 30° field of view	
DPU and power conv.	none	

P/L accommodation II

Some accommodation issues can only be addressed through detailed analysis and design at a later stage

Mass Spectrometer

The inlets need to be opened and closed by a valve.

- the design of the valve is tbd
- the flow of gas and aerosol into and out of the instrument requires detailed analysis

Camera and photometer

Both look through a transparent window (quartz, diamond etc.)

- analysis of optical interferences and transparency for specific wavelength required
- trade-off between scientific objectives, environment and possible instrument design

ASI/MET

Some sensors sit outside the probe e.g. pressure and temperature. Connection to main instrument backend through harness and connector into pressurized housing

- no specific challenges identified

Descent Duration and Profile

Venus

68 – 45km, down to surface (science requirement)
CASE A: descent from ~68 to 92 bar in 60 min
CASE B: descent from 65 to 45 km in 30 min, 30 min free fall
=> ~60 minutes of data collection

Saturn

0.1 to 10 bar (science requirement)
Descent from 1 to 100 bar in 90 min
=> ~90 minutes of data collection

Uranus

0.10 to 100 bar (science requirement)
Descent from 0.06 to 4 bar (drogue chute) in ~26 minutes
Freefall to 100 bar in 60 minutes
=> ~90 minutes of data collection

Neptune

0.10 to 100 bar (science requirement)
Descent from 0.1 to 10 bar (drogue chute) in ~60 minutes
Freefall to 100 bar in 30 minutes
=> ~90 minutes of data collection

END

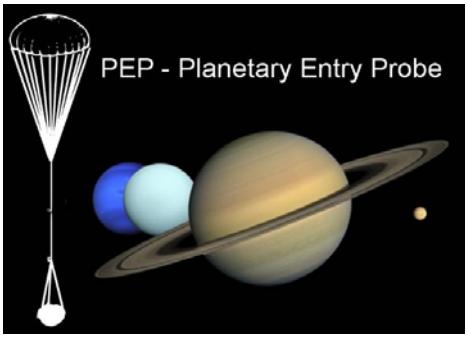
PEP
Planetary Entry Probes

Configuration

IFP

ESTEC, 30th June 2010

Prepared by the PEP/ CDF* Team



(*) ESTEC Concurrent Design Facility

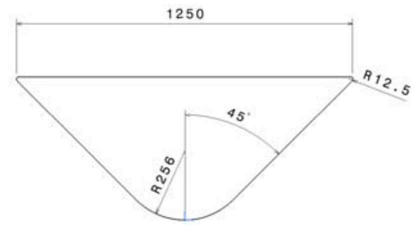
Requirement

- Use of the aerodynamic parameter for shape of the Front shield
- Accommodate subsystem units acc. to their requirement such as pointing direction, field of view
- Mounting interfaces shall allow for easy maintenance, mounting and dismounting
- c.o.g. of the probe shall not be higher then the Front shield base

Design driver 1

- Aerodynamics parameter:
  - Base diameter = 1250 mm
  - Half-cone angle = 45°
  - Nose radius = 256 mm
  - Corner radius = 12.5 mm

    (taken from shoulder ratio = r_c/d_{base} =0.01)

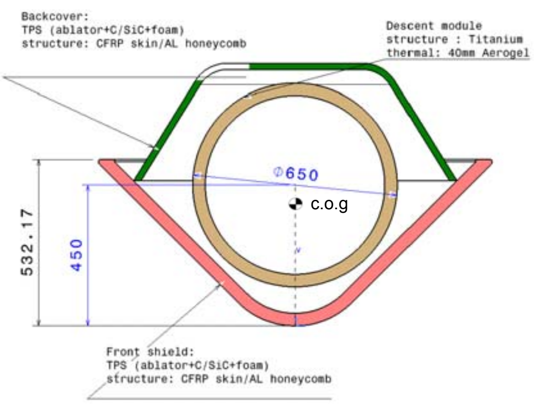


Design driver 2

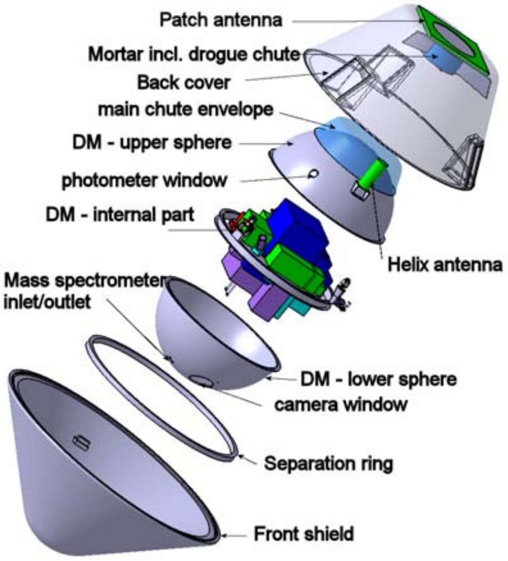
- TPS: Thermal Protection System:

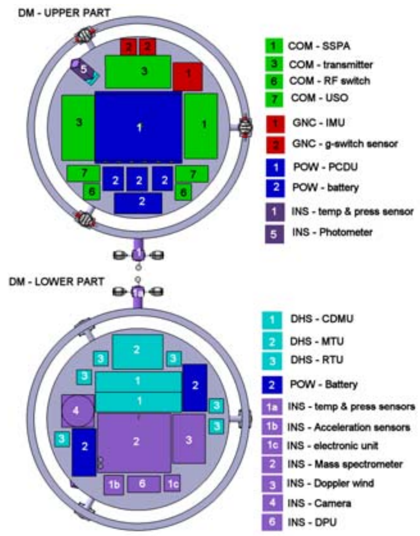
FS-thickness in mm	Venus	Saturn	Uranus	Neptune
Ablator	16.2	36.9	27.9	27.9
C/Sic	2.4	2.4	2.4	2.4
IFI	5	5	5	5
Sandwich	21.8	21.8	21.8	21.8

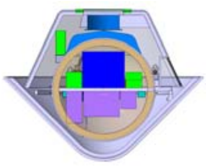
BC-thickness in mm	Venus	Saturn	Uranus	Neptune
Ablator	3.6	9	9	9
C/Sic	2.4	2.4	2.4	2.4
IFI	5	5	10	20
Sandwich	21.2	21.2	21.2	21.2



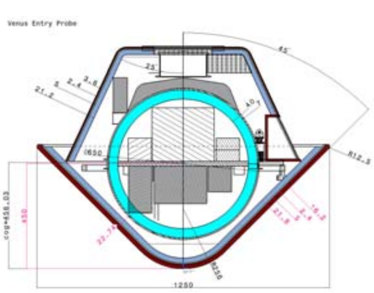
Entry Probe element







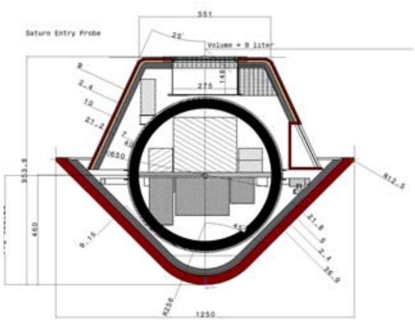
Overall dimension



Mass = 261 kg

CoG = 456.03 mm

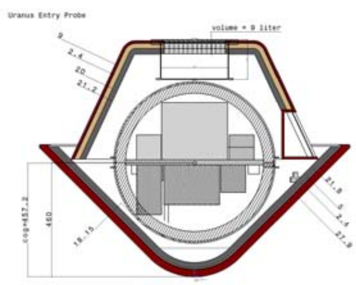
Clearance FS-DM = 22.74mm



Mass = 323.35 kg

CoG = 456.56 mm

Clearance FS-DM = 9.15 mm



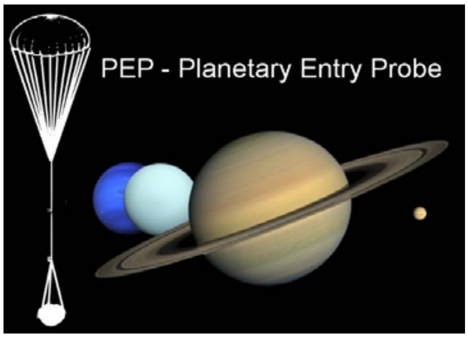
Mass = 310 kg

CoG = 457.2 mm

Clearance FS-DM = 18.15 mm

PEP
Planetary Entry Probes

Structures



IFP

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Prepared by the PEP/ CDF* Team

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Requirements – Venus

- Maximum descent Pressure = 92Bar (assume 100Bar).
- Entry deceleration = 200g to 360g (dependant upon FPA).
- Front shield pressure = 300kPa to 700kPa
- Resulting in load of 360kN to 840kN
- Use JEP as starting point:
  - Diameter of Descent Module (DM) = 600mm, 40Bar external pressure, t=2mm
  - Dia DM = 650mm, 100Bar External Pressure, t=4mm
  - Calculation of shell thickness and hence mass did NOT include any safety/qualification factors and were under valued (JEP DM mass = 23kg)

Structure breakdown

- Descent Module
  - Material – Titanium Alloy
  - Diameter = 650mm
  - Shell thickness = 6.81mm (assumed 7mm in Catia)
- Interfaces/stiffeners
  - Material – Titanium Alloy
- Front Shield structure
  - Composite panel assumed, 20mm thick
  - Very High Density core to carry shear loads.
  - DM Connection Ring mounts at 3 separation points – V.High loads
  - DM connection ring would be better interfacing to a monolithic ring attached to Composite front shield.
- Back Cover structure
  - Same approach as for front shell.
- Equipment panel
  - Composite panel assumed
  - Medium Density core assumed
  - Diameter 630mm

Calculation of mass – Descent Module (1)

- Based on uniform pressure applied to a spherical shell.
- From Roark, minimum external pressure, *q'* is given by:

$$q' = \frac{2Et^2}{r^2\sqrt{3(1-\upsilon^2)}}$$ For an ideal case

$$q' = \frac{0.365Et^2}{r^2}$$ Probable actual minimum *q'*

- Knock down factor modified from 0.365 to 0.5 after discussion, to reduce mass by 15kg

Reference Roark's formulas for Stress and Strain, 7th Edition, page 737, Table 15.2, number 22.

Calculation of mass – Descent Module (2)

- Equation is rewritten to give t, in terms of *q'*, R and E.
- *q'* has qualification and buckling factors applied according to ECSS-E-ST-32-10C Rev.1 (2 and 1.25 respectively).
- For Venus requirement of 100Bar external pressure, this becomes 250Bar
- Giving shell thickness t= 6.81mm (4.35mm for ideal case)
- Using the area from the Catia model the mass of the Descent module shell using a Titanium Alloy is 37.42kg

Calculation of mass – Front Shield

- 20mm thick composite assumed
- Very High Density core (197kg/m^3) used in first estimate to transfer high Shear loads
- 600kN shear load to be distributed
- Assuming insert capability of 10kN, 60 inserts would be required
- For 3 hold down positions, approximately 100kN capability required!
- Conservatism required for mass estimate
- Coupon tests required to confirm insert shear load capability
- Inserts limited by diameter of Descent module
- May need to use monolithic structure
- Mass calculated at 7.5kg
- Back Cover based on this approach for simplicity

Mass breakdown

Item	Nr.	Item mass [kg]	M_struct [kg]	Material	Maturity	Unit Margin [%]	Unit mass with margin [kg]
FS - cold structure	1	7.495	7.50	sandwich	New dev.	20	8.99
FS - IF bracket	3	1.323	1.32	TITANIUM	New dev.	20	1.59
BS - cold structure	1	4.047	4.05	sandwich	New dev.	20	4.86
BS - DM - IF - bracket	3	1.323	1.32	TITANIUM	New dev.	20	1.59
BS - ribs (mortar support)	3	1.000	1.00	TITANIUM	New dev.	20	1.20
DM - upper shell	1	18.711	18.71	TITANIUM	New dev.	20	22.45
DM - lower shell	1	18.711	18.71	TITANIUM	New dev.	20	22.45
DM - connection ring	1	5.665	5.66	TITANIUM	New dev.	20	6.80
DM - mounting platform	1	1.034	1.03	sandwich	New dev.	20	1.24
DM - main parachute support structure	3	1.679	1.68	TITANIUM	New dev.	20	2.01
miscellaneous	1	5.000	5.00	TITANIUM	New dev.	20	6.00
11			76.64			20.0	91.97

Requirements – Saturn, Neptune and Uranus

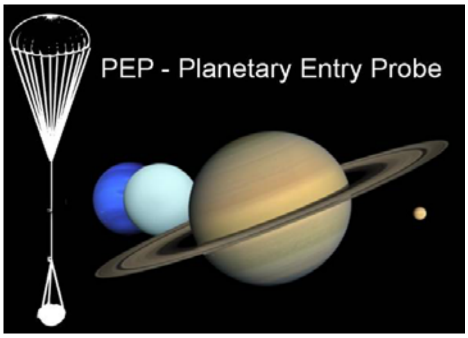
- Requirements in terms of structure have not changed from Venus
- Dimensions and hence mass of components remains unchanged from Venus

Conclusions

- Mass budget needs to remain conservative
- Detailed FEA required to analyse stress concentrations around instrument holes
- Additional stiffeners may be required around instrument holes, increasing mass
- Aeroshell support structure needs detailed FEA to confirm if composite panel can be used.
- Structure is highly loaded at all times.
- Pressurising DM by 10 to 20Bar has minimal effect on mass of structure

PEP
Planetary Entry Probes

Mechanisms



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ESTEC, 30th June 2010

Prepared by the PEP/ CDF* Team

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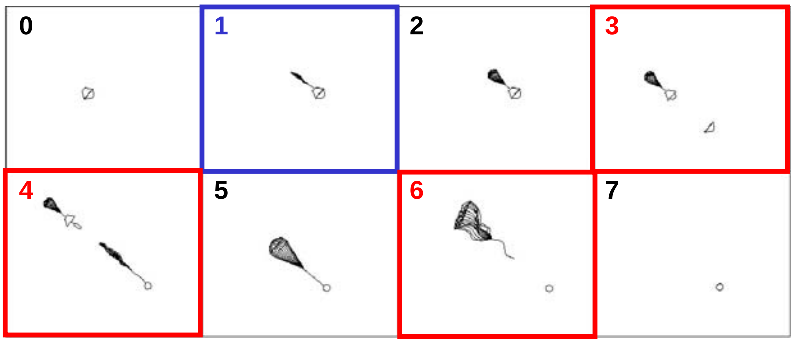
Contents

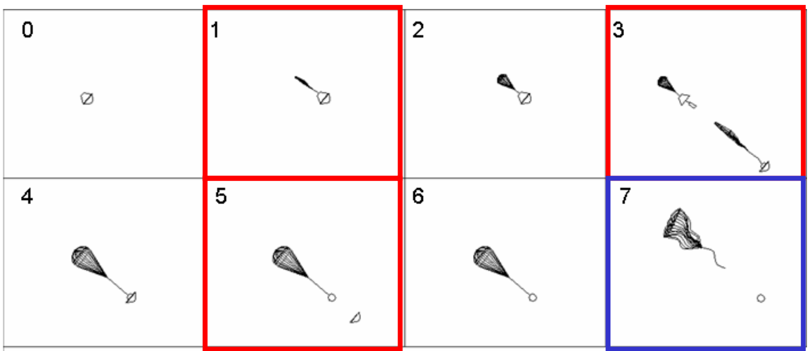
- VEP separation sequence
    - Alternative sequence
- Outer Planets separation sequence
- Why use Mechanisms from Huygens Mission as baseline?
- Mechanisms required for VEP
- Mechanisms required for Outer Planets Probes
- Mass budgets
    - VEP
    - Outer Planets Probes
- Power budgets
    - VEP
    - Outer Planets Probes

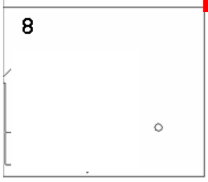
VEP EDLS Separation Sequences



Event number	Event	Nr. Of pyros
0	End of entry interface	0
1	Drogue mortar activation	1
2	Completely inflated drogue parachute	0
3	Activation of heat shield separation pyro bolts	3
4a	Activation of Back Cover separation pyro bolts	3
4b	Extraction of the main parachute	0
5	Fully inflated main parachute; start of measurements	0
6	jettison main chute	3
7	Free fall to the surface	0
		10

VEP Alternative EDLS Separation Sequences:

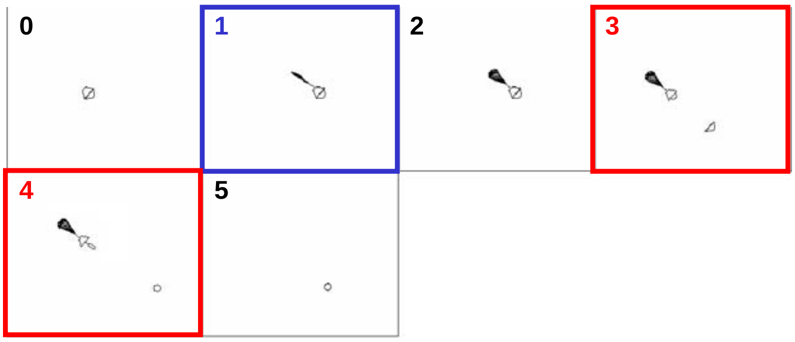




Alternative sequence has No effect on Mechanism design only timing of pyro actuation.

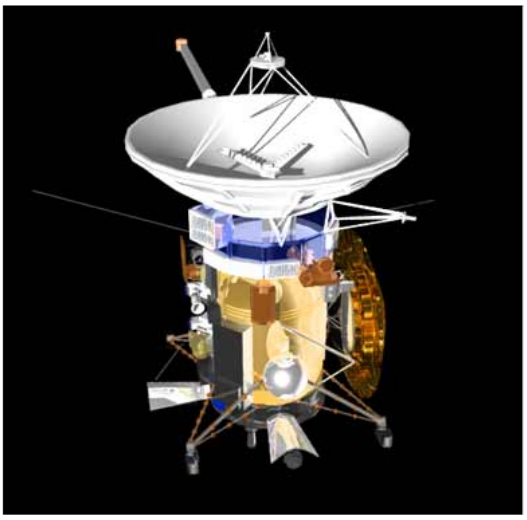
Event number	Event	Nr. of pyros
0	End of entry interface	0
1	Drogue mortar activation	1
2	Completely inflated droque parachute	0
3	Activation of Back Cover separation pyro bolts	3
		1
4	Fully inflated main parachute	0
5	Activation of heat shield separation pyro bolts	3
		0
6	Start of measurements	0
7	Option: jettison main chute	3
		0
		8 / 11

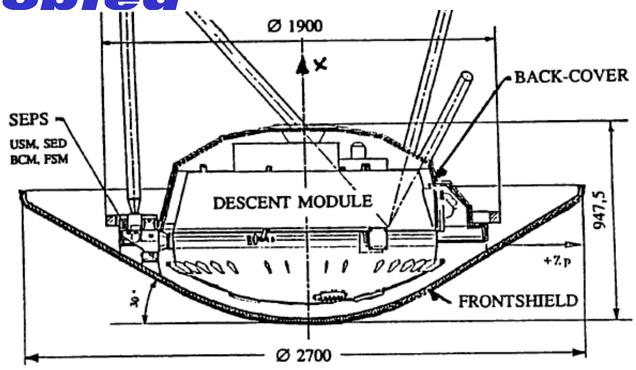
Outer Planets EDLS Separation Sequences



Event number	Event	Nr. Of pyros
0	End of entry interface	0
1	Drogue mortar activation	1
2	Completely inflated drogue parachute	0
3a	Activation of front shield umbilical cable cutters	2
3b	Activation of front shield separation pyro bolts	3
4a	Activation of Back Cover umbilical cable cutters	2
4b	Activation of Back Cover separation pyro bolts	3
5	Free fall to the surface	0
Total		11

Why Huygens Mechanisms are adopted





Using Huygens mechanisms offers:

- Good margin on preload of hold down and release mechanisms (due to larger Huygens mass)
- Guarantee that spring motorization forces are adequate (due to larger Huygens mass)
- Proven Flight Heritage

Separation Mechanisms (Huygens)

Separation Subsystem (SEPS) consist of:
- Spin-up and Ejection Device (SED)
  - Structural fixation to main S/C
  - Deploy probe with required force/direction using springs
  - Separation using pyro-nut
- Back Cover Separation Mech (BCM)
  - Structural fixation to probe
  - Separation using bolt cutters
- Frontshield Separation Mech (FSM)
  - Structural fixation to probe
  - Reduce heat flux to probe
  - Release via spring & bolt cutter

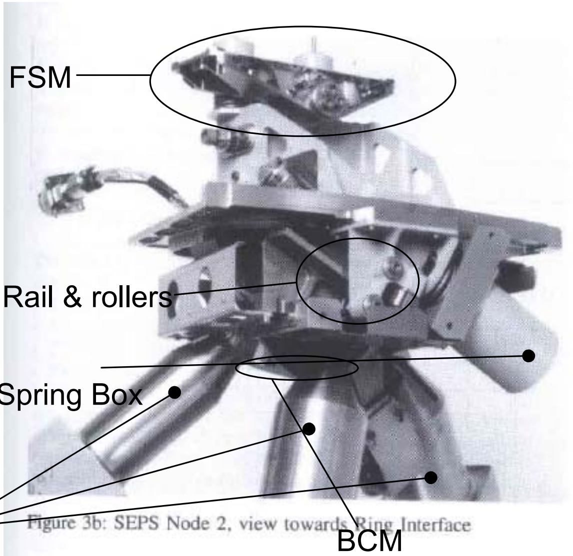
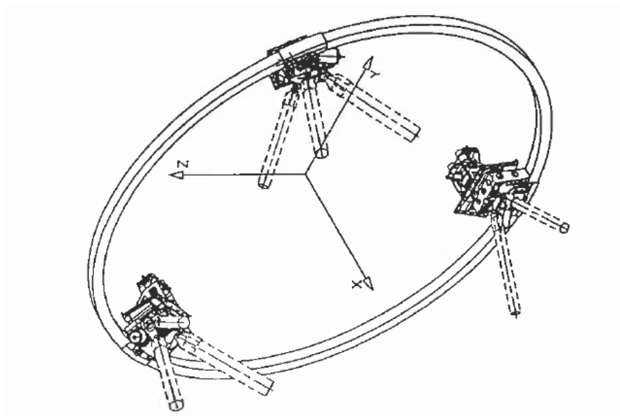
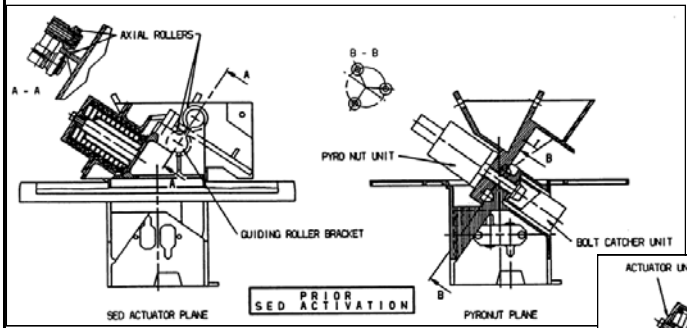


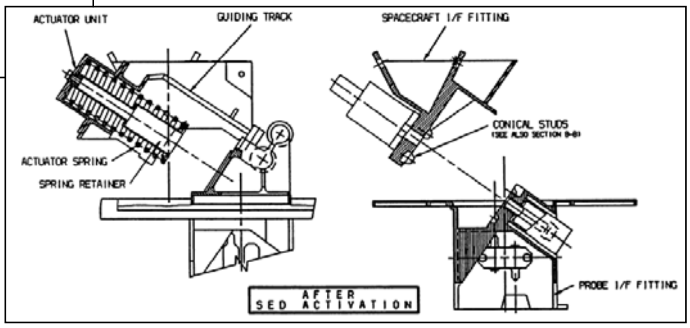
Figure 3b: SEPS Node 2, view towards Ring Interface

Separation Nodes (Huygens)



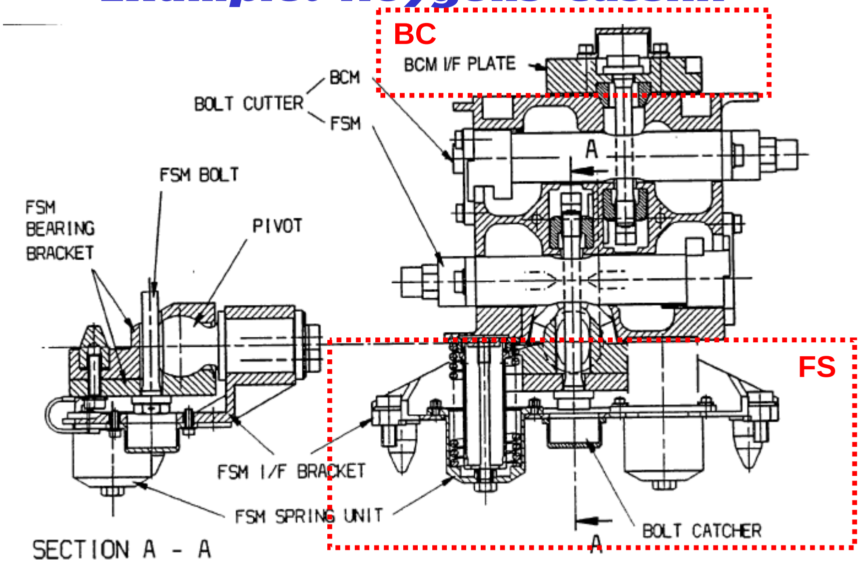
Spin-up and Ejection Device (SED)
Example: Huygens-Cassini





- Reliability of probe separation: ≥ 0.996
- axial velocity: v_x = -0.3 m/s, +25%/-10%
- spin: $5 \leq \omega_x \leq 10$ rpm
- lateral velocity: $|v_t| < 25$ mm/s (3σ)

Back Cover (BCM) and Front Shield (FSM) Separation Mechanisms
Example: Huygens-Cassini

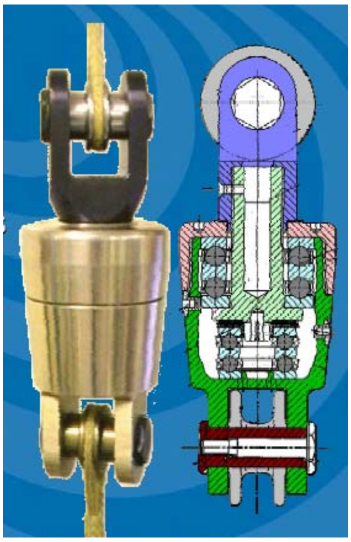


Parachute Jettison Mechanism (PJM) and Main Parachute Swivel (MPS)

Example: Huygens-Cassini

PJM:
- 3 mechs, one per each bridle leg
- fully redundant rod cutters

MPS:
- Redundant main thrust bearings
- Redundant preload bearings
- MoS_2 Coating on races
- TiC and MoS_2 coating on balls



VEP Mass budget and list of equipments

Resizing of Huygens-Cassini mechanisms

Taking into account:

- HUY mass 325 kg > VEP mass 235 kg
- HUY Probe Ø 1.9 m (FS Ø 2.7 m) > VEP FS Ø 1.25 m

Element 1	-			MASS [kg]			
Unit	Unit Name Click on button above to **insert new unit**	Part of custom subsystem	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
1	Probe, incl. SED, FSM & BC I/F		3	1.3	To be modified	10	4.3
2	Front shield separation		3	0.8	To be modified	10	2.6
3	Back cover separation		3	0.3	To be modified	10	1.1
4	Parachute Jettison mech'sm		3	0.3	To be modified	10	0.8
5	Cable cutter		4	0.3	To be modified	10	1.1
6	Main parachute swivel		1	0.5	To be modified	10	0.5
-	Click on button below to insert new unit						
SUBSYSTEM TOTAL			6	9.5		10.0	10.4

N.B: Total mass of the Separation Subsystem is 17 kg.
A mass of 10 kg remains on the Orbiter after separation.

SEP Mass budget and list of equipments

Element 1	-			MASS [kg]			
Unit	Unit Name Click on button above to **insert new unit**	Part of custom subsystem	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
1	Probe, incl. SED, FSM & BC I/F		3	1.3	To be modified	10	4.3
2	Front shield separation		3	0.8	To be modified	10	2.6
3	Back cover separation		3	0.3	To be modified	10	1.1
4	Cable cutter		4	0.3	To be modified	10	1.1
-	Click on button below to insert new unit						
SUBSYSTEM TOTAL			4	8.3		10.0	9.1

UEP and NEP Mass budget and list of equipments

Element 1	-			MASS [kg]		
Unit	Unit Name Click on button above to **insert new unit**	Part of custom subsystem	Quantity	Mass per quantity excl. margin	Maturity Level	Margin
1	Probe, incl. SED, FSM & BC I/F		3	1.3	To be modified	10
2	Front shield separation		3	0.8	To be modified	10
3	Back cover separation		3	0.3	To be modified	10
4	Cable cutters		4	0.3	To be modified	10
5	Drogue Parachute Swivel		1	0.5	To be modified	10
-	Click on button below to insert new unit					
SUBSYSTEM TOTAL			5	8.7		10.0

VEP - Power budget

Mechanism	Nr. Of pyros	Nr. of ESI (2 per Pyro)
Drogue Deployment	1	2
Front shield Separation	5	10
Back cover Separation	5	10
Main Parachute Jettison	3	6
Total	14	28

Per ESI (European Standard Initiator) Unit (2x Pyro):

E=0.15 J total energy
T = 10 ms max peak duration
P= E/t= 15W average power
I = 5 A initiation current

N.B: Separation from the S/C: firing of 3 pyros to be included in Orbiter power budget

Outer Planets - Power budget

Mechanism	Nr. Of pyros	Nr. of ESI (2 per Pyro)
Drogue Deployment	1	2
Front shield Separation	5	10
Back cover Separation	5	10
Total	11	22

Per ESI (European Standard Initiator) Unit (2x Pyro):

E=0.15 J total energy
T = 10 ms max peak duration
P= E/t= 15W average power
I = 5 A initiation current

N.B: Separation from the S/C: firing of 3 pyros to be included in Orbiter power budget

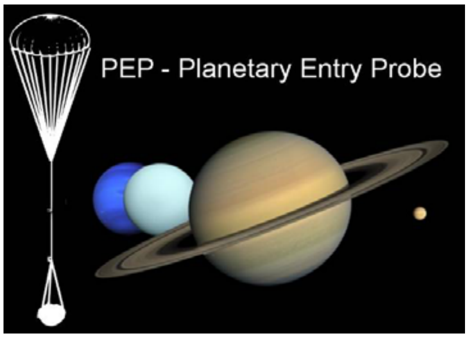
PEP
Planetary Entry Probes

GNC

IFP

ESTEC, 30th June 2010

Prepared by the PEP/ CDF* Team



(*) ESTEC Concurrent Design Facility

PEP GNC Results

- Requirements & design drivers
  - Passive attitude control (spin-stabilized Entry, no powered descent)
  - Limited GNC role: triggering events, trajectory reconstruction
  - SED performance & coasting phase duration
- Baseline Design
  - GNC equipment list and trade-offs
- Simulations
  - Probe ejection accuracy (3 DoF)
  - Coasting disturbance analysis (6 DoF)

GNC requirements

- Main Mission Requirements:
  - Detect EIP
  - Provide accurate initialization & triggering of EDS sequence
- Science & Post-flight analysis (Huygens):
  - provided by 2 radial ACC -> (insensitive to sign of spin rate !)
  - extensive a posteriori work to perform the attitude reconstruction. *c.f. "Huygens attitude reconstruction based on flight engineering parameters"*)
- Assumptions
  - Spin Rate measurement is required
  - Attitude a posteriori reconstruction is required

PEP GNC design (1)

- Trade-offs :
  - Radial Accelerometers (Huygens like)
    - (+) radial accelerometers = mass effective (~80 g per accelero)
    - (-) only 1-axis angular rate sensing (spin axis)
    - (-) spin rate sign is unknown
  - IMU (JEP-like)
    - (+) 3-axis attitude and angular rate knowledge during all entry & descent
    - (-) mass : 750g for LN200S
    - (-) power : 12W for LN200S (TBD for European IMU)
- Baseline GNC equipment: IMU
  - LN200-S incl. 3 gyroscopes (1°/hr) & 3 acceleros (300µg, range > 70g). TRL 7.
  - Alternative : European IMU (based on SEA MEMS gyroscope) (10°/hr)– feasibility study on-going (TRP). TRL 3-4.

PEP GNC design (2)

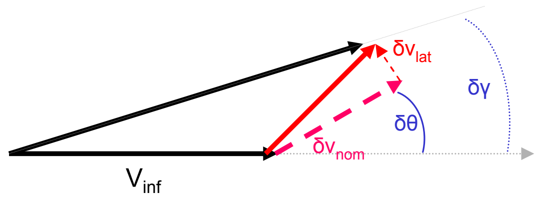
- Mission Critical Tasks
  - Wake-up probe at EIP – 3 hours (IMU calibration strategy)
  - Enable triggering events (EIP, deployment, release, etc…)
- Redundancy Approach
  - 3 Timer Units (= 100mW per timer hot redundancy) for wake up (=Huygens)
  - 2 g-switch to backup the timer units (2*50g, no power) for EIP detection (=Huygens)
  - 1 IMU (Huygens : 3+2 acceleros + 4 g-switches in hot / majority voting) + internal redundancy (1 additional accelero)
- Option : atmospheric sensor for parachute deployment
  - Direct measurement of Mach / Pdyn instead of indirect based on acceleration.
  - No such sensor currently exists for planetary applications.

3D Simulations – FPA accuracy @ EIP

- Drivers for FPA accuracy @ EIP :
  - Initial Navigation Error
  - FPA initial error :
    - Initial Attitude Error
    - Separation Accuracy
  - Coasting phase duration
  - Gravity Model accuracy (esp. around giant planets with numerous satellites)

3 DoF Simulation – Entry accuracy

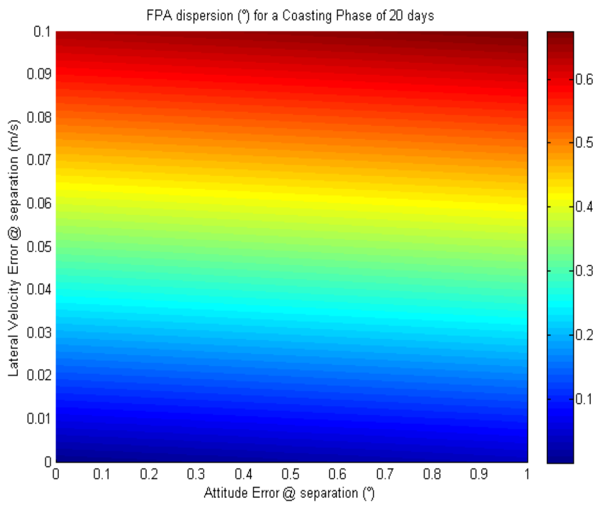
- FPA
  - Initial Navigation Error
    - $\delta r0 = [0, 1]$ km
    - $\delta v0 = [0, 1]$ cm/s
  - Nominal Separation Velocity
    - $\delta V_{nom} = 30$ cm/s
  - Initial FPA Error
    - Attitude error : $\delta\theta = [0, 1$ deg$]$ (nominal: 0.3°, 1σ)
    - Separation Velocity Error $\delta V_{lat} = [0, 10$ cm/s$]$ (nominal: 1 cm/s, 1σ)



$$\delta\gamma \approx \frac{\delta V_{nom} \cdot \delta\theta + \delta V_{lat}}{V_{\inf}}$$

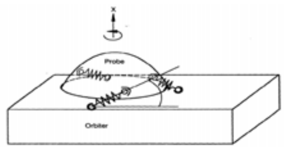
Matlab 3 DoF simulations

- Results of mini Monte Carlo campaign FPA error @ EIP SED & attitude errors
  - ~0.1° (3 σ, nominal) for 20 d (SED impact > attitude)
- Worst case NAV error :
  - 0.41° (3 σ) for 20 d
  - 0.21° (3 σ) for 10 d



6 DoF Simulation (ASTOS) Assumptions

- **SEPARATION MECANISM:** same SED and errors as Cassini-Huygens.



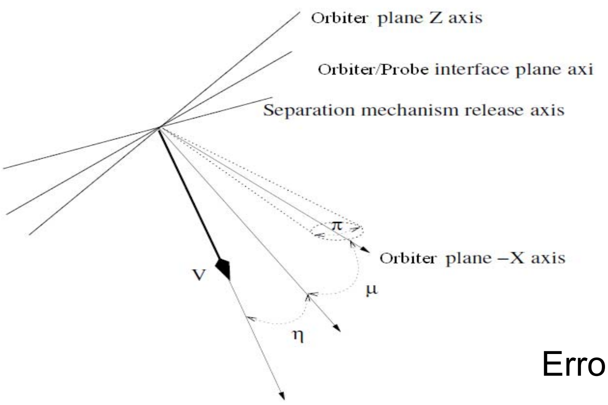
- **PROBE FEATURES:** Venus MCI from Configuration Epoch, E-20d state vector provided by ESOC.

- **TRAJECTORY:** First phase of the trajectory is sun influence until the probe reach the sphere of influence of Venus (**6x10⁴ km**).

- **SOLAR RADIATION PRESSURE:** main disturbance.

$$F_{SR} = -p_{SR} c_R A_\odot r_{\oplus\odot}$$

SED Errors 1

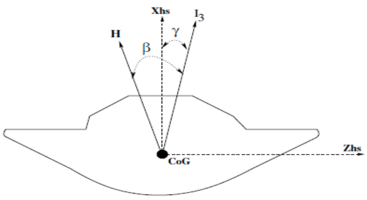


Errors on the direction of the velocity:

Error contribution	Direction	Magnitude
Compound spacecraft state vector accuracy at separation time	$\pi = 1.9deg$	$\Delta V_\pi = 0.001m/s$
Interface plane between Cassini and Huygens	$\eta = 0.12 + 2.0deg$	$\Delta V_\eta = 0.012m/s$
Separation mechanism misalignment	$\mu = 0.05deg$	$\Delta V_\mu = 0.032m/s$

SED Errors 2

Bore-sight error angle definition:

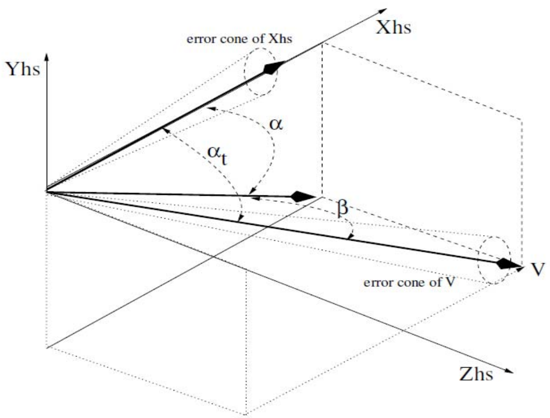


Attitude Errors (inaccuracy on bore-sight direction):

Error contribution	Magnitude
misalignment of the I_3 principal axis of inertia respect to the boresight of the probe	$\gamma = 0.5deg$
misalignment of the I_3 principal axis of inertia respect to the direction of the angular momentum **H**	$\beta = 9deg$
misalignment of the boresight of the probe respect to the local horizon at entry gate and at drag interface	$\tau = 0.5deg$

Main 6 DoF Simulation Results

Angle of attack – side slip angle definition:



	Worst case ([º])
Angle of Attack	[-4, 3]
Side Slip Angle	[-3, 4]
Total AoA	[-5, 5]

Assumptions (ASTOS Simulator Data)

Epoch
11 June 2020

Mass [Kg]
238.89

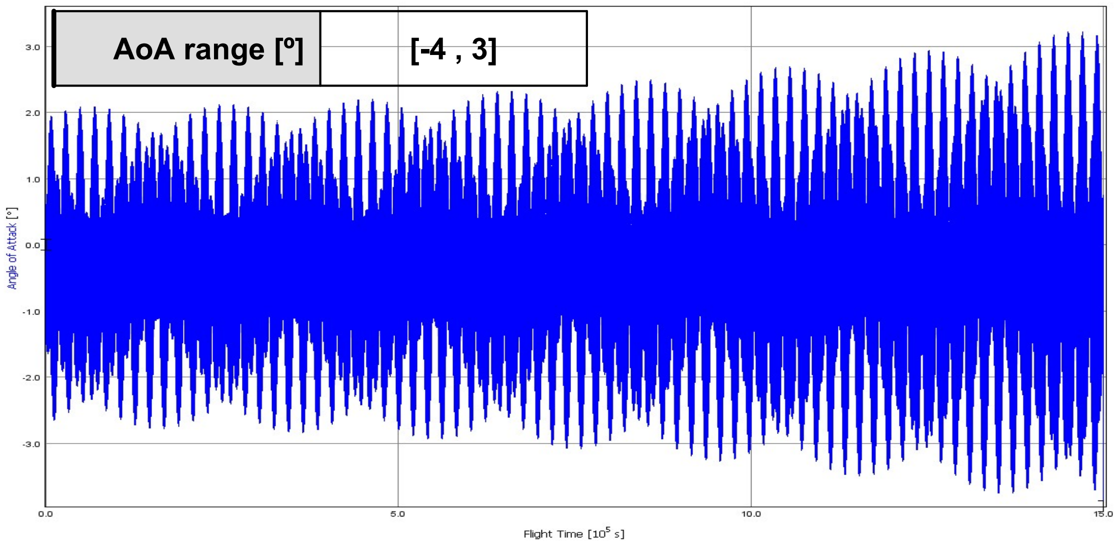
Inicial Angular Velocity [º/s]	
Angle rate	Probe
ωx	44.3912
ωy	1.22733
ωz	.009375

Initial State Vector	
EME2000 centred on Venus	
X [km]	1303291.511
Y [km]	-7145019.309
Z [km]	-8385421.011
Vx [km/s]	-0.756421728
Vy [km/s]	4.114826944
Vz [km/s]	4.834309573

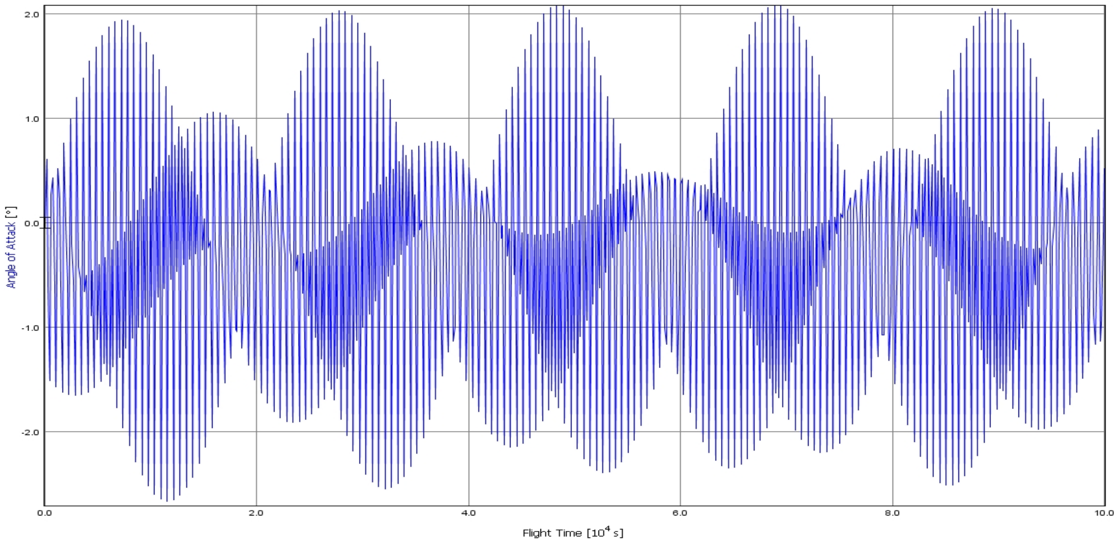
Moment of Inertia w.r.t. the ASTOS axes [change x and z from original]			
[kgxm2]	X	Y	Z
X	28.3324	0.0239	-0.0326
Y	0.0239	23.1587	0.037
Z	-0.0326	0.037	22.9077

AoA evolution

AoA range [º]	[-4 , 3]



AoA Detail



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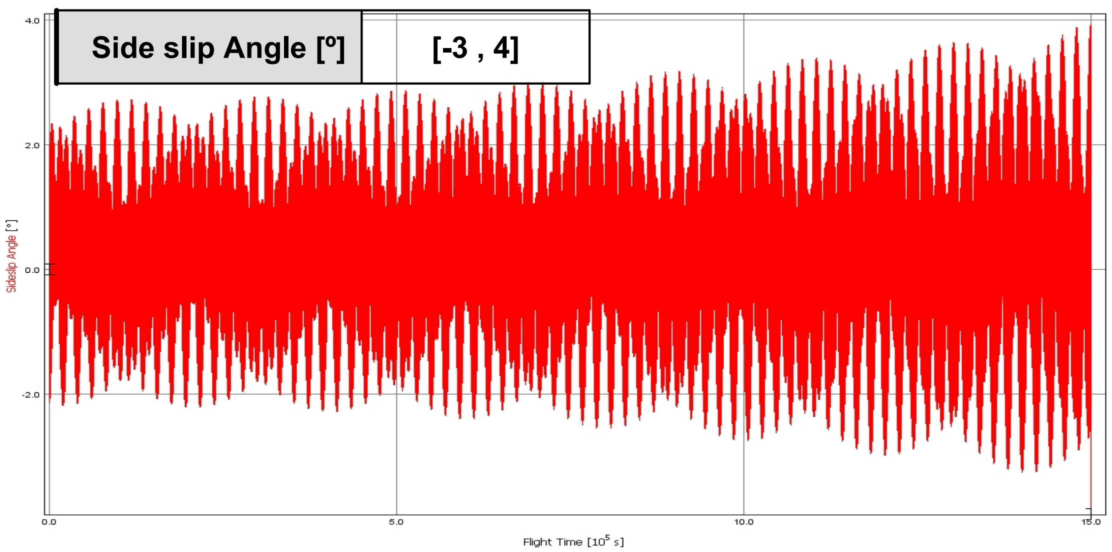
Slide Slip Angle Evolution



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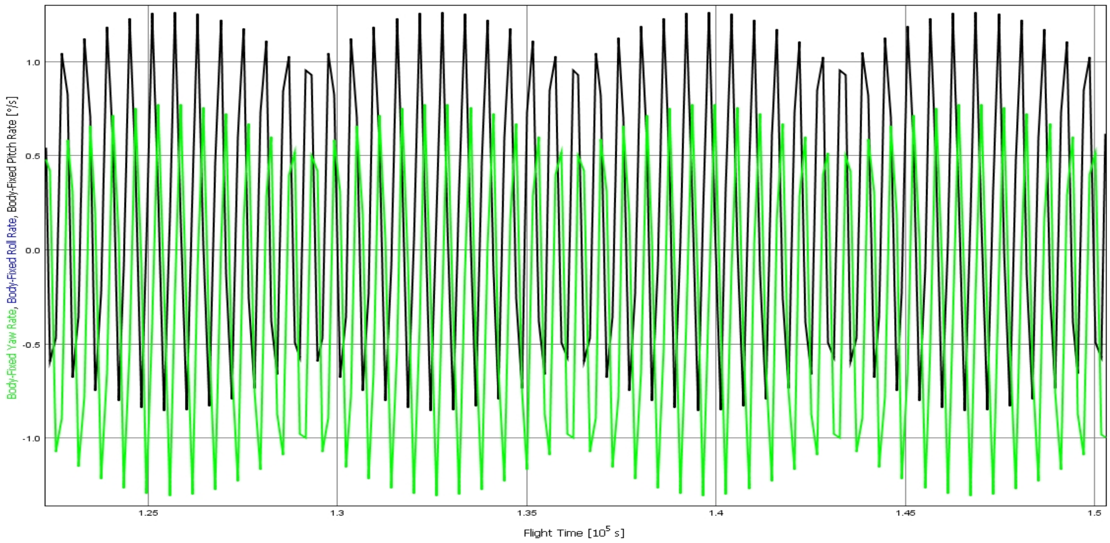
Body Omegas (Pitch-Yaw) Detail



esa

Concurrent Design Facility

Outer planets

- Same GNC design
- Expected results similar to JEP's
- 6 DoF Simulator ready

PEP GNC Model

Element 1	-			MASS [kg]			
Unit	Unit Name Click on button above to **insert new unit**	Part of custom subsystem	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
1	Inertial Measurement Unit		1	0.750	To be modified	10	0.8
2	g-switch sensors		2	0.050	Fully developed	5	0.1
-	Click on button below to insert new unit						
SUBSYSTEM TOTAL			**2**	**0.9**		**9.4**	**0.9**

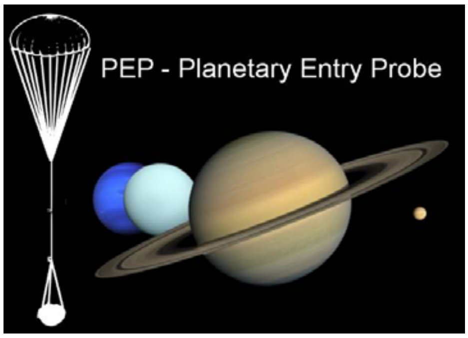
PEP
Planetary Entry Probes

Power

IFP

ESTEC, 30th June 2010

Prepared by the PEP/ CDF* Team



(*) ESTEC Concurrent Design Facility

Venus

Requirements and Design Drivers. Venus

- Atmospheric entry probe with:
  - Less than 1 year interplanetary transfer, attached to carrier craft.
  - 20 days post-separation cruise, with power required for timers and for brief periodic wake-up periods.
  - 1 hour entry/descent phase, with power required by platform and payload.

Electrical Power Source Selection

× Solar Power:
  - Fundamentally not suitable for an entry probe.

× Radioisotope Power Source (e.g. RTG)
  - RPS have much greater energy density than chemical batteries over a multi-year mission, but their energy/mass ratio is less impressive over 20 days. They have very low power density compared to batteries, and in this application they must be sized according to (peak) power demand, rather than total energy need.
  - For instance: USA MMRTG: 125W, 44 kg. ASRG: 150W, 20 kg. The cost of radioisotope systems and their associated procedures means that they are generally only considered when they are mission enabling (i.e. there is no reasonable alternative).

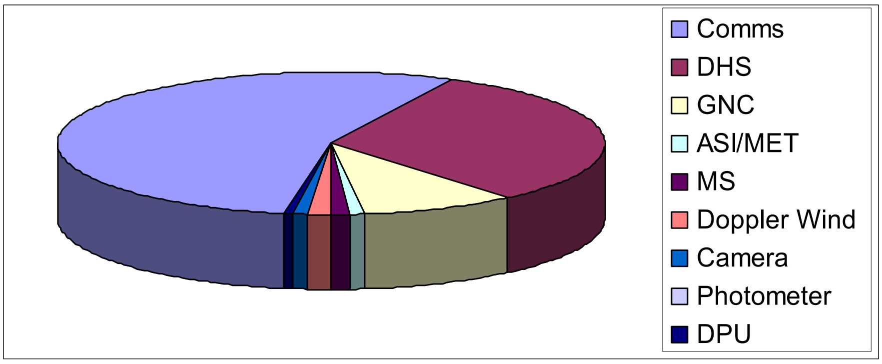
× Secondary batteries
  - Energy density of newer Li-Ion technology is now closer to that of primary batteries, but requires BCR electronics to charge after interplanetary phase. May be considered in longer missions, where the performance of primary batteries is compromised by self-discharge (see later).

✓ Primary batteries
  - Best solution for this application. Selection of the type depends on the details of the power and energy requirements…………

Power & Energy Budget. Venus

		Comms	DHS	GNC	ASI/MET	MS	Doppler Wind	Camera	Photometer	DPU	Harness (excl. PSS)	TOTAL CONSUMPTION	TOTAL CONSUMPTION INC. PCDU	Power Provided By
		linked	linked	linked	linked	linked	linked	linked	linked	linked				
	Ppeak	315 W	0 W	15 W	10 W	10 W	18 W	10 W	2 W	3 W	8 W	391 W		
Coast Mode	Pon	45 W	19.672 W	15 W	0 W	0 W	0 W	0 W	0 W	0 W	2 W	81 W	86 W	Battery
	Pstdby	0 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	
	Duty Cycle	0.22 %	1.97 %	0.63 %	0 %	0 %	0 %	0 %	0 %	0 %				
	Paverage	0.1 W	0.4 W	0.1 W	0 W	0 W	0 W	0 W	0 W	0 W	0.01 W	0.6 W	0.6 W	
Tref 28800 min	Total Wh	47 Wh	186 Wh	45 Wh	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	6 Wh	284 Wh	299 Wh	
Entry Mode	Pon	15 W	19 W	15 W	0 W	0 W	0 W	0 W	0 W	0 W	1 W	50 W	53 W	Battery
	Pstdby	0 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	0 W	
	Duty Cycle	0 %	100 %	100 %	0 %	0 %	0 %	0 %	0 %	0 %				
	Paverage	0 W	19 W	15 W	0 W	0 W	0 W	0 W	0 W	0 W	0.69 W	35 W	37 W	
Tref 2 min	Total Wh	0.00 Wh	0.6 Wh	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	1 Wh	1 Wh	
Descent Mode	Pon	315 W	23 W	15 W	5 W	8 W	10 W	8 W	1 W	3 W	8 W	395 W	416 W	Battery
	Pstdby	0 W	0 W	0 W	1 W	4 W	2 W	4 W	1 W	1 W	0 W	13 W	13 W	
	Duty Cycle	100 %	100 %	100 %	100 %	100 %	100 %	10 %	0.0 %	100 %				
	Paverage	315 W	23 W	15 W	5 W	8 W	10 W	4 W	1 W	3 W	7.68 W	392 W	412 W	
Tref 60 min	Total Wh	315 Wh	23 Wh	15 Wh	5 Wh	8 Wh	10 Wh	4 Wh	1 Wh	3 Wh	8 Wh	392 Wh	412 Wh	
Wh TOTALS:		362 Wh	210 Wh	60 Wh	5 Wh	8 Wh	10 Wh	4 Wh	1 Wh	3 Wh	13 Wh	677 Wh	712 Wh	

Energy Budget Breakdown by Sub-System



- ~62% (130Wh) of the DHS energy is for the timer units (272mW).
- Timers account for only ~18% of total energy budget.
- ~82% of the energy is required at high power (>300W). This drives the choice of primary cell type.
- JEP study proposed dedicated low-current/high capacity cells for the timers. This approach is not appropriate here. However, the JEP selection of $LiSO_2$ high-current spiral electrode cells for the PCDU supply can be re-applied for PEP.

Characteristics of SAFT LO26SHX

Electrical characteristics

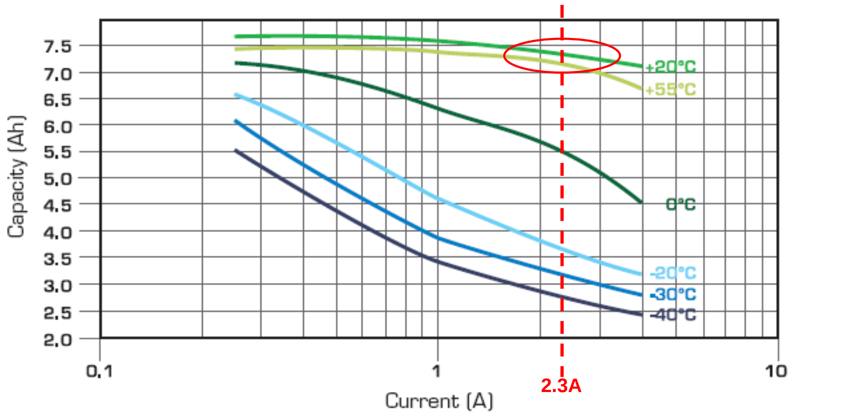
(typical values for cells stored for one year or less)		
Nominal capacity *(at 1 A + 20°C 2.0 V cut off. The capacity restored by the cell varies according to current drain, temperature and cut off)*		7.5 Ah
Open circuit voltage	(at + 20°C)	3.0 V
Nominal voltage	(at 0.8 A + 20°C)	2.8 V
Maximum recommended continuous current *(to avoid over-heating. Higher currents possible, consult Saft)*		4 A
Pulse capability : Typically up to 15 A. *(The voltage readings may vary according to the pulse characteristics, the temperature, and the cell's previous history. Fitting the cell with a capacitor may be recommended in severe conditions. Consult Saft)*		
Storage	*(recommended)* *(possible without leakage)*	+ 30°C (+ 86°F) max - 60°C / + 85°C (-76°F / + 185°F)
Operating temperature range *(Short excursions up to + 85°C possible at currents below 1 A)*		- 60°C / + 70°C (-76°F / + 158°F)

Physical characteristics

Diameter *(max)*	34.2 mm (1.345 in)
Height *(max; finish without radial tabs)*	59.3 mm (2.33 in)
Typical weight	85 g (3 oz)

Heritage: MER descent phase

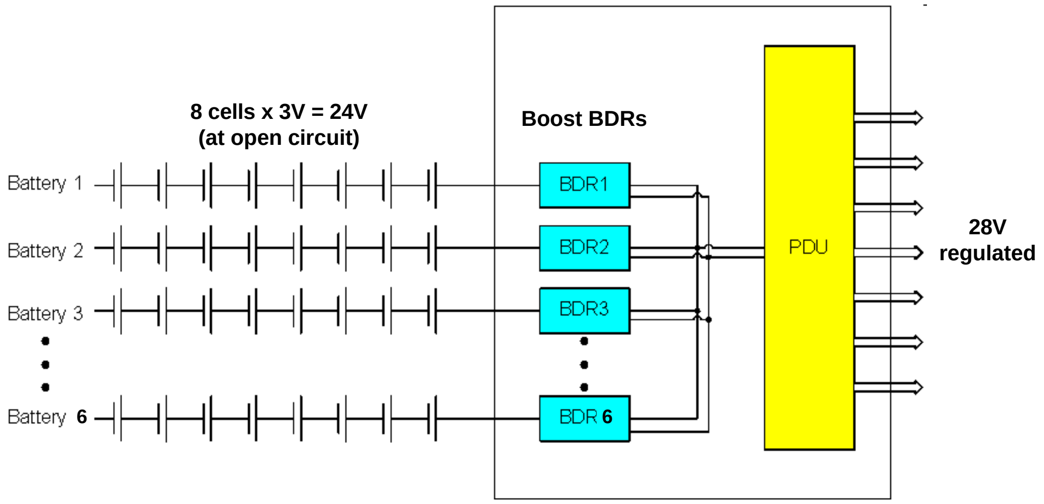
Characteristics of SAFT LO26SHX



Capacity versus Current and Temperature (continuous discharges - 2.0 V cut off)

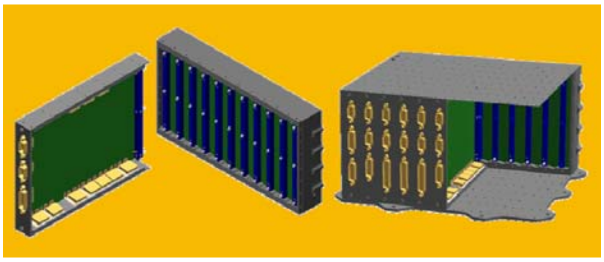
- 6 batteries of 8 cells each gives 1012 Wh at ≤24V (at 20°C).
- Total mass of 4.9kg including a 20% "cells-to-batteries allowance"
- PCDU must implement a depassivation routine to prepare the batteries for use after the interplanetary phase.

Power System Architecture



PCDU

- TERMA generic modular "Future Power System" components used to estimate PCDU size & mass.
  - It is assumed that a TERMA BCDR unit can be modified into a dual BDR unit of similar mass



Module/PCB	Capability per Module		Number of modules Required	Weight per module [Kg]	Total Weight [Kg]
BDR (2 per board)	225	W	3	0.55	1.65
Command Module	2	required	2	0.35	0.7
Distribution Module 1.5A	32	lines 1.5A	1	0.55	0.55
Distribution Module 5A	16	lines 5A	1	0.55	0.55
Pyro Control	16	pyro lines	1	0.5	0.5
Total modules			8		3.95
Structure/Backplane					6.6
TOTAL PDU			**8**		**10.6**

- Mass: 10.6 kg
- Dimensions: 190x270x230 mm

Power sub-system summary

Element 1	-		MASS [kg]				DIMENSIONS [m]		
Unit	Unit Name Click on button above to insert new unit	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin	Dim1 Length	Dim2 Width or D	Dim3 Height
1	PCDU	1	10.6	To be developed	20	12.7	0.192	0.265	0.230
2	Battery	6	0.82	To be modified	10	5.39	0.073	0.145	0.063
-	Click on button below to insert new unit		0.0	To be developed	20	0.0		-	
SUBSYSTEM TOTAL		2	15.5		16.8	18.1			

These dimensions are for 1 battery (6 are required in total)

Outer planets

Requirements and Design Drivers. Saturn

- Main deltas for power:
  - 10 year interplanetary transfer, so battery capacity loss is now significant. 3% per year is assumed for the Li-SO_2 cells, so 74% is remaining after 10 years.
  - 90 minute descent phase is the main driver to increase the energy budget to 916Wh (vs. 712 for Venus).

Power subsystem - Saturn

- Battery – Cell selection logic for Venus remains valid. 12 batteries are proposed, each comprising 7 cells in series. These are packaged and connected to BDRs in pairs.
- PCDU – Same architecture as Venus, 6 BDRs.
- 1/6th of the power system is redundant.
- Long transfer phase means that battery depassivation before probe separation is essential. This should not be a problem – experience from Huygens

Element 1	-		MASS [kg]				DIMENSIONS [m]		
Unit	Unit Name Click on button above to insert new unit	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin	Dim1 Length	Dim2 Width or D	Dim3 Height
1	PCDU	1	10.6	To be developed	20	12.7	0.192	0.265	0.230
2	Battery	6	1.43	To be modified	10	9.42	0.073	0.254	0.063
-	Click on button below to insert new unit		0.0	To be developed	20	0.0		-	
	SUBSYSTEM TOTAL	2	19.1		15.5	22.1			

Requirements and Design Drivers. Uranus and Neptune

- Main deltas for power:
  - Power budget remains as per Saturn.
  - 16/19 years interplanetary transfer, so battery capacity loss is very significant. 3% per year is assumed for the Li-SO_2 cells, so 56% is remaining after 19 years.
  - **Question** – Is it therefore advantageous to use Li-Ion rechargeable batteries? These would be left discharged during the interplanetary phase, and would have to be charged before probe separation.
  - Real data on Li-Ion storage degradation over such long periods is unavailable. Battery experts advise that the value may not be so much different than the 3% per year assumed for the primary cells. There are also the following disadvantages:
    - Secondary cells have a lower energy density at BOL.
    - BCR circuitry would be required.
    - Charging the battery may be a significant problem for the power system of the carrier craft (at the outer planets!)
  - Therefore, we select the same Li-SO_2 primary cells.

Power subsystem – Uranus and Neptune

- Battery –12 batteries are proposed, each comprising 9 cells in series. These are packaged and connected to BDRs in pairs.
- PCDU – Same architecture as Venus, 6 BDRs.
- 1/6th of the power system is redundant.
- Long transfer phase means that battery depassivation before probe separation is essential. This should not be a problem – experience from Huygens

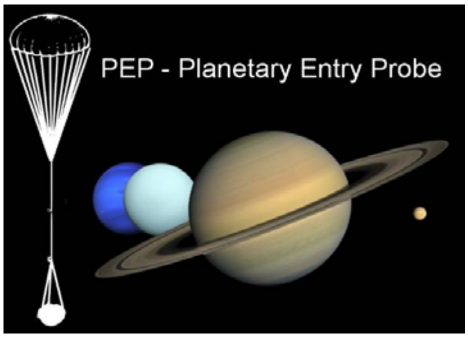
Element 1	-		MASS [kg]				DIMENSIONS [m]		
Unit	Unit Name Click on button above to insert new unit	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin	Dim1 Length	Dim2 Width or D	Dim3 Height
1	PCDU	1	10.6	To be developed	20	12.7	0.192	0.265	0.230
2	Battery	6	1.84	To be modified	10	12.12	0.073	0.327	0.063
-	Click on button below to insert new unit		0.0	To be developed	20	0.0	-		
	SUBSYSTEM TOTAL	**2**	**21.6**		**14.9**	**24.8**			

RHU aspects

- RHUs are not baselined for the PEP design, but we should consider the option and the potential impacts if they are required:
- **RHU**:
  - USA LWRHU may be available if NASA is a partner. 1W output, 40g, 32 x 26mm.
  - Russian Angel RHU may be purchased – this option was examined for Exomars. 8.5W, 180g, 40 x 60mm.
  - ESA nuclear power roadmap aims to have a European RHU at TRL 6 by 2016.
- **Mech interface**:
  - Both designs are plain cylinders, and some form of holder(s) needs be included in the spacecraft design. Add 50% of the RHU mass?
  - Spacecraft design can be significantly driven by the requirement for RHU installation on the launchpad.
- **Launch safety approval:**
  - A major project in itself. If USA LWRHU are used with a USA launch, then the risk is reduced due to prior experience. Likewise for Russian Angel RHU with a Russian launch.

PEP
Planetary Entry Probes

Communications



Internal Final Presentation

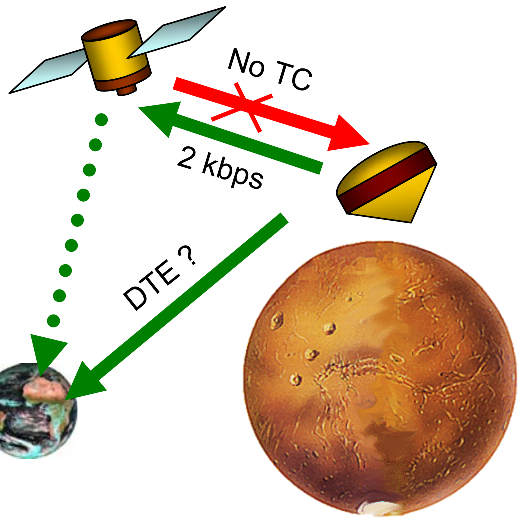
ESTEC, 30th June 2010

Prepared by the PEP/ CDF* Team

(*) ESTEC Concurrent Design Facility

Requirements

- **Telecommands link** (carrier to probe) is not required.
- During coast phase the telemetry link shall be available during one hour over 20 days (power ON duty cycle = 0.2%).
- During descent phase the telemetry link shall be able to transmit real time data at **2kbps**.
- The probe shall be able to transmit telemetry at **elevations higher than zero degrees**



Assumptions: frequency

VHF, UHF	L- band	S- band, X-band, …

← 1 GHz | 2 GHz →

- Antenna size increases
- More than 30 cm for UHF

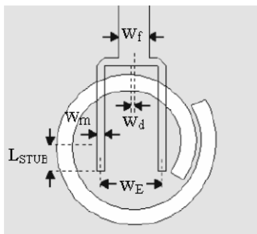
- Atmospheric loss increases
- More than 25 dB in Saturn S-band

- **Selected frequency UHF = 400 MHz**
  - Patch antenna size allows to be place on the back cover
  - Atmospheric loss extrapolated from previous technical studies.
    - Venus = 2 dB
    - Saturn, Neptune and Uranus = 15 dB
- A dedicated study on the planetary atmosphere effect (loss, noise temperature, misspolarization, …) is needed for an final frequency selection.

Assumptions: antennas

Coast phase antenna

- Circular patch antenna on the back cover
- A design with a hole in the centre allows the parachute release.
- Diameter of the radiating element: 300 mm



- Descent phase antenna:
- Helix antenna in the probe
- The helix antenna ensures full link coverage down to 0 degrees elevation.
- Size of the radiating element 250 mm

Descent phase antenna

Assumptions: atmosphere effect

- Molecular attenuation:
  - Absorption: The energy of the photons is taken up by matter.

Assumptions: atmosphere effect

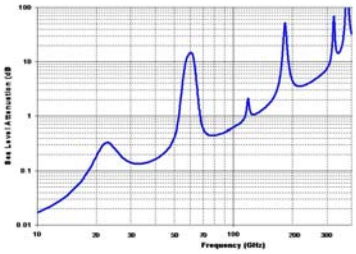
- Molecular attenuation:
  - Absorption: The energy of the photons is taken up by matter.
  - Scattering: The electromagnetic wave is deviated from its straight path.

Assumptions: atmosphere effect

- Molecular attenuation:
  - Absorption: The energy of the photons is taken up by matter.
  - Scattering: The electromagnetic wave is deviated from its straight path.
  - Dipole momentum: The energy of the photons is taken up by dipole molecules.

Assumptions: atmosphere effect

- **Atmospheric attenuation**: The previous physical principles will attenuate the EM signal when it passes through the atmosphere. The tottal attenuation in dB will depend on:
  - Atmosphere composition (O_2, CO_2, NH_3, …), phase of the matter (gas, clouds, ice), pressure, temperature.



- **Noise figure**: The radiation of the planets mainly caused cause by moving charged particles can block some frequencies.
- **Polarization mismatch** shall also be addressed.

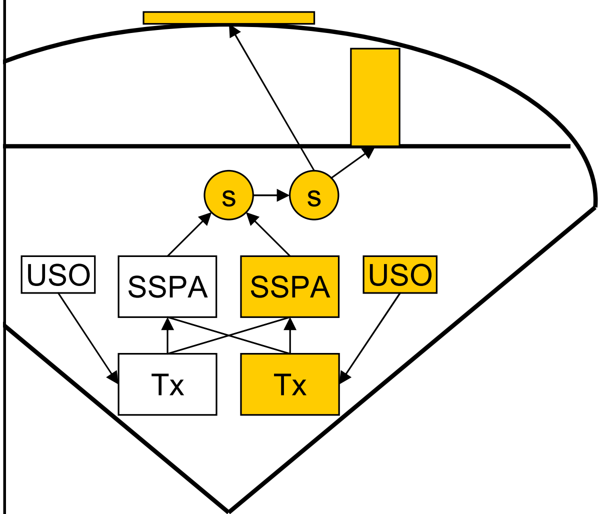
Assumptions: atmosphere effect

- During this study the impact of the atmosphere effect on the communications have been identified as a key issue.
- There is a lack of knowledge on the atmospheric effects, especially for outer planets.
- The final **atmospheric attenuation** considered in UHF will be a worst case extrapolated from previous studies:

		Latm [dB]			
		Venus	Saturn (10 bars)	Uranus	Neptune
X-band	8 GHz	8 ****			
S-band	2 GHz		30 **		
L-band	1 GHz		25 *	?	?
UHF	400 MHz	1 ***	1.2 **		
VHF	100 MHz		0.5 **		

- Venus: -2 dB
- Saturn: -15 dB
- Uranus and Neptune: -15 dB

Communications subsystem design



	Current TRL	Comments
1 patch antenna (on the back shield)	5	
1 helix antenna	5	
2 RF switches	5	
2 SSPA	5	Cold redundancy
2 Transmitters	5	Cold redundancy
2 Ultra Stable Osc.	5	Cold redundancy
Cables and harness	5	

Total mass (excluding margin)	**7.4 kg**
Total consumption	**315 W / 45 W**

Communications subsystem design

- **TRL 5:** All equipment to be developed in order to resist an extreme environment.
- **Transmitters:** GMSK with Turbo codes and variable data rate.
- **Solid State Power Amplifier:** Variable output power 10 to 100 W
- **Patch antenna:** Released with the back shield and with a hole in the middle for parachute release.
- **Helix antenna:** Omnidirectional with at least 0 dBi at 0 degrees elevation.
- **Ultra Stable oscillator:** low phase noise for DTE carrier recovery link and Doppler wind experiment.

Link budget telemetry relay

	Telemetry relay	Data rate [kbps]	RF output power [W]	Atm loss [dB]	Slant range [km]	Rx antenna [m]	Link margin [dB]
Venus	Coast	0.2	10	0	38000	0.2	**3.05**
	Start of descent	2	100	0	38000		**3.05**
	End of descent	2	100	2	22000		**5.80**
Saturn	Coast	2	10	0	90000	1.5	**3.07**
	Start of descent	2	100	0	90000		**13.07**
	End of descent	2	100	15	60000		**1.59**
Uranus	Coast	2	10	0	100000	1.5	**2.15**
	Start of descent	2	100	0	100000		**12.15**
	End of descent	2	100	15	40000		**5.11**
Neptune	Coast	2	10	0	80000	1.5	**4.09**
	Start of descent	2	100	0	80000		**14.09**
	End of descent	2	100	15	25000		**9.19**

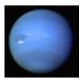
Link budget DTE carrier recovery

	Carrier Recovery DTE	RF output power [W]	Atm loss [dB]	Slant range [AU]	Rx antenna [m]	Link margin [dB]
Venus	Coast	10	0			6.91
	Start of descent	100	0	0.4	35	16.91
	End of descent	100	2			14.91
Saturn	Coast	10	0			-5.30
	Start of descent	100	0	10	SKA	4.70
	End of descent	100	15			-10.30
Uranus	Coast	10	0			-11.35
	Start of descent	100	0	20	SKA	-1.35
	End of descent	100	15			-16.35
Neptune	Coast	10	0			-15.21
	Start of descent	100	0	30	SKA	-5.21
	End of descent	100	15			-20.21

- Telemetry link also possible for Venus with SKA or VLBI
- 5 – 7 dB can be gained by using VLBI techniques.

Conclusions

- Atmosphere effect needs to be addressed.
- Subsystem design: Flexible power and data rate to optimise the data return (2 kbps) and power consumption (> 300 W).
- Telemetry and carrier recovery as follows:

	Venus 	Saturn 	Uranus 	Neptune 
Telemetry relay	OK	OK	OK	OK
Carrier recovery DTE	35 m	OK	NOK	NOK
Telemetry DTE	SKA	NOK	NOK	NOK

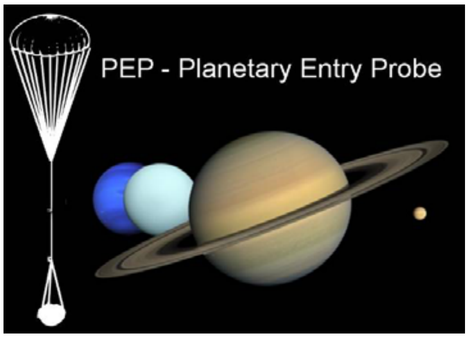
PEP
Planetary Entry Probes

DHS

IFP

ESTEC, 30th June 2010

Prepared by the PEP/ CDF* Team



(*) ESTEC Concurrent Design Facility

Requirements

- **Pre-separation**
  - ➢ Probe DHS shall provide a connection with the Orbiter for periodic health check, DHS and DPU software patches, Mission Timers update
- **Coast**
  - ➢ Probe DHS shall be able to periodically wake up Communication system and GNC
- **Entry**
  - ➢ Probe DHS shall be in charge to control timing events (Parachute deployment etc.)
- **Descent**
  - ➢ Probe DHS shall trigger the initial Payload DPU switch-on
  - ➢ Probe DHS shall collect and transmit basic telemetry to the orbiter to indicate probe status and sequence phase

Assumptions

- No attitude control is required
- Low data processing capability is required during coast and entry phase
- Mission Timers are active during coast and entry
- Most of the data handling tasks are performed by the Data Processing Unit (DPU) as part of the Payload:
  - Scheduling of experiments
  - Data from Payloads acquisition, storage and transmission to the orbiter
  - Data formatting to transponder (encoding telemetry)

Design drivers

- High reliability and availability during entry and descent phase
  - Single point failure free design
  - Hot redundant system
  - Rad-hard design
- Very low power consumption during coast phase
  - Power-off not used functions
- Limited mass

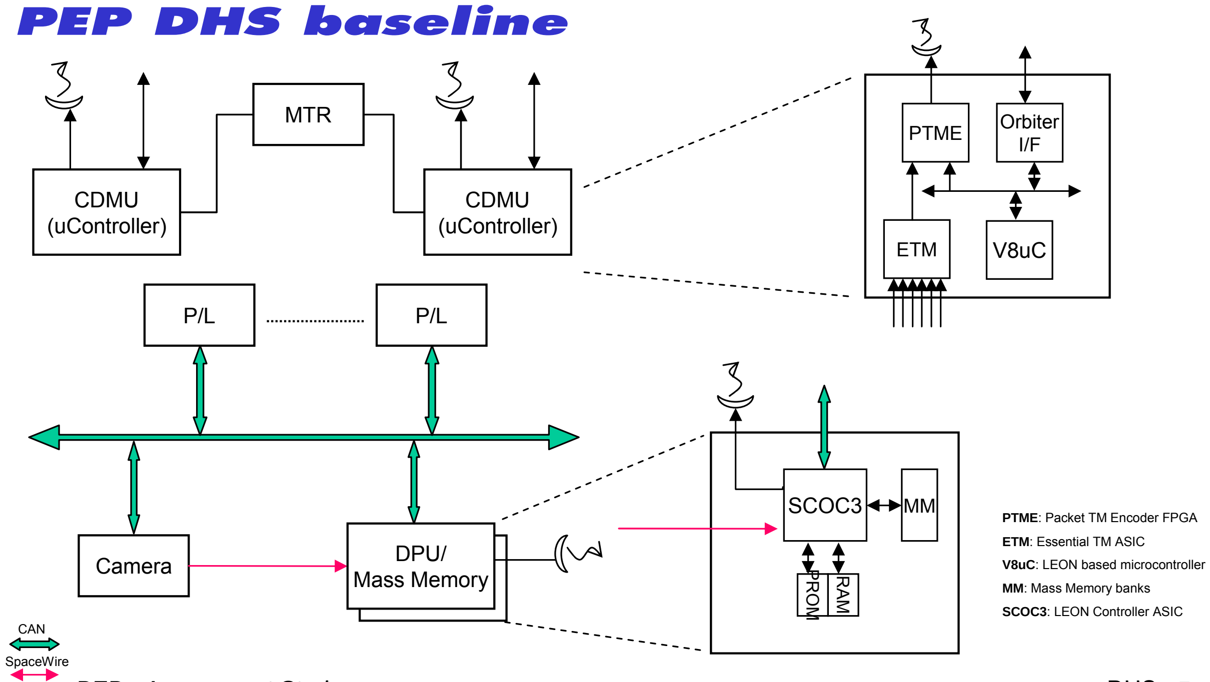
Design summary

- There are three main units: one MTU, two CDMUs and a number of micro Remote Terminal (uRTU)
  - *Mission Timer Unit* (**MTU**)
    - Three independent hot redundant timer circuits and two hot-redundant voting and command circuits.
    - When at least two out of three time-out are received commands are sent to the PCDU to switch-on both CDMUs
    - During cruise all three timers can be programmed independently from one of the two CDMUs
    - During coast phase only the timers are powered
    - During entry/descend phase MTU is off

Design summary

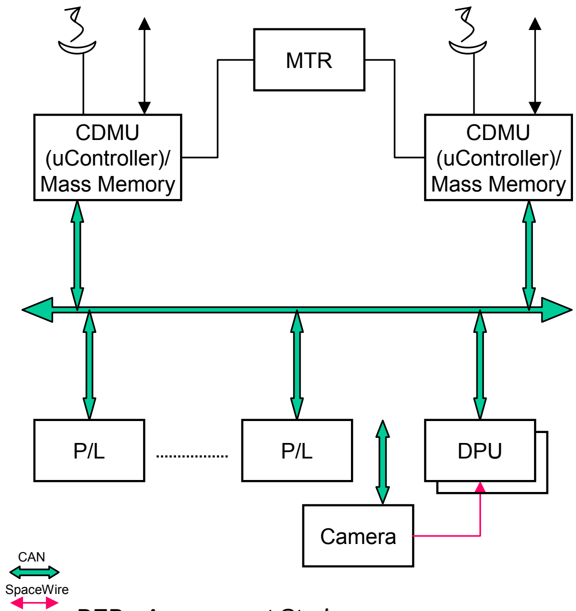
- Command & Data Management Unit (**CDMU**)
  - Two hot redundant identical units executing the same functions
  - Each CDMU includes a simple and low power V8uC microcontroller. V8uC is a simplified version of the LEON2 processor with program memory and most of the peripherals on-chip
  - Essential Telemetry (ETM) ASIC is used to collect TM from uRTU during coast and entry and descent phase with no software intervention.
  - No main data connection between CDMU and Payloads
  - Events sequence during entry is software controlled by the CDMU
  - All Payload operations, data processing and delivery are controlled by DPU

PEP DHS baseline



PTME: Packet TM Encoder FPGA
ETM: Essential TM ASIC
V8uC: LEON based microcontroller
MM: Mass Memory banks
SCOC3: LEON Controller ASIC

PEP DHS: option 1

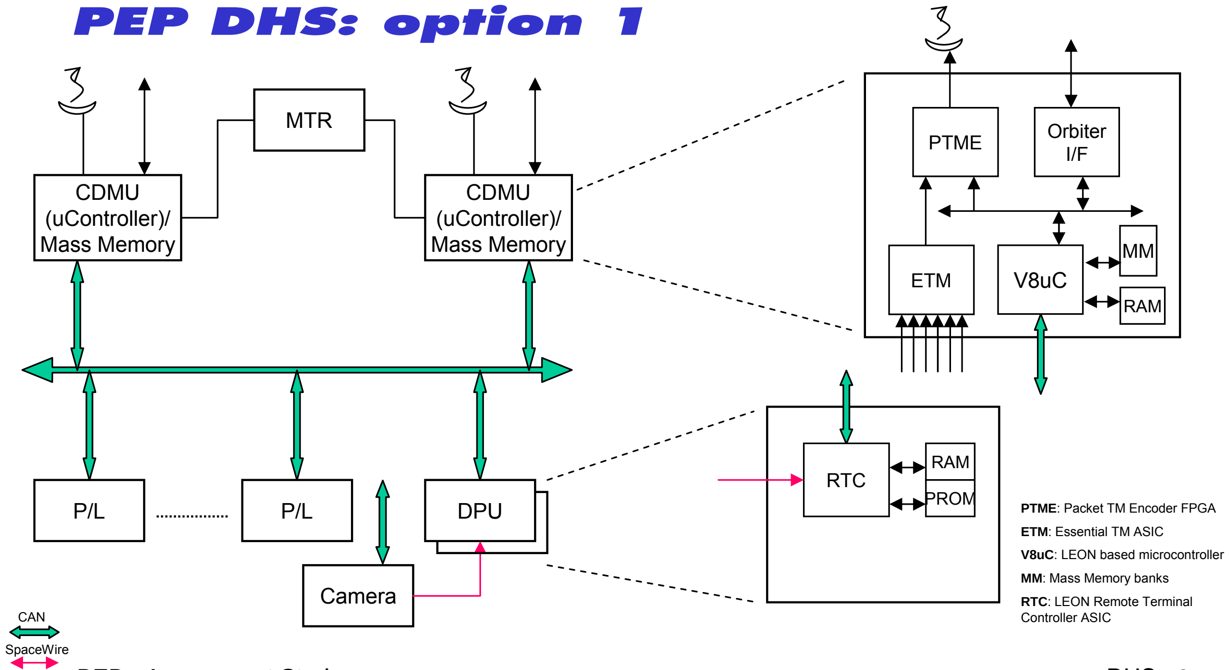


- JEP-like architecture but with power optimization in CDMU
- CDMU based on low power LEON uController (V8uC)
- Event sequences during entry / descent is software controlled by the CDMU
- Scheduling of experiments under CDMU software control
- Payload data processed by DPU but stored and delivered to the Orbiter by CDMU

+
- High CDMU flexibility

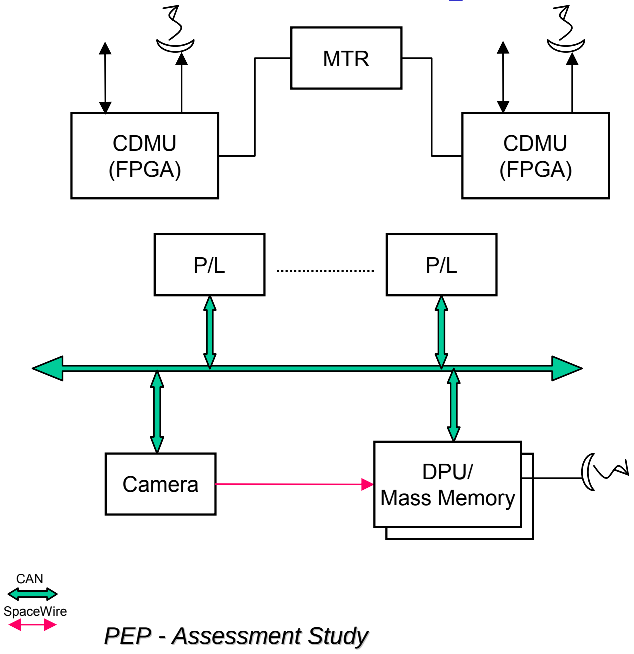
—
- CDMU hardware and software complexity

PEP DHS: option 1



PTME: Packet TM Encoder FPGA
ETM: Essential TM ASIC
V8uC: LEON based microcontroller
MM: Mass Memory banks
RTC: LEON Remote Terminal Controller ASIC

PEP DHS: option 2



- CDMU based on fixed FPGA design, no software running.
- Events sequence during entry / descent is hardware controlled by the CDMU FPGA.
- Instruments operations controlled by DPU
- All Payload data handled, stored and transmitted to orbiter by DPU
- No main data connection CDMU-P/L

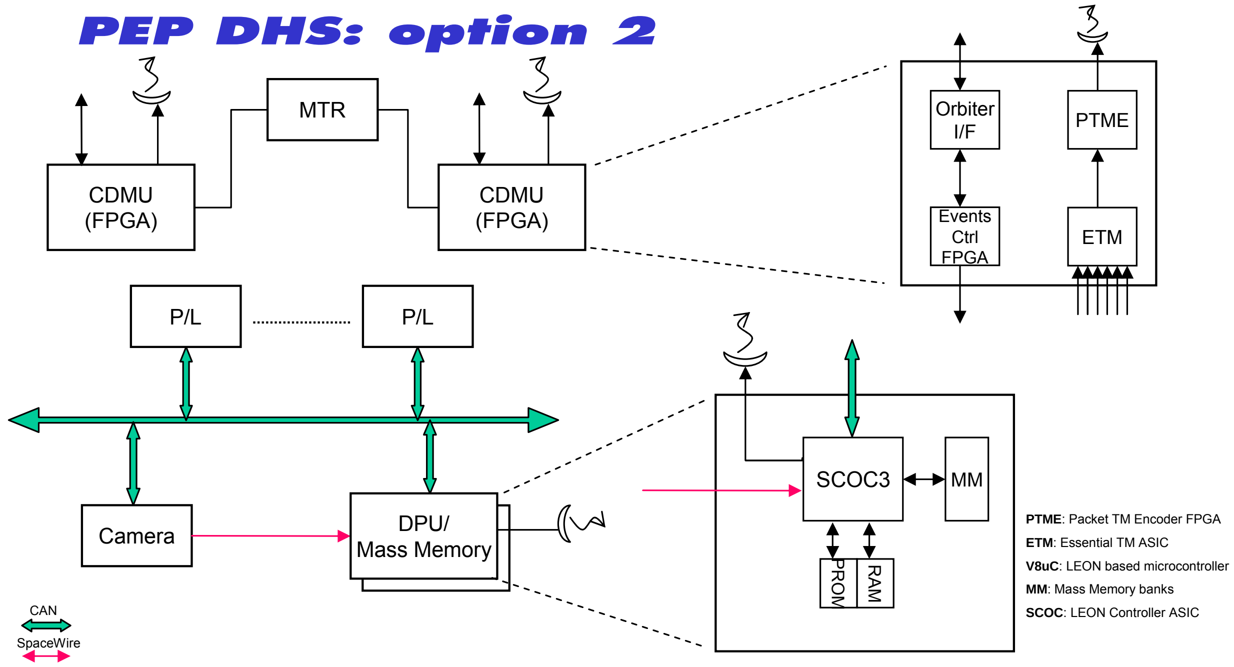
\+

- Reduced harness
- Very low power CDMU
- Very simple and reliable CDMU

–

- Low CDMU flexibility

PEP DHS: option 2



PTME: Packet TM Encoder FPGA
ETM: Essential TM ASIC
V8uC: LEON based microcontroller
MM: Mass Memory banks
SCOC: LEON Controller ASIC

PEP DHS baseline budget

Mass

Element 1	-			MASS [kg]			
Unit	Unit Name Click on button above to **insert new unit**	Part of custom subsystem	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
1	CDMU		2	3.4	To be modified	10	7.5
2	MTU		1	2.3	To be developed	20	2.8
3	uRTU		6	0.2	To be modified	10	1.3
-	Click on button below to insert new unit						
SUBSYSTEM TOTAL			3	10.3		12.2	11.6

Power consumption

Element 1	-			PPEAK AND POWER SPECIFICATION PER MODE									
Unit	Unit Name Click on button above to **insert new unit**	Part of custom subsystem	Quantity	Ppeak	Coast Pon	Coast Pstby	Coast Dc	Entry Pon	Entry Pstby	Entry Dc	Descent Pon	Descent Pstby	Descent Dc
1	CDMU		2		17.8	0.0	0.6	17.8	0.0	100.0	17.8	0.0	100.0
2	MTU		1		0.3	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0
3	uRTU		6		1.6	0.0	0.6	1.6	0.0	100.0	4.8	0.0	100.0
-	Click on button below to insert new unit												
SUBSYSTEM TOTAL			3	0.0	19.7	0.0		19.4	0.0		22.6	0.0	

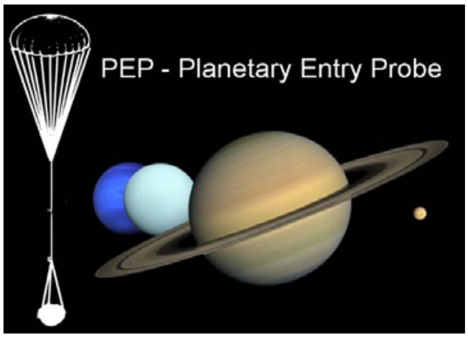
PEP
Planetary Entry Probes

G/S and Operations

IFP

ESTEC, 30th June 2010

Prepared by the PEP/ CDF* Team



(*) ESTEC Concurrent Design Facility

Release Sequence from Interplanetary Orbit

- Confirm and correct targeting
  (usually 3 manoeuvres over 1 month duration)
  Problems: Allow for a safe mode => set timing accordingly and use balanced thrusters, provide adequate coverage
- Baseline: Release of probe 20 days before Probe entry.
- Point spacecraft at entry point for Lander.
- Release spacecraft (from turntable): Pointing and release operations: several hours (longer with feedback loops)

Spacecraft Entry Sequence

- Typically one combined manoeuvre for heading spacecraft for orbit insertion manoeuvre and phasing for probe coverage.
- Tracking to adapt insertion manoeuvre parameters according to manoeuvre/approach errors.
- Spacecraft approach correction manoeuvre TBD.
- Insert safe mode recovery slots into planning.
- Probe entry under coverage from Earth and spacecraft (see SR-5)

Release Sequence Drivers (1)

- Requirement to monitor the landing by the spacecraft (see SR-5)
- Arrival time to be adjusted by ΔV manoeuvre and distance of separation manoeuvre (see SR-7)
- Special spatial relation of spacecraft and landing site required (see SR-7)
- Point spacecraft antenna) at entry point for Lander
- Relaxed sequence (20 days) operationally preferable to 6 days minimum sequence (but see SR-8)
- Safe fuel by early deflection manoeuvre (contradiction to SR-8)
- Do not require permanent coverage during drift phase

Release Sequence from Interplanetary Orbit Drivers (2)

- Relax requirements on ΔDOR
- Relax requirements on safe mode or special modes
- Use redundancy for probe communications (DTE + relay)
- Reduce accuracy of the spacecraft targeting on b-plane

Beagle Release Sequence from Mars Express Spacecraft

- 6 days between Beagle Release and landing
- Targeting manoeuvre on the day after Beagle release
- Possibility of safe mode planned for, last day in fail safe mode with drastically reduced capability set
- Tracking required to adjust orbit insertion manoeuvre
- No tasks for Beagle relay or tracking for Mars Express at Beagle landing
- Sequence only possible with permanent coverage and ΔDORs.

- Very compressed schedule requiring a lot of preparation and many simulations.

- Free choice of SOM would rather have been two weeks, but Beagle timer was only 6 days!

- Fail safe mode was drastic choice, switch off of Mass Memory meant no info on fuel usage (i.e. impact on life time still unknown).

THE HUYGENS PROBE RELEASE (no Cassini capture into moon orbit)

- Upon Saturn arrival in June 2004, the spacecraft executed a Saturn Orbit Insertion manoeuvre.
- After this manoeuvre, Cassini initial orbital period around Saturn was about 152 days.
- Approximately 76 days after orbit insertion, the spacecraft executed a manoeuvre to raise its orbit periapsis and to target the combined Orbiter and Probe for Titan impact.
- The Probe was released from the Orbiter **20 days** before the third Cassini Titan flyby.
- Two days after Probe release, the Orbiter performed an Orbit Deflection manoeuvre to place itself into a trajectory flying over the Probe landing site, to allow collection of Probe descent telemetry data.
- In order to receive relay data from the Probe, the Orbiter pointed its high-gain antenna at the predicted Probe entry point on Titan.

Possible Sequences Overview Table

Sequence Type	Tracking Campaigns	Tracking Duration	Manoeuvre after day	Number of manoeuvres (TCR + touch up TBC)	Manoeuvre Duration (incl. pointing/ repointing)	Manoeuvre Calculation with tracking info	Wait for Manoeuvre Uplink	(Safe Mode) Recovery Slot	Total
	[number]	[days]	[days]	[number]	[hours]	[hours]	[hours]	[days]	[days]
Probe Release and Descent and Landing Communications	1	7	2	1	4	0	0	3	12
Probe Release and Descent and Landing Communications Correction Manuoevre	2	6	2	2	4	8	12	3	19

The sequence is driven by the number of manoeuvres, because they require tracking slots in between.
A single deterministic manoeuvre is compatible with the accuracy requirements for spacecraft capsule communications during capsule EDL.

Capsule Housekeeping Data Requirements

- General Housekeeping Control guideline:
  - Things happen (and change) only if the satellite/spacecraft is doing something
  - ⇒ Very little change to be expected during cruise
  - critical event to suddenly shut down communications very unlikely something
  - ⇒ Status report at long intervals proposed
  - Amount of data: few kb (can be negotiated)
  - HK compression proposed, will compress status data to few % or less something
  - ⇒ Send bursts of data every several hours (e.g. 25 kbit twice per day, i.e. 100 b/s for 5 minutes) during cruise
  - ⇒ Traditional (continuous) housekeeping TM during descent

Back-up Slides

Possible Sequences Overview Table

Sequence Type	Tracking Campaigns	Tracking Duration	Number of manoeuvres (TCR + touch up TBC + insertion)	Manoeuvre Duration (incl. pointing/ repointing)	Manoeuvre Calculation with tracking info	Wait for Manoeuvre Uplink	(Safe Mode) Recovery Slot	Total	Comment
	[number]	[days]	[number]	[hours]	[hours]	[hours]	[days]	[days]	
ΔDOR Single Manoeuvre	1	3.5	2	4	8	4	1.5	6.0	very time pressed, permanent coverage
Doppler Single Manoeuvre	1	7.0	2	4	8	16	3.0	12.0	Feasible, but baseline is operationally preferred
Doppler Double Manoeuvre	2	7.0	3	4	8	16	3.0	20.2	Baseline, reduces insertion error

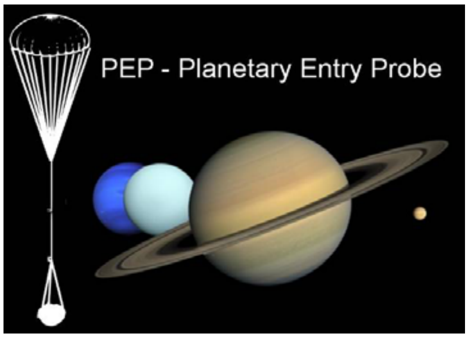
PEP
Planetary Entry Probes

Programmatics / AIV

IFP

ESTEC, 30th June 2010

Prepared by the PEP/ CDF* Team



(*) ESTEC Concurrent Design Facility

Requirements & Design Drivers

- Design a probe for entry and descent to either Venus, Saturn, Uranus or Neptune
  - Hyperbolic deployment of the probe from a carrier
  - Overall probe mass 200 kg to 300 kg
  - RF-link via carrier serving as relay to Earth
- Mission duration
- Environmental conditions
  - Aerothermodynamics phenomena and heat flux
  - Deceleration and temperature gradient during descent
  - Pressure during entry & descent
- Test capabilities

Comparison of the Four Cases

Subject	Venus	Saturn	Uranus	Neptune
Transfer time [year][1]	0.33-0.5	9 18.5		19.3
Coast time [days]	20	20	20	20
Entry time [minutes]	1.77	1.77	1.77	1.77
Descent ime min. t	60 [	90	90	90]
Atmosphere	CO	He, H+	He, H+	He, H+
Entry velocity [km/s]	11.8	36.0	21.7	24.7
Max. heat flux [MW/m2]	59 (81)[2]	114	104	109
Max. deceleration [g]	-250 (-360)[2]	-200	-300	-325
Structure T [deg. C]	< 450	< 190	< 50	
Pressure [bar]	92	1 – 100	4 – 100	10 - 100

[1]) worst scenario assumed [2]) flight path angle = -50 instead of -25

Assumptions & Trade-Offs

- The design of the four probes is similar in general layout, mass, payload
- Differences are in details like TPS thickness, parachute deployment scenario
- “Test as you fly”, as far as possible
- Test requirements are similar, at least for the outer planets
- Lifetime and radiation dose might require special attention

Payload

- The payload consists of 5 instruments, based on existing units with high TRL:
  - ASI/MET
  - Mass spectrometer (MS)
  - Doppler Wind
  - Camera
  - Photometer
  - Data processing unit and power converter
- A challenge is the mission duration to the outer planets.

Options

- Alternative equipment or components might be developed, providing better performance or reliability e.g.
  - TPS
  - batteries

Technology Development

- Most TRL of envisaged subsystem and equipment are 5 or higher
- Exceptions are:
  – GNC IMU TRL 4-5 (guidance navigation and control – inertial measurement unit)
  – Front heat shield TRL < 5
  – Back cover TRL 3-4

TPS Testing

- Aerothermodynamics analysis and TPS design will have to rely heavily on modelisation
- Models will have to be validated by testing
- TPS material will have to be qualified at very high heat fluxes
- Aerothermodynamics phenomena and heat flux range generally beyond the capabilities of existing facilities

European available aerothermodynamic facilities

- In Europe, facilities from:
- - ALTA (Pisa, Italy);
- - ARC (Seibersdorf, Austria);
- - ASTRIUM-ST (Aquitaine, France);
- - CAEPE (Aquitaine, France);
- - CIRA (Capua, Italy);
- - CORIA (Rouen, France);
- - DLR (Cologne and Göttingen, Germany);
- - FOI (Stockholm, Sweden);
- - GDL (Farnborough, United-Kingdown);
- - HTG (Katlenburg-Lindau, Germany);
- - ICARE (Orléans, France);
- - IRS (Stuttgart, Germany);
- - ISL (Saint-Louis, France & Germany);

European available aerothermodynamic facilities

- - Oxford University (UK);
- - IUSTI (Marseille, France);
- - LAEPT (Clermont-Ferrand, France);
- - Max Planck Institute for Plasma Physics (Garching, Germany);
- - ONERA (Toulouse and Modane, France);
- - PROMES (Odeillo, France);
- - RWTH (Aachen, Germany);
- - TNO (Rijswijk, The Netherlands);
- - TU Braunschweig (Braunschweig, Germany);
- - UMIST (Manchester, United-Kingdown);
- - UNINA (Naples, Italy);
- - VKI (Brussels, Belgium).
- - NLR, Amsterdam, The Netherlands
- - DNW, various locations in NL and D

Future ESA Aerotherm.-facility

- **Kinetic shock tube** for radiation data base for planetary exploration -(almost) at KO June/July 2010 – end July 2012

  - TRP: T217-052MP-

The focus of the activity is on the construction and acceptance of a shock tube and associated initial instrumentation set

  - Test evaluated costs – **120 k€/test campaign** (200 shots, 3 months)

  - Activity focuses on defining, constructing and commissioning a shock tube for the study of high temperature chemical kinetics and radiation. Provides clean high temperature plasmas, at ranges of enthalpies and pressures relevant for Mars, Venus and Earth orbital and hyperbolic entries, for representative gas mixtures.

  - Additional objectives include:

- setting adequate measur^{ts} techniques incl. data handling H/W and S/W
- studying relaxation after a shock wave
- validating chemical models
- identifying the main radiative species and transition
- measuring heat flux directly
- Assessing aero forces and moments on models (needs further develop)

TPS Testing – Plasma facilities

Starting point JEP with updated values

- **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 - 12 MW/m^2 @ 1300mbar**
  - **Plasmatron (VKI) - available 6.5 MW/m^2@ 600mbar**
  - **SIMOUN (EADS) – Huels arc heater - 7 MW/m^2 @ 170-270mbar**
  - **COMETE (EADS) – Plasmatron – 7 MW/m^2**
  - **JP 200 (EADS) - Huels arc heater**
    - **- 80 MW/m^2 @ 5-50bar**
    - **- 5 MW/m^2 @ 1.5bar & 25 MW/m^2 @ 9bar**
  - **High Pressure (EADS) – Huels arc heater – 150 MW/m^2 (**NOT confirmed from Aerothermodynamic group**)**
  - **PWK4 (IRS) – Magnetoplasmadynamic generator – 3 MW/m^2@ 5kPa**
  - **RD5 (IRS) 14 MW/m2 @ 50 mbar**

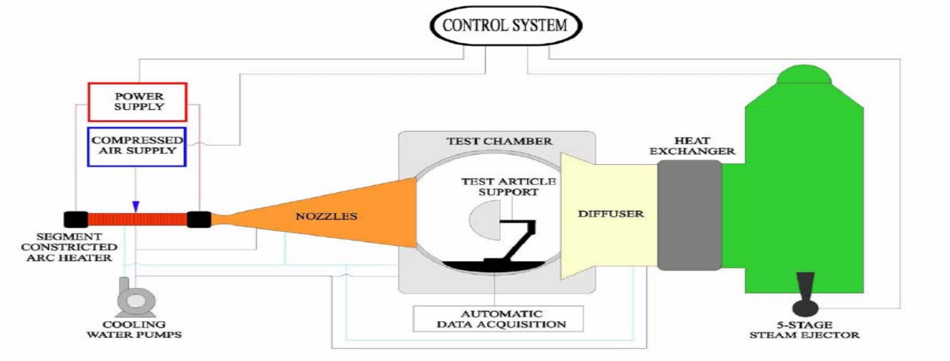
TPS Testing – Plasma facilities

- SCIROCCO (CIRA) – arc jet test facility for large model testing
- Available: **3.8 MW/m² @ up to 200mbar***

- Test campaign ~ 75k/test
- Future projects: - ESA TRP (Aurora E15) - up-grade SCIROCCO facility to more than **20 MW/m²** at approximately 1 atmosphere for 2.5 cm sample in order to validate the TPS for super-orbital Earth Entries (focuses on flow determination around the capsule in realistic pressure and enthalpy). Delays. Expected November 2010
- **Scirocco does not operate with CO2**. SIMOUN does. Upgrade of SCIROCCO for CO2 feasible to allow CO2 flow, but cost could not be offered by Aurora – estimated to about 1.5MEuros (necessary for **Venus**).

  - heat fluxes/pressure combinations between **15MW/m² @ 1300mbar and 6MW/m² @ 350 mbar** investigation of the feasibility to up-grade SCIROCCO Plasma Wind Tunnel to reproduce flows representative of super-orbital Earth entries.
- * SCIROCCO has a potential of more, but was not tested. From the chart of the AWG meeting 25-26/1/07, there are values up to 10MW/m² indicated.

TPS Testing – Plasma facilities



"SCIROCCO" SCHEMATIC DIAGRAM

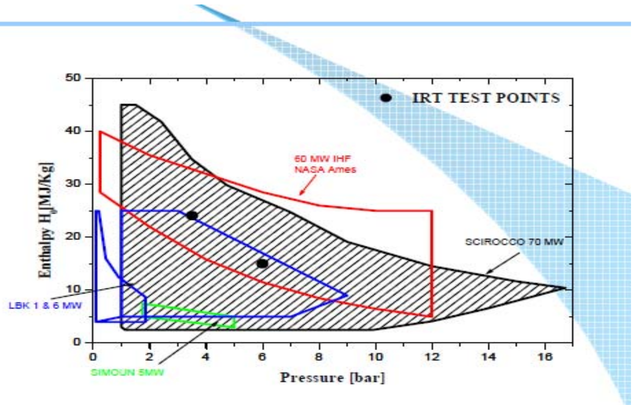
- large size model tests
  - Test Articles Size: 600 mm from design/ 800 mm tested
  - Test Chamber Size: H=9m, D=5m;
  - Not cooled,
  - Many windows
  - 4 Conical Nozzles available: 900, 150, 1350, 1950 mm

TPS Testing – Plasma facilities

- SCIROCCO (CIRA) – arc jet test facility for large model testing

PERFORMANCES
Test Duration (max) 1800s
Stagnation Pressure 5.0 – 175.0 mbar
Test Gas Dry Air + Argon (1-4%)
Stagnation Heat flux(1) 125 – 1035kW/m²
Massflow 0.2 – 3.5kg/s
Total Enthalpy 2.5 – 45MJ/kg
Reservoir Pressure 1.0 – 17bar
Maximum Arc Power 70MW
Flow Speed 2000 – 7000 m/s

Nozzle A offers **10MW/m² @20-50kPa**



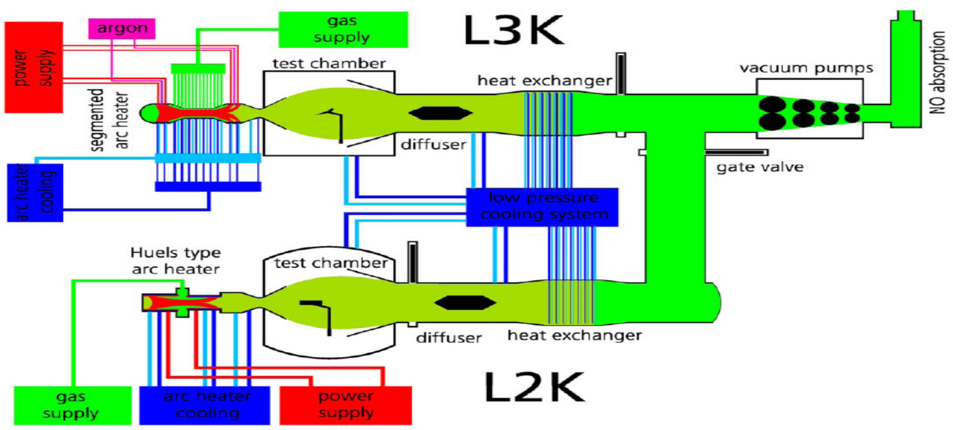
► SCIROCCO is the most powerful low pressure single constrictor segmented A.H. PWT in the world.

► SCIROCCO accepts very large models in scale 1:1

TPS Testing – Plasma facilities

- **DLR (Cologne and Göttingen, Germany)**

Arc heated facilities LBK
Setup



TPS Testing – Plasma facilities

– L3K (DLR)

- segmented arc heater – small samples (max 40mm in diameter, 40 in height)
- Available: **11.5 MW/m² @ 1300mbar**
- Test campaign: **~100- 200 k**
- Future projects: DLR is considering to upgrade L3K up to **14** MW/m² @ More representative pressure levels (TBC depending on available funding)

- If ESA-DLR join efforts, the ESA contribution is estimated to about 50k (extension from 4 to 5-pack burner, characterisation tests)

TPS Testing – Plasma facilities

- Plasmatron – VKI –Belgium
- Available up to **6.5 MW/m2@ 600mbar** and tested also at **10 MW/m²**
- Test campaign – **ROM cost:?**
- Future proj ects: 2009-VKI decid ed to construct and bui ld a new ly designed nozzle which accelerates the flow and thus helps to achieve higher heat flux. Using the new nozzle, VKI expects to reach the order of **10MW/m²** and dynamic pressures close to **800 mbar**. The characterization tests with this nozzle are expected to be finalized end of 2009 (presented at 6-th workshop April 2009)
- The Plasmatron is a subsonic facility which has to be compared with the MPD RD5/ RD7 facilities of IRS. This faci lity makes proper simul ation of shear forces impossibl e and puts so me question mark concerning the reported pressures (other rules might apply for different situations).

TPS Testing – Plasma facilities

- MPD RD5 (IRS)

- Available: Demonstrated up to 14 MW/m^2, but @ < 50 mbar
- Compliant with high heat fluxes requirement but compromising on flux/pressure combination

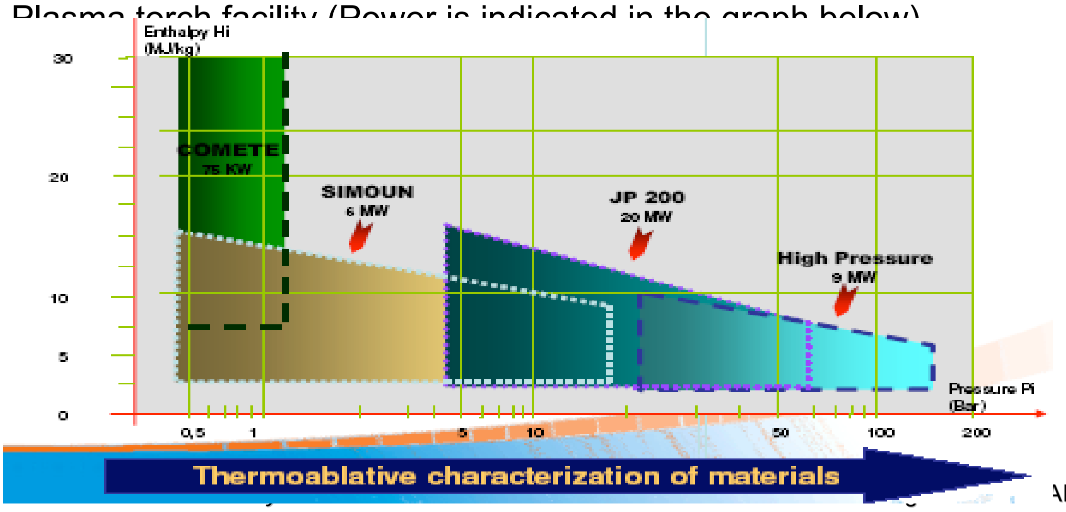
- price equivalent ~ It is mostly the price of PhD or researcher. It is not a real cost. Typical is 50-100 kEuros for a campaign.

TPS Testing – Plasma facilities

– EADS/ST

– Plasma torch facility (Power is indicated in the graph below)

•



TPS Testing – Plasma facilities

– EADS/ST

- - SIMOUN facility -heat fluxes close to **7 MW/m² @ 170-270 mbar** Accumulated heat load during testing was ~170 MJ/m², but other configuration also possible: **5MW/m² @ 200-500 mbar** stagnation point configuration.
- - SIMOUN advantage- operates with CO_2 flow (necessary for Venus)
- JP 200 facility – 2 configurations can be tested:

- In the stagnation configuration an axysymmetric nozzle is used to test hemispherical, cylindrical and conical test samples. Maximum cold wall heat fluxes up to **80 MW/m² @ 5-50 bar** (dynamic pressures)
- In the duct configuration a rectangular nozzle exit is used to test parallelepipedic test samples under parallel flow. Heat flux/pressure combinations are between **5 MW/m²/1.5 bar and 25 MW/m²/9 bar**.

TPS Testing Approach

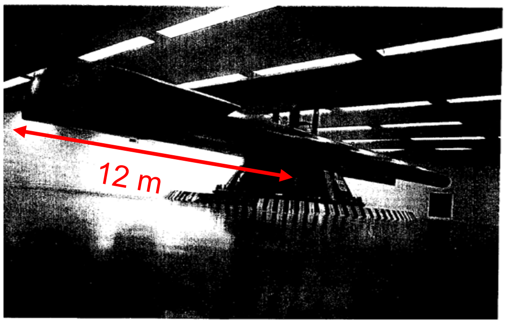
1. Build a new facility capable to reproduce as close as possible the aerothermodynamics of the outer planets entry and that can be used for CFD validation and TPS testing
2. Split the testing problem in two:
   – Partial validation of CFD models in existing facilities (with modifications)
   – Testing of TPS at high fluxes generated by e.g. radiative facilities

Deceleration Testing

Galileo experienced 228 g during descent (comparable to our Probe)

Individual probe components on a (small) centrifuge to as high as 350 g

- Fully assembled, the probe was too massive to be spun that high on any centrifuge in the world.
- Fully assembled probe tested at 200 g on large centrifuge at Sandia National Laboratories Centrifuge facility (was already existing)
- This centrifuge can subject test packages weighing up to 7,260 kg to 100 g, or lighter weight packages up to 300 g.
- Such facility does not exist in Europe. Test will probably have to be done in US



Deceleration Testing

- Centrifuges up to 200 g for equipment exist in Europe (DLR, Berlin, **Centrifuge Z100 / 200)**
  - Max. payload: 200 kg (at 50 g)
  - Max. acceleration: 200 g (with50 kg)
  - Max. dynamic load: 100 000 N
  - Effective central radius: 1800mm
- For components even higher levels can probably be achieved in Europe on smaller centrifuges (tbc)
- At probe level test is preferable over analysis because property or workmanship variations can initiate failure under extreme loads, in particular for non-conservative structures, e.g. TPS, EDS

Pressure Testing

- During descent high pressure, up to 100 bar is encountered by the probes.
- Pressure testing up to such pressures is not difficult, but typically high pressure chambers are not used in aeronautical testing.
- Identification of suitable facilities, in particular concerning cleanliness is necessary. Possibly such facility needs to be procured.

Testing Conclusions

- Validation of CFD models is the key issue. More detailed investigation on the existing European facilities is needed to assess limitations
- Faithful reproduction of flow field and associated phenomena will be anyway impossible
- Heat flux computation will be subject to high uncertainty. High margin on TPS design required
- Testing of TPS at the required high fluxes is possible on small samples
- High qualification factors will have to be applied (e.g. factor 2 on heat fluxes)

Model Philosophy

	Probe Models					
	Sample	**SM**	**EM**	**QM**	**Scaled models**	**FM**
TPS	For high thermal flow test	X		X		X
Entry and Descent System	For high thermal flow test	X		X	Hypersonic testing + high thermal	X
Parachutes	TBD			TBD units for optimisation + qualification	Aerodynamics testing	X
Descent Module		Including acceleration & pressure test	Functional testing	Functional and environ. tests	Aerodynamics testing	X
Probe System			Separation, Comm's etc.	EM+ environm. + ref. ground config.	TBD	X

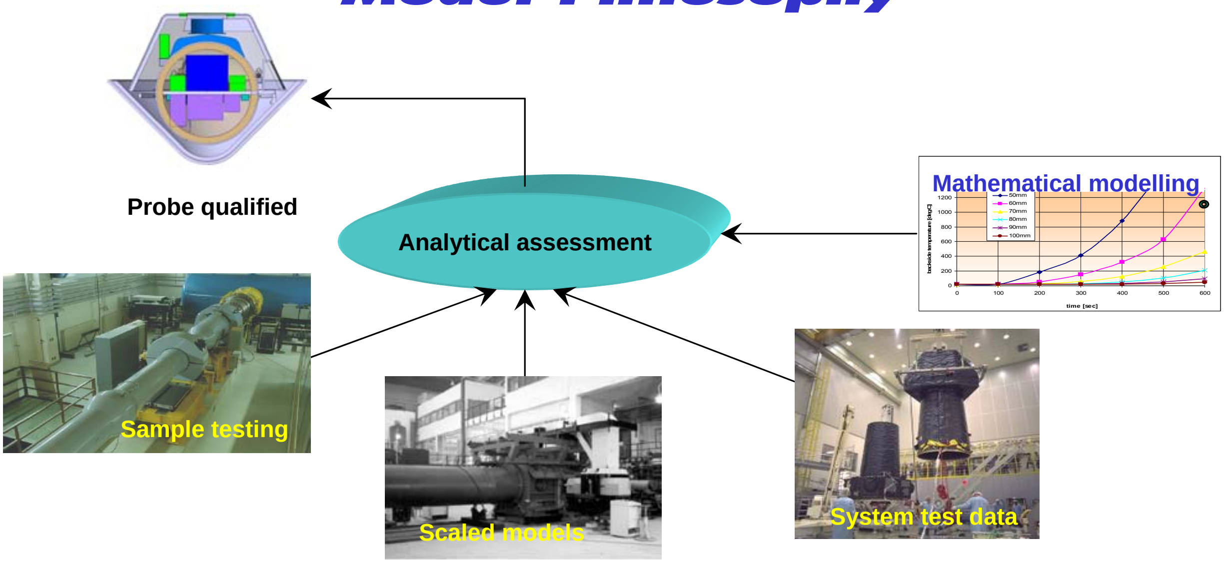
Model Philosophy

	Description	Remarks
SM Structural Model	Flight standard structures and mechanisms	Pressure tests required on all sealed structures
EM Engineering Model	Functional and electrical performances represented. Commercial components.	Also representative of layout, shapes and interfaces.
QM Qualification Model	Full flight standard with all redundancies.	Shall include acceleration and pressure tests. Facilities TBD
Scaled models	Representative for aerodynamics / aero-thermal (depending on the test)	Special facilities needed for the higher part of the aero-thermal field
FM Flight Model	Flight vehicles, including spare units and parts	Including pressure tests
Samples	Assessing TPS and shield vs. high aero-thermal	Special facilities needed

Model Philosophy

- Environmental test is challenging due to outer planet's and Venus' extreme environment
- In addition to providing adequate facilities, also making representative testing is a hot topic
- i.e. extreme environment conditions could be reached, but not in the proper combination, or not for long enough
- Qualification will anyway have to trust analytical extrapolation on top of correlation
- Thus the extreme environmental conditions will NOT be qualified on a FULL SCALE test model.
- Unit level: acceleration qualification needed

Model Philosophy



Schedule Assumptions

- Only one probe is considered here – building two probes together, even for different planets, will benefit from each other
- Most of the development on TPS material shall be completed within Phase B.
- TPS material development should begin about 3 years before Probe Phase B K.O. (even by making use of ***existing*** facilities)
- Combined functional tests with an Orbiter are taken into account in the schedule
- Combined environmental tests with an Orbiter are taken into account
- Orbiter development is not included

Schedule Assumptions

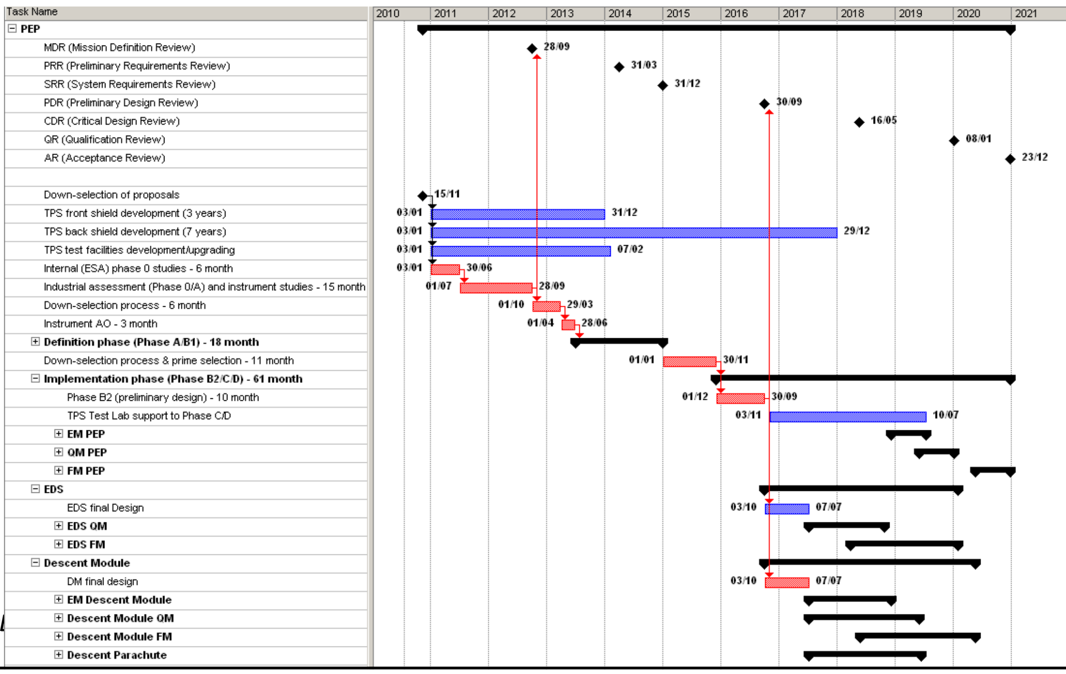
- Facility needed for qualifying the Probe TPS, should be ready and operational ***by the beginning of Phase B***
- Facility should be kept available ***along Phase C/D until QR***, in support of Probe development.
- NOTE: EM Probe level functional tests are marked on the schedule as TBD because there is a possibility that they are not needed, in case all functions can be verified at DM EM level.

(Free piston shock tunnel HEG, Picture: Courtesy DLR)

Schedule Assumptions

- Assessment phase starting in 2011, duration 2 years
- Phase A / B1 duration 2 years
- Phase B2 / C / D duration 5 years

Overall Schedule



Summary & Critical Issues

- TPS qualification and acceptance
- Equipment qualification and acceptance for very high deceleration
- System qualification and acceptance for high pressure
- Long mission duration to outer planets *(Will it still work?)*
- Planetary protection issues?
- Use of RHU has an important impact on programmatics

Conclusions

- Provided development starts early 2011, the acceptance review could be foreseen end 2020
- This requires early identification of detailed development and verification approach and ensuring the readiness and availabilty

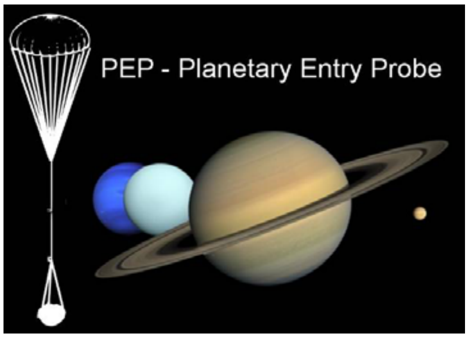
PEP
Planetary Entry Probes

Risk

Internal Final Presentation

ESTEC, 30th June 2010

Prepared by the PEP/ CDF* Team



(*) ESTEC Concurrent Design Facility

Outline

- Risk Management Policy
  - Objective
  - Project Goals
  - Severity & Likelihood Categorizations
- Top Risk Log
- Probabilistic Risk Assessment
- Conclusions

Risk Management Policy: Objective

- **Maximize** the probability of achieving **PEP's** intended goals and to contribute to the projects' risk management process
- The CDF risk management policy for **PEP** aims at **handling risks** which may cause serious negative cost, schedule, technical and/or science value impacts on the project
- **Risk Management Process definition:**

An organized, systematic decision making process that efficiently identifies, analyzes, plans, tracks, controls, communicates, and documents risk to increase the likelihood of achieving the project goals.

Risk Management Policy: Project Goals

SRE	The Planetary Entry Probe(s) shall investigate the characteristics of the Planetary atmospheres of Venus (VEP), Saturn (SEP), Uranus (UEP) and Neptune (NEP): ● Atmospheric profiles (temperature, pressure, density) ● Chemical composition (abundances & isotopes) ● Optical properties and features (surface and atmosphere) ● Measure wind direction and magnitude
Technical	The Planetary Entry Probe(s) platform shall perform correctly during all mission phases incl. launch, transfer, separation, **coast, entry, and descent.**
Schedule	Mission Timeframe shall be 2020-2035
Cost	Cost at completion shall be within the M-class mission budget

Risk Policy: Severity/Likelihood Categorization & Risk Index

Severity	Schedule	Science	Technical (ECSS-Q-30 and ECSS-Q-40)	Cost
Catastrophic 5	Launch opportunity lost	Failure leading to the impossibility of fulfilling the mission's scientific objectives.	Safety : Loss of system, launcher or launch facilities. Loss of life, life-threatening or permanently disabling injury or occupational illness; Severe detrimental environmental effects.	Cost increase result in project cancellation
Critical 4	Critical launch delay (TBD) months	Failure results in a major reduction (70-90%) of the mission's science return.	Dependability: Loss of mission. Safety: Major damage to flight systems, major damage to ground facilities; Major damage to public or private property; Temporarily disabling but not life-threatening injury, or temporary occupational illness; Major detrimental environmental effects.	Critical increase in estimated cost (TBD M€)
Major 3	Major launch delay (TBD) months	Failure results in an important reduction (30-70%) of the mission's science return.	Dependability: Major degradation of the system. Safety: Minor injury, minor disability, minor occupational illness. Minor system or environmental damage.	Major increase in estimated cost (TBD M€)
Significant 2	Significant launch delay (TBD) months	Failure results in a substantial reduction (<30%) of the mission's science return.	Dependability: Minor degradation of system (e.g.: system is still able to control the consequences) Safety: Impact less than minor	Significant increase in estimated cost (TBD K €)
Minimum 1	No/ minimal consequences	No/ minimal consequences.	No/ minimal consequences.	No/ minimal consequences.

Score	Likelihood	Definition
E (5)	Maximum	Certain to occur, will occur once or more times per project.
D (4)	High	Will occur frequently, about 1 in 10 projects Pf=0.1 R=0.9
C (3)	Medium	Will occur sometimes, about 1 in 100 projects Pf=0.01 R=0.99
B (2)	Low	Will occur seldom, about 1 in 1000 projects Pf=0.001 R= 0.999
A (1)	Minimum	Will almost never occur, 1 in 10000 projects Pf=0.0001 R=0.9999

Severity					
5	5A	5B	5C	5D	5E
4	4A	4B	4C	4D	4E
3	3A	3B	3C	3D	3E
2	2A	2B	2C	2D	2E
1	1A	1B	1C	1D	1E
	A	B	C	D	E
					Likelihood

Top Risk Log

Risk Type	Risk index	Risk scenario	Classification	Cause	Mitigating Action 1	Mitigating Action 2	Mitigating Action 3
Launcher							
	5C	Launch window constraints for missions to outer planets (Uranus, Neptune and to a lower extent Saturn).	Schedule	Very lengthy gap between launch windows. Missing launch opportunity would imply mission cancellation.	Plan schedule accordingly with sufficient risk margins.	At least 6 month margin between FAR and the launch campaign.	Baseline launch date offering 2nd launch opportunity within acceptable timeframe. (e.g. Neptune LD 2030 case)
Mission							
	4D	Uncertainties related to planetary atmospheric models specially in the case of the outer planets (Uranus and Neptune) with impact on the TPS materials choice and design.	Technical	Wrong estimates of heat fluxes, heat loads (int. of heat fluxes), peak deceleration.	Refine atmospheric models and entry trajectory analyses for the outer planets.	Design including sufficient safety margin	
	4D	Long mission lifetime for outer planets.	Technical	18-20 year transfer time for Neptune and Uranus entry probe missions. Challenging reliability issues.	Technology investment/development required.	New technology qualification approach focusing on assurance of long duration missions.	Optimize trajectories, study alternative propulsion technologies to reduce transfer time.
	4C	Critical probe-orbiter tracking, targeting & separation sequence. Heavy impact on spacecraft operations.	Technical	High accuracy of spacecraft targeting. Tracking required. Compressed schedule demands a lot of preparation and many simulations.	Relaxed release sequence. Release at least 20 days ahead of entry (piggy-back case).	Use doppler double maneuver sequence (preferred OPS) which reduces insertion error as compared with doppler single maneuver. ΔDOR Single Maneuver requires only 6 days rather than 20 days but is very time pressed and requires continuous coverage.	Insert safe mode recovery slots into planning.

Top Risk Log

Risk Type	Risk index	Risk scenario	Classification	Cause	Mitigating Action 1	Mitigating Action 2	Mitigating Action 3
Mission							
	4C	Critical planetary entry conditions. Limited entry trajectories satisfying all requirements (sun illumination, Earth visibility (DTE comms) or orbiter visibility (relay comms). Short probe coverage time throughout descent.	Technical	Sun illumination. Loss of orbiter/Earth visibility before end of nominal science mission.	Optimize entry trajectories to maximize probe coverage throughout descent.	Accept limited entry cases.	Use redundant DTE & relay communication.
	4B	Critical Saturn ring gap crossing. Particle collision risk.	Technical	Higher probability of impact with small size debris (water Ice).	Precisely defined ring regions. Relatively well-known environment.	Low impact probability if passage is at clear gaps (e.g. between the rings F and G rings)	Single ring crossing. Appropriate shielding.
	3D	Planetary protection issues impact on technical requirements and schedule.	Schedule/technical	Forward contamination of target celestial bodies. Requirements on documentation, cleanliness standards, and sterilization.	COSPAR PP classification: Category I: Venus. No protection of such bodies is warranted and no planetary protection requirements are imposed by this policy. Category II: Saturn, Uranus, and Neptune.	Outer planets: Preparation of a short planetary protection plan is required for these flight projects primarily to outline intended or potential targets, brief Pre and Post-launch analyses detailing strategies, and a End-of-Mission report.	Plan schedule accordingly with sufficient margins to account for PP related delays.

Top Risk Log

Risk Type	Risk index	Risk scenario	Classification	Cause	Mitigating Action 1	Mitigating Action 2	Mitigating Action 3
Platform							
	4D	Low TRL of mid/low density ablative TPS heat shield materials (optimal TPS solution for Venus case instead of heritage Carbon Phenolic). Development risk implications	Schedule/technical	Large number of non-qualified materials or elements at research level only. Development challenges.	Development program to raise the TRL and reduce the risk of ablative TPS materials and heat shield systems.	Invest in technology and testing. Evaluate arc jet and other testing capabilities. Piecewise determination of material properties and failure modes. Certification by combination of testing and analysis	Development time is considered sufficient given launch date objectives (2020-2035).
	4D	Uncertainties in RF signal atmospheric losses in Venus/Saturn/Uranus/Neptune.	Technical	Atmospheric loss can be significant due to high pressure. Clouds can cause high attenuation at specific frequencies. Planet radiation can also block some frequencies.	An assessment of the atmospheric composition shall give the final exact frequency.	A scenario in which the carrier is directly overhead as the probe goes deep in the atmosphere of the entry planet is suitable.	Select appropriate frequency to minimize signal attenuation.
	4D	Uncertainties in parachute deployment dynamic pressure leading to parachute malfunction, insufficient drag, higher than expected descent velocity.	Science/technical	Uncertainties in the external environment (atmospheric density), deployment Mach number.	Design parachute to operate safely without failure in a wide range of dynamic pressures.	Refine atmospheric models and entry trajectory analyses for the outer planets.	

Top Risk Log

Risk Type	Risk index	Risk scenario	Classification	Cause	Mitigating Action 1	Mitigating Action 2	Mitigating Action 3
Platform							
	4D	Criticality of 100 bar pressure vessel and associated technologies and testing facilities.	Schedule/technical	No existing European representative testing facilities. PV's represent one of the single largest mass elements in a deep atmospheric probe. Present state of the art PV technologies are not adequate for the mass requirements of these missions.	Appropriate PV design guidelines with adequate margins.	Develop manufacturing engineering plans and obtain prototypes for leading candidate materials. Perform testing on prototypes under representative environmental conditions for temperature and pressure survivability.	Invest in testing facilities.
	4D	Critical planetary entry parachute technology and related control systems.	Schedule	Low TRL of representative European parachute technologies.	Beagle2 heritage (Lindstrand Technologies Limited UK)	Invest in European technology and testing facilities.	Sub-contract to US manufacturers in case of schedule constraints (e.g. IRVIN Aerospace (USA) was responsible for Huygens' parachutes and the probe's descent control sub-system under contract to Martin-Baker Space Systems UK)
	4C	Critical Planetary Entry Probe separation and entry sequence (incl. carrier separation, parachute deployment/jettison, front/back shield separation, harness cut)	Technical	Single Point Failure Mechanisms	Single actuation and short duration events.	Mechanisms' reliability should be demonstrated to be greater or equal to the reliability goal with at least 95% confidence. Use mechanisms with heritage (e.g. Cassini-Huygens)	All Pyrotechnic devices are equipped with redundant ESA standard actuators.

Top Risk Log

Risk Type	Risk index	Risk scenario	Classification	Cause	Mitigating Action 1	Mitigating Action 2	Mitigating Action 3
Platform							
	3E	Challenging thermal-structural analysis for ablative materials.	Technical	Statistical material properties do not exist for most TPS materials. Obtaining mechanical properties (highly non-linear) across a wide temp. range is challenging and for TPS materials often produce large variations. Failure modes are poorly understood.	Thermal-structural design and analysis based upon FEM is insufficient – combined environment testing, with thermal gradients and mechanical loads is needed	Experience/time required to develop a credible and validated series of FEM models for an integrated heat shield to assess various load cases.	Invest time in establishing an acceptable thermal-structural margins policy.
	3E	Heritage carbon phenolic from Pioneer-Venus and Galileo (Venus entry case) no longer manufactured.	Schedule	Very limited supply of heritage CP. Current CP employs carbon cloth derived from new rayon source. Limited arc jet tests show performance similar to heritage	Characterization and qualification is straightforward but will require time and resources. Test in high energy laser facility to demonstrate capability at max combined heat flux. Verify absence of failure modes.	Test in CO_2 arc jet to demonstrate applicability of theoretical thermochemical ablation models to performance in Venus atmosphere.	Validate/update heritage in-depth thermal response models via arc jet tests of instrumented samples at well-defined conditions. Combine surface ablation and in-depth thermal response models into Venus entry design model for carbon phenolic.

Top Risk Log

Risk Type	Risk index	Risk scenario	Classification	Cause	Mitigating Action 1	Mitigating Action 2	Mitigating Action 3
Platform							
	3D	Limited capability of ground testing facilities (arc jet) for TPS ablative materials (e.g. EADS Simoun 6 MW Facility or DLR L2K)	Schedule	Low number of available testing facilities. Even an ideal ground test facility will not fully replicate flight environments forcing difficult ground-to-flight traceability efforts. Prone to high down time.	Plan schedule accordingly. Insert margins in schedule.	Invest in facilities.	
	3C	Ablative materials manufacturing complexity	Technical	Restarting the manufacturing of previous TPS materials takes significant time and resources. Significant fabrication experience is required to produce quality and consistency.	Investment required to establish necessary infrastructure.	Selection of experienced TPS manufacturer.	

Risk Index Chart

- High risks are typical of a Pre-Phase A Project. Areas with lack of definition or little previous experience pose a priori more risk to the mission and therefore are the ones with more risk reduction potential.
- Experience shows that all risk items with a critical risk index (red/yellow area) must be analyzed and proposals for risk treatment actions elaborated.
- For the remaining risk items there is an alert with respect to a possible increase of the Risk Index.
- In the end, ideally all risk items should reach a level of justifiable acceptance.
- The risk management process should be further developed during the project definition in order to analyze the entire system, refine the risk identification and classification, and provide evidence that all the risks have been effectively controlled.

Severity					
5			1		
4		1	3	7	
3			1	2	2
2					
1					
	A	B	C	D	E
					Likelihood

PRA

- Methodology* based on Event Sequence Diagrams (ESD)
- Modelling capabilities:
  – System hierarchy and mission timeline
  – Each scenario in an ESD consists of a unique sequence of occurrences and non-occurrences of pivotal events leading to an end state, which designates the severity of the outcome of a particular scenario
- Analysis Procedure:
  – Individual EDS's are resolved , resulting in Boolean expressions for each scenario and state
  – Results of individual ESD's are aggregated, in order to compute risk at higher levels in the system hierarchy

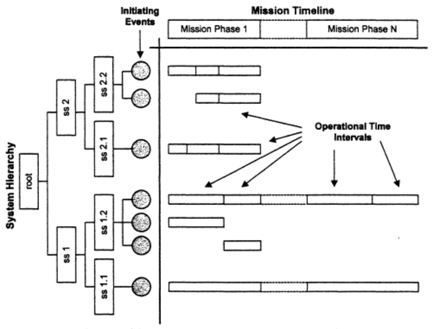


Figure 1: High-Level Model Structure based on System Hierarchy and Mission Timeline.

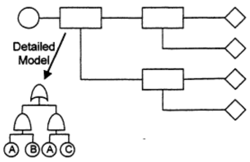


Figure 2: Multilayered Event Sequence Diagram / Fault Tree model.

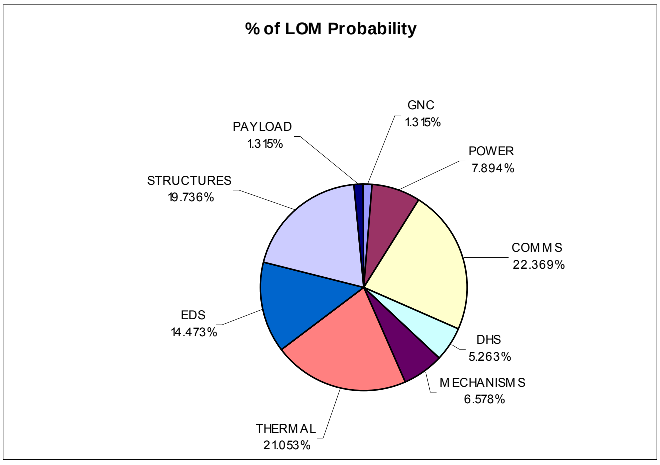
*Source: Mosleh, A., Rutledge, P. , Groen, F.J., "QRAS for Space Mission PRA" , Procedings of Joint ESA-NASA Space Flight Safety Conference, ESTEC, Noordwijk (NL), 11-June 2002 (ESA SP-486, August 2002)

PRA Assumptions

- Equipment list and redundancy from VEP CDF Model
- Mission timeline begins at t=0 orbiter separation and consists of 3 main phases:
  – Cruise
  – Entry
  – Descent
- Equipment operational intervals and/or actuation times from CDF Model
- Equipment failure rates extracted from in-house database (time based-operational interval)
- Point value estimates for on-demand based events
- No uncertainty considered in input variables

PRA Results

- VEP System End State Results:
  - Loss of Mission (LOM) Probability: 19.03%
  - Minor Mission Degradation: 11.98%
- % contribution by S/S to LOM Probability
- # Cut sets leading to LOM considering all mission phases:90
  - Max Order 2: 53
  - Max Order 3: 36
  - Max Order 4: 1



Conclusions

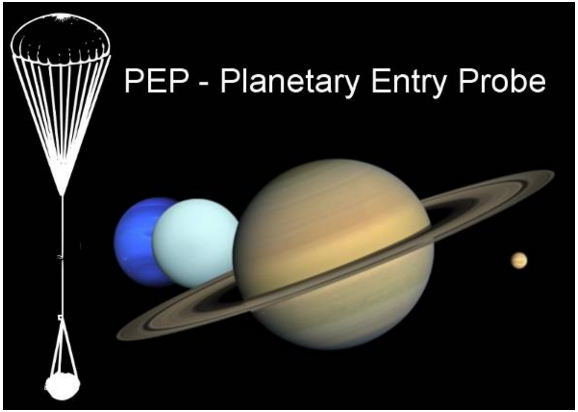
- Environment
  - Atmospheric modelling and its impact on TPS, communication, and EDL (parachute deployment)
- Technology Development
  - European low density TPS materials and manufacturing processes
  - European parachute technology
  - 100 bar pressure vessel
- Major Mission Events (Targeting/Separation/Entry/Descent)
  - Minimize SPFs
  - Demonstrate mechanisms/EDL system reliability on-ground
- Long mission duration (lifetime) for outer planets
  - Uranus & Neptune transfer time 18-20 years

PEP
Planetary Entry Probes

Annex I: Atmospheric Models for Outer Planets

IFP

ESTEC, 30th June 2010



Prepared by the PEP/ CDF* Team

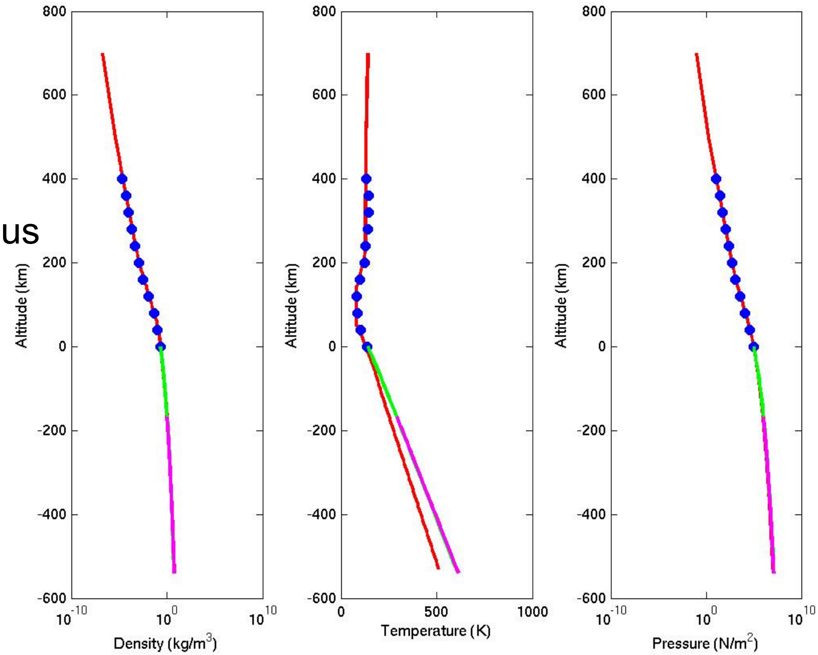
(*) ESTEC Concurrent Design Facility

Atmospheric Models for Saturn

- Initial models used in the calculations were derived by ESA technical support and are denoted as Reference [B]
- These models have been compared to the data provided in [RD1: Giant Planets of Our Solar System: Atmospheres, Composition, and Structure; P.Irwin; 2009] and [RD2: The Planetary Scientist's Companion; K. Lodders, B. Fegley Jr, 1998].
- Furthermore, the models have been compared to models kindly provided by Dr. A. Coustenis of the SSEWG: [RD5: Tristan Guillot, published in Guillot, 1999 "A comparison of the interiors of Jupiter and Saturn", Plan. Space Sci. 47, 1183; and Saumon & Guillot, 2004, "Shock Compression of Deuterium and the Interiors of Jupiter and Saturn", ApJ 609, 1170; numerical data via personal communication].
- General remarks about the models:
  - Profiles for simulation are for +700 to -500 km for Saturn. Profiles available through references cover only parts, [RD5] mainly the lower parts from > 1bar. This data does not affect the entry phase but impacts the descent phase.
  - The models from [RD5] differ strongly in the altitude at which they reach 10 bar. Within 2 km there is a 9 bar discrepancy between the models.
  - 1 bar altitude shifted to 0 km to make comparison possible (reference used at CDF).
  - Two models provided: One static homogeneous model without He discontinuity at 1 Mbar (not matching observed J4) and one static model with He discontinuity at 1 Mbar (matching observed J’s)

Comparison to References - Saturn

- Red Lines: Model used in study [B]
- Blue dots: RD[1,2]
- Green Line: RD[5], Model w/ He - discontinuity
- Magenta Line: RD[5], static homogeneous Model w/o discontinuity



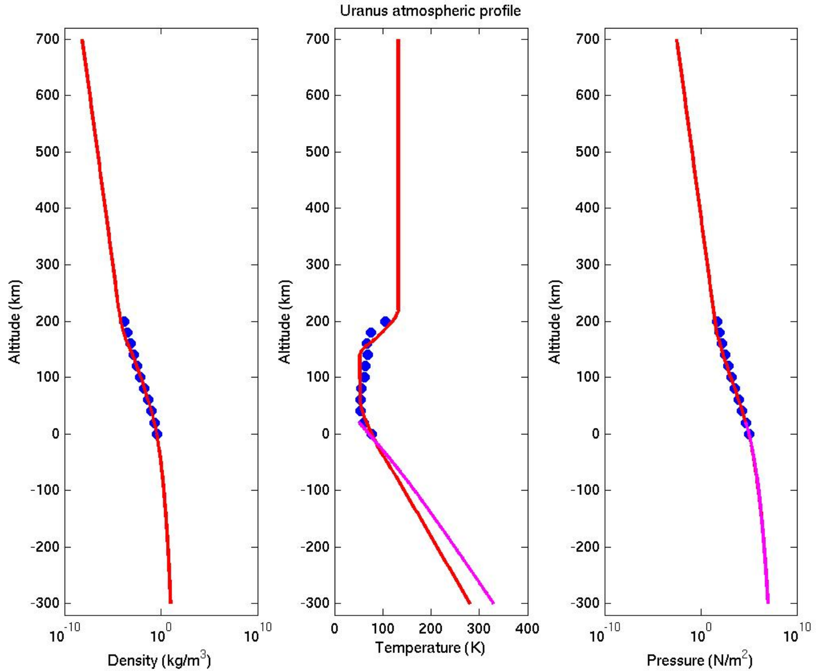
- Evaluation:
  - Density difference is <2% between [B] and [RD5] (both models)
  - Pressure difference <15% between [B] and [RD5] (both models)
  - Temperature profile differs strongest by <18% (gradually increasing to that value with depth)
  - ***Good agreement between models in lower parts***

Atmospheric Models for Uranus and Neptune

- Initial models used in the calculations were derived by ESA technical support and denoted as Reference [B]
- These models have been compared to the data provided in [RD1: Giant Planets of Our Solar System: Atmospheres, Composition, and Structure; P.Irwin; 2009] and [RD2: The Planetary Scientist's Companion; K. Lodders, B. Fegley Jr, 1998].
- Furthermore, the models have been compared to models kindly provided by Dr. A. Coustenis of the SSEWG: [RD3: M. Herzig et al., in preparation, obtained via personal communication] and [RD4: Fortney, Ikoma, Nettelmann, Guillot & Marley, submitted to Icarus, via personal communication].
- General remarks about the models:
  - Profiles for simulation are from +700 to -300 km for Uranus and +600 to -225 km for Neptune. Profiles available through references cover only parts, [RD3,4] mainly the lower parts from +20 to -400/500 km. This data does not affect the entry phase but impacts the descent phase.
  - There are relatively large differences between [RD3 and RD4]
  - Differences in the lower part, however, mainly lead to different descent timing and thermal evolution.
  - Taking into account the largest differences, the margin policy applied during the study should be able to cope with these variations during entry and not lead to significant impacts on the design. (cf the sensitivity analysis and margin policy sections)

Comparison to References I - Uranus

- Red Lines: Model used in study [B]
- Blue dots: RD[1,2]
- Magenta Line: RD[3]



- Evaluation:
  - All profiles in good agreement
  - Pressure differences < 5%
  - Temperature differences <17%
  - Differences in the temperature profile mainly affect the thermal calculation but are small enough to be covered by the study margin

Comparison to References II - Neptune

- Red Lines: Model used in study [B]
- Blue dots: RD[1,2]
- Magenta Line: RD[3]
- Green Line: RD[4]

- Evaluation:
  - Except temperature, profiles in good agreement
  - Between [B] and [RD3]: <5% difference in pressure, <20% difference in temperature
  - Between [B] and [RD4]: density differs by factor of 2, pressure by factor 2 ½ , temperature max. difference is factor 2.
  - Between [RD3] and [RD4]: roughly as between [B] and [RD4].
  - In general, [RD4] profiles change faster with altitude than [B] and [RD3].