PHOEBUS
a hypervelocity entry demonstrator

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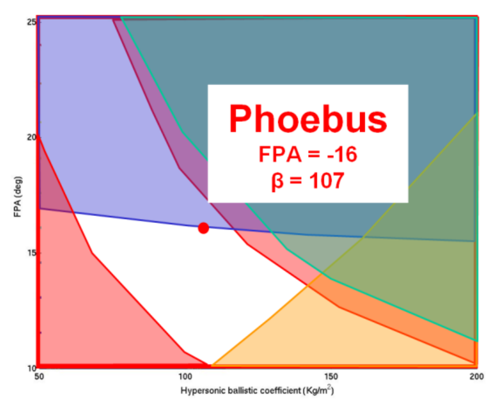

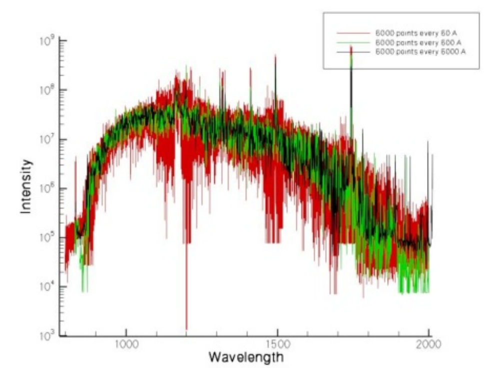

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Outline

Introducing PHOEBUS Project for a High-speed Of Entry Ballistic multi-User System

- Technological objectives
- Rationale
- Relevance
- Heritage

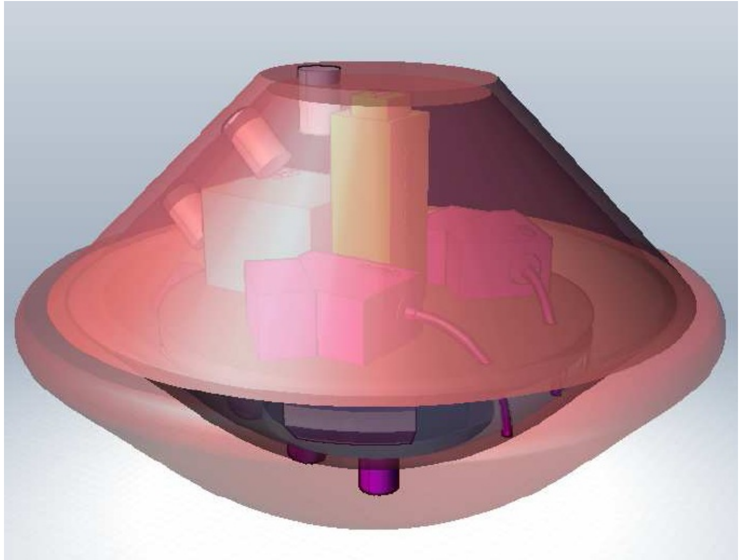
An aerothermodynamics assessment

- A parametric analysis of the re-entry phase
- A non-equilibrium reacting CFD analysis…
- …with radiation transport

Final remarks

Technological Objectives

- **First ESA Demonstrator for high speed entry applications**
- **Maturation and demonstration of critical technologies for:**
  - ✓ Materials for Thermal Protection Systems (light ablators)
  - ✓ Aerothermodynamics Tools (uncertainties)
  - ✓ Entry Descent and Landing Systems
  - ✓ Concepts for crushable structures
  - ✓ Sensors for harsh environments
  - ✓ Data for design for demise
  - ✓ Data for space surveillance
  - ✓ Data for civil security
  - ✓ Radiation Data Base
  - ✓ Recovery operations…



Rationale

	EXPERT 	IXV 	PHOEBUS 
Objective	Flight platform for data acquisition on critical LEO-entry aerothermodynamics	Intermediate system demonstrator for LEO operations	Technologies demonstrator for hypervelocity entries
Beneficial for	Aerothermodynamics design of mission to LEO	Cargo and Human Space Transportation from/to LEO	Small sample return missions from Moon, Mars, NEO, Lagrange Points
Entry speed	5 km/s (sub-orbital)	7 km/s (orbital)	12 km/s (hyperbolic)
TPS	Metallic & ceramic	Ceramic & ablator	Lightweight ablator
EDL	Ballistic & supersonic parachute	Aerodynamic controlled & supersonic parachute	Ballistic & crushable structure

Relevance

- **Useful for Science, Robotic Exploration and Human Space Flight Missions**
  - ✓ Pathfinder for any sample return mission
  - ✓ Mastering technologies for hard landing
  - ✓ Mastering sensors for harsh environments

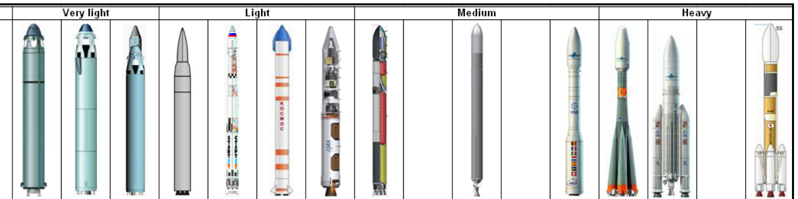
- **Crosslink contribution to**
  - ✓ CleanSpace Program, Design for Demise
  - ✓ Surveillance of space (hypervelocity impact)
  - ✓ Civil security (hypervelocity entry)

- **SME's role improvement** (better positioning in the market)

Heritage

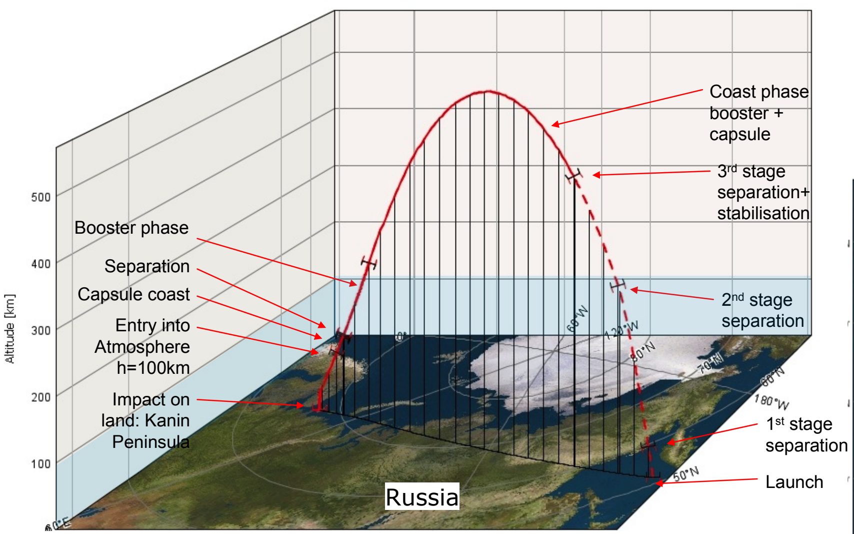
- Preliminary cooperation with KAIST
- 2 GSP (2008-2009) industrial phase A studies (TAS and AST primes, support from Makeev SRC)
- Different solutions found (but feasibility with Volna established)
- CDF study in Feb. 2011
- Four years development plan (Phase B/D) beginning of Phase B planned in 2012

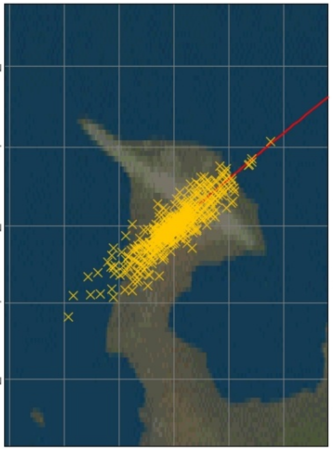
- The Concurrent Design Facility (CDF) at ESA-ESTEC is an integrated design environment for interdisciplinary and inter-directorate applications, based on concurrent engineering methodology
  - Real-time interaction between disciplines
  - Complete sharing of system/subsystem data
  - Active participation of the customer
  - Teamwork and real-time decision-making



Cathegory		Very light			Light				Medium				Heavy				
Name		Volna	Shtil 1	Shtil 2.1	Strela	Start 1	Kosmos	Epsilon	Dnepr	Rockot	F1e	Zenit	Vega	Soyuz	A5	PSLV	HII A
Origin		Russia	Russia	Russia	Russia	Russia	Russia	Japan	Russia		USA		Europe	Europe	Europe		Japan
Operational status		< 2016		Dev				Dev					Dev				
Launch type		D	D	D				D	D		D		D	PB	PB		
Compatibility	Smal	x	x	x				x	x		x		x	x	x		
	Large	x						x	x		x		x	x	x		
Require	KM	Yes	Yes	Yes				No (tbc)	No (tbc)		No (tbc)		Yes				

Different launcher considered





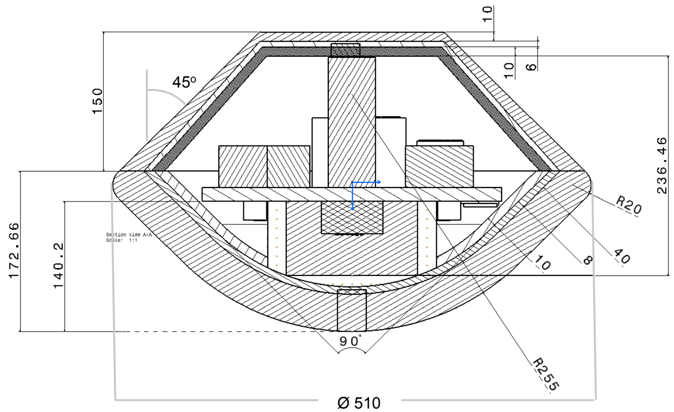
A typical trajectory (left) and landing dispersion (right) : Volna case

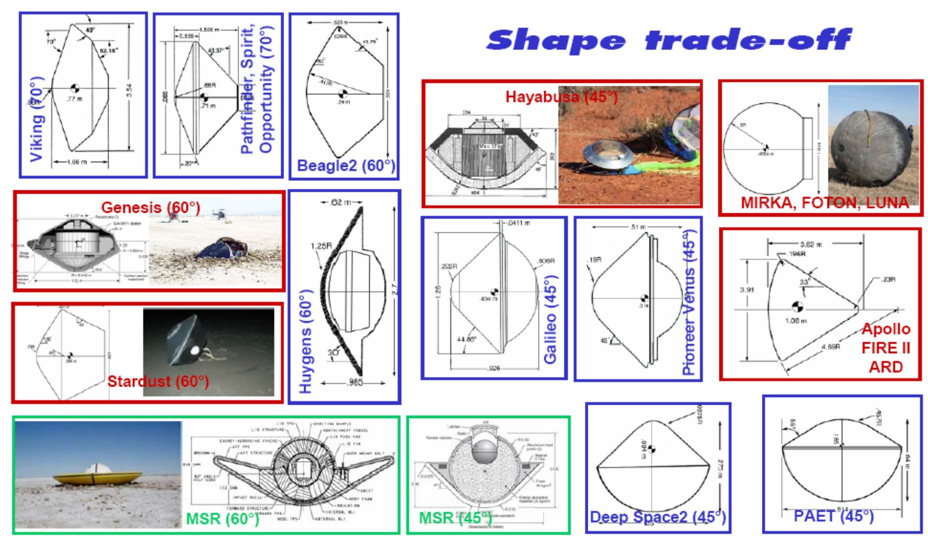
	Without Margin	Margin %	Margin kg	Total kg	% of Total
Target Spacecraft Mass at Launch				25.00 kg	
Below Mass Target by:				2.97 kg	
Dry mass contributions					
Structure	2.35 kg	19.05	0.45	2.79	15.23
Thermal Control	6.10 kg	20.00	1.22	7.32	39.85
Mechanisms	0.00 kg	-	-	-	-
Communications	1.20 kg	20.00	0.24	1.44	7.84
Data Handling	0.92 kg	9.89	0.09	1.01	5.51
GNC	0.28 kg	5.00	0.01	0.29	1.57
Propulsion	0.00 kg	-	-	-	-
Power	0.28 kg	20.00	0.06	0.33	1.80
Harness	1.00 kg	0.00	0.00	1.00	5.45
Instruments	3.63 kg	15.04	0.55	4.18	22.75
DLS	0.00 kg	0.00	0.00	0.00	0.00
Total Dry(excl.adapter)	15.74 kg			18.36 kg	
System margin (excl.adapter)		20.00 %		3.67 kg	
Total Dry with margin (excl.adapter)				22.03 kg	

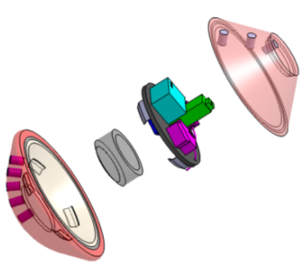
ERC mass break down

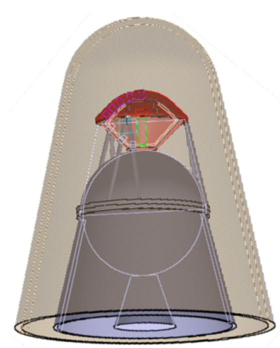
Small, simple capsule (Ø = 510 mm, m = 25 kg) to fit in many launchers, (integrated with a solid booster to provide ΔV), costs reduced to the minimum, instrumented:

- Passive descent system, no parachute
- Crash resisting memory and beacon
- Data storage for
  - Trajectory, stability & camera data
  - Temperature and pressure on TPS
  - radiative heat flux
- Passive navigation system, no ACS
- (HS-Camera for capturing booster-entry)









Parametric analysis of the re-entry phase

Assumptions

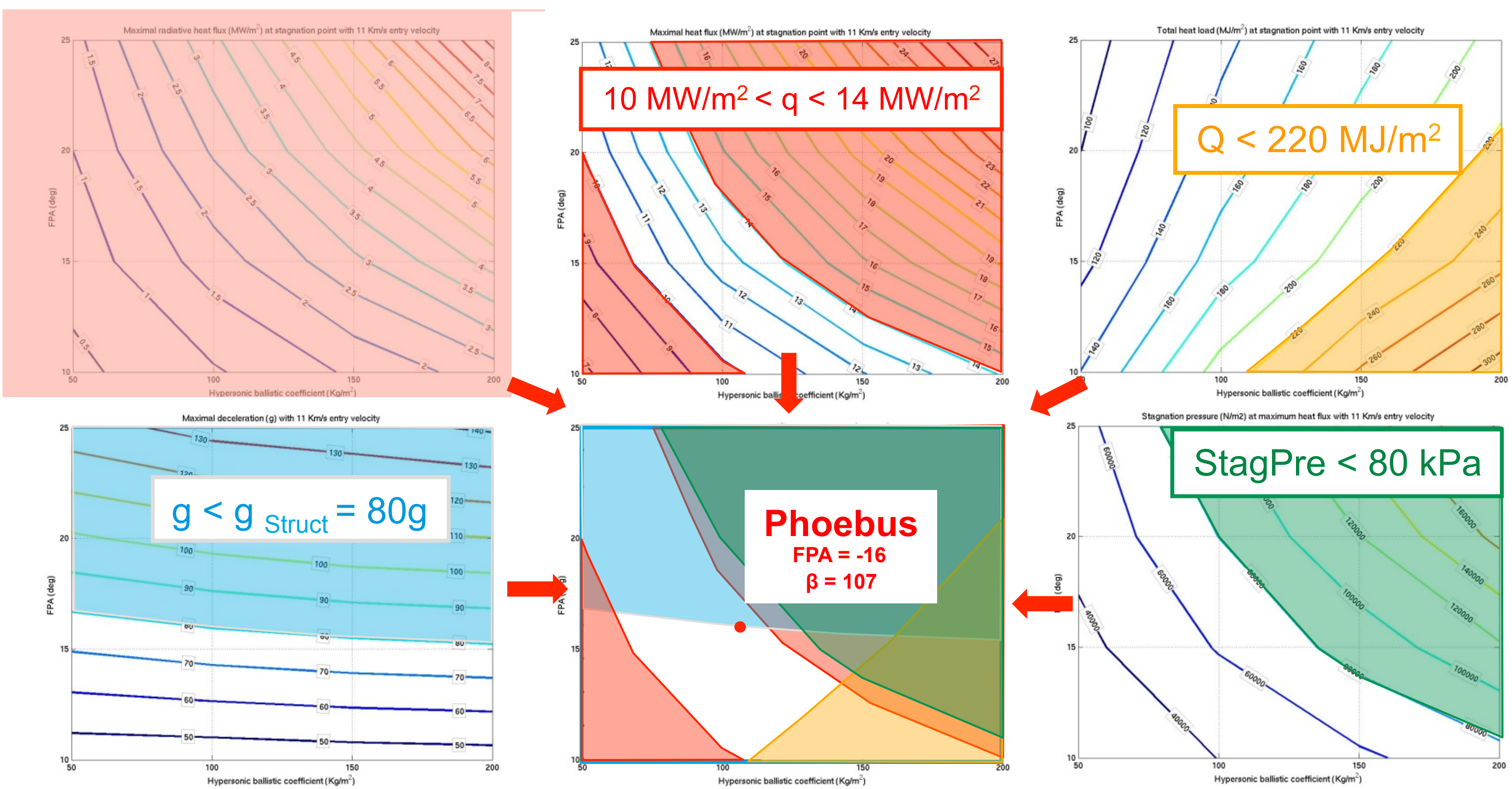
- Hayabusa aerodynamics coefficients have been assumed (scaled dimension)
- 3 degree of freedom TRAJ3D code (FGE)
- US 1976 standard model
- Detra-Hidalgo ($V < 9$ km/s) and Tauber-Sutton (9 km/s $< V < 16$ km/s) formulation for radiative heat flux; Detra and Hidalgo for the convective contribution

Parameters

- entry (inertial) velocity at the interface altitude of 120 km : 8 km/s – 12 km/s
- Flight path angles (FPA): -10 deg to -25 deg
- Different design configurations of the entry capsule have been included considering different ballistic: 50 kg/m² to 200 kg/m²

Constraints / Design Drivers

- (total) maximal heat fluxes below 14 MW/m² (requirement of DEAM)
- to be representative, minimum heat flux (at stagnation point) of 10 MW/m²
- total heat load below 220 MJ/m²
- maximal deceleration below 80 g
- stagnation pressure below 800 mbar at maximum heat flux (14 MW/m²)



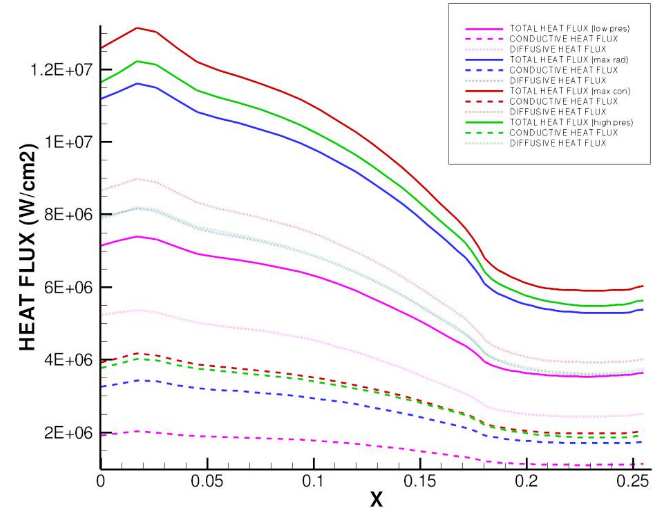
A non-equilibrium reacting CFD analysis…

4 points along the trajectory
- **Max convective**
- **Max radiative**
- **Low pressure**
- **High pressure**

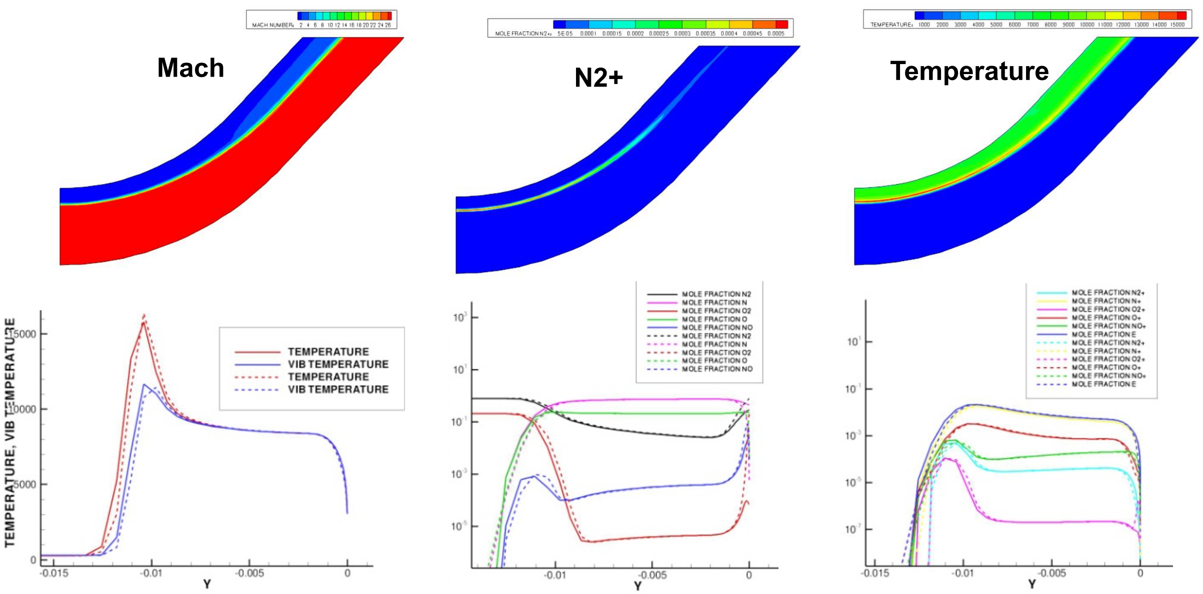
11 species air
2 temperature
2 wall conditions:
- **Fully-catalytic**
- **non-catalytic**

	time (s)	altitude (m)	density (kg/m3)	temperature (K)	pressure (Pa)	velocity (m/s)	mach
test 1: low pressure	18.4	64981	1.64E-04	233.3	10.96	10916	35.65
test 2: max rad	21.8	55449	5.38E-04	259.5	40.1	10348	32.04
test 3: max conv	24.1	49464	1.10E-03	270.6	85.28	9518	28.86
test 4: high pressure	26	45004	2.00E-03	264.2	149.1	8456	25.95

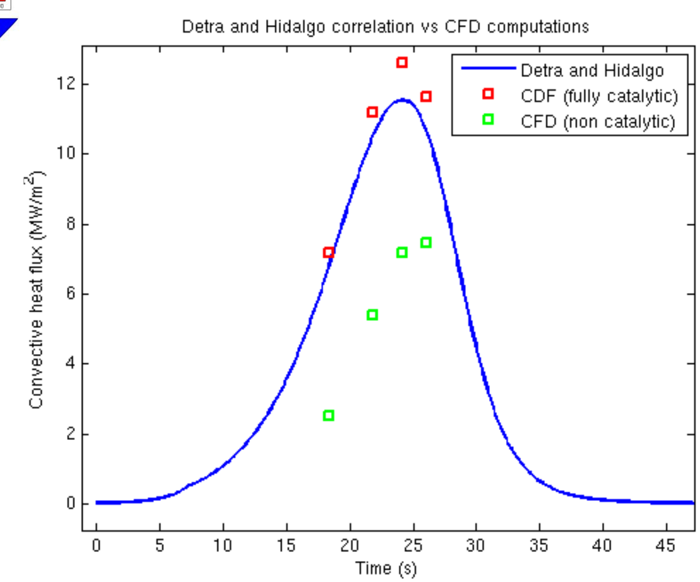
CFD test matrix



convective (total, conductive and diffusive) heat flux (fc)



Typical 2D plot (top) and stagnation line quantities (bottom) of max convective point (fc, nc)



Comparison of the simplified correlation and the CFD computations

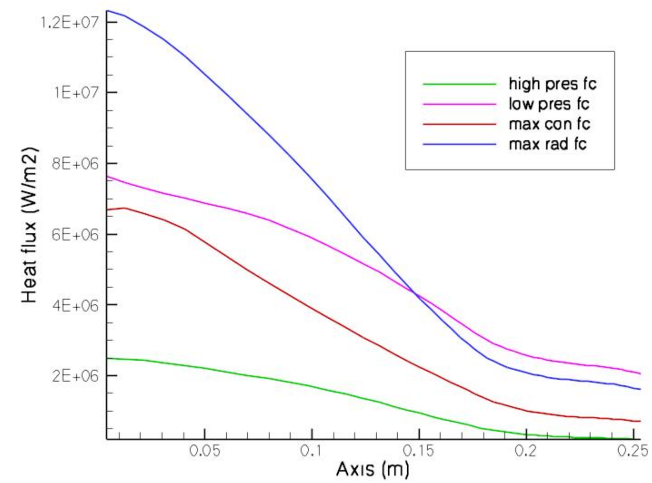
...with radiation transport

Radiative heat flux on the front (and back) shield computed has been computet (PARADE coupled with a Monte Carlo approach, HERTA)

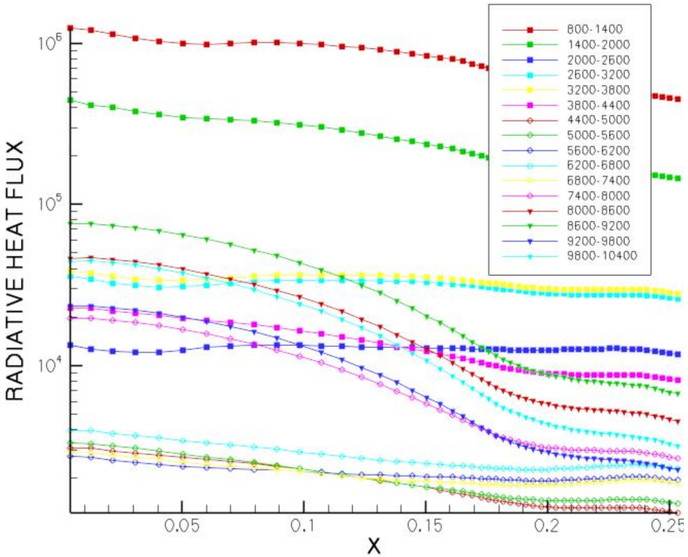
N, O, N^+ and O^+, N_2, O_2, NO, the molecular band systems, N_2 1st Pos, N_2 2nd Pos, N_2 Birge-Hopfield, O_2 Schumann-Runge, NO β, NO γ, NO δ, NO ε, N_2^+ 1st Neg and N_2^+

Equally wavelength discretization in the range between 800 Å and 10400 Å with resolution of 1 Å (for all four points)

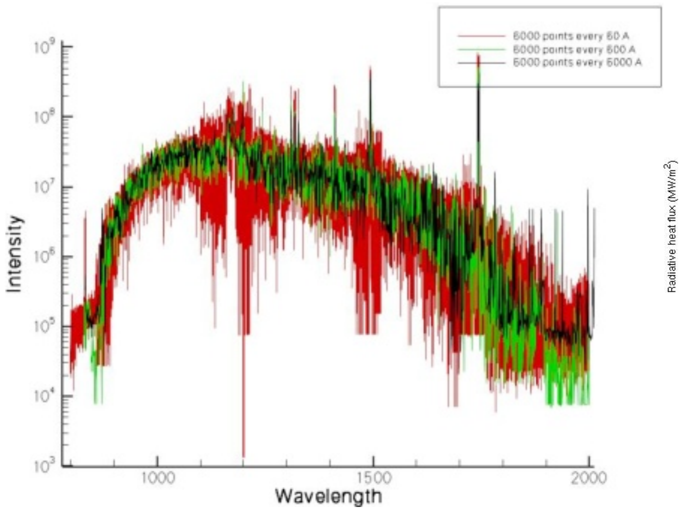
Employing 6000 (adaptive) points for each 600 Å wavelength interval (and 6000 points for each 60 Å wavelength interval) for max radiation point



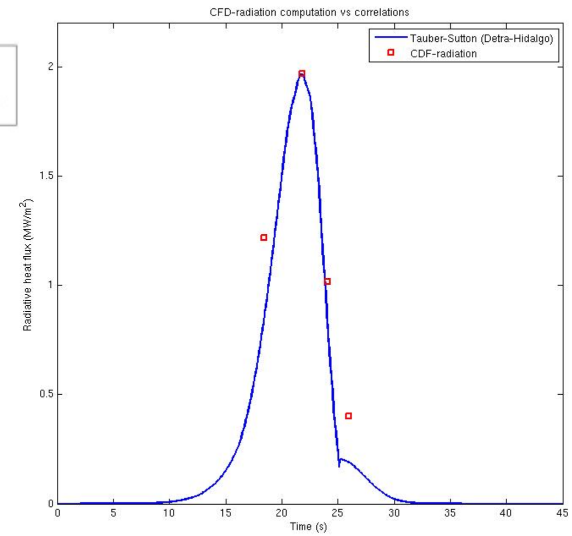
Radiative heat flux (fc) for the four different trajectory points between 800 Å and 10400 Å with 1 Å resolution



Contribution (at stagnation point) of different wavelength (6000 points for each 600 Å wavelength interval)



Comparison of the absorption coefficients (VUV range, stagnation point) calculated with different resolution



Comparison of the simplified correlation and the CFD-radiation computations

Final remarks: Phoebus is…

… relevant for

✓Science and Robotic Exploration

✓Human Space Flight Missions

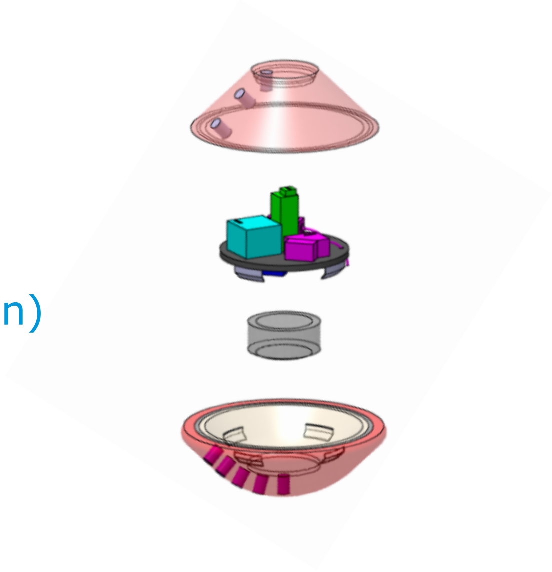
✓CleanSpace Program …

… a challenge mission with respect to …

✓EDL strategy

✓crushable-structure application (recovery)

✓instrumentation



… which requires more attention on

✓capsule stability

✓TPS performance (radiation/ablation, material regression)

… but FEASIBLE