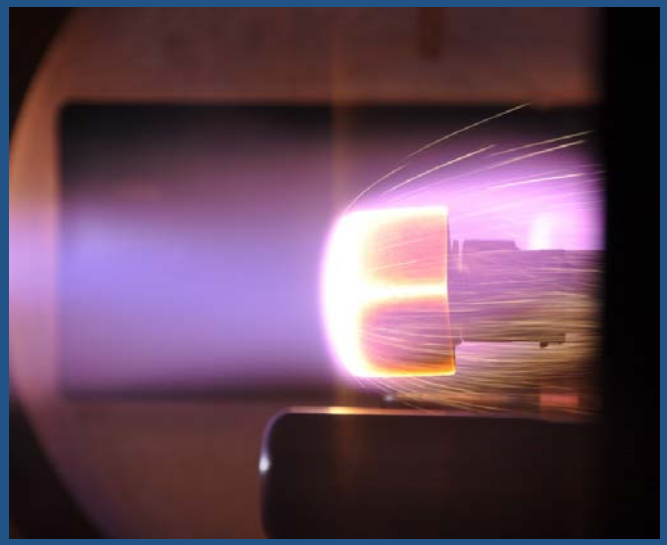
Atmospheric Entry Aerothermodynamics Flight Test On CubeSat Platform



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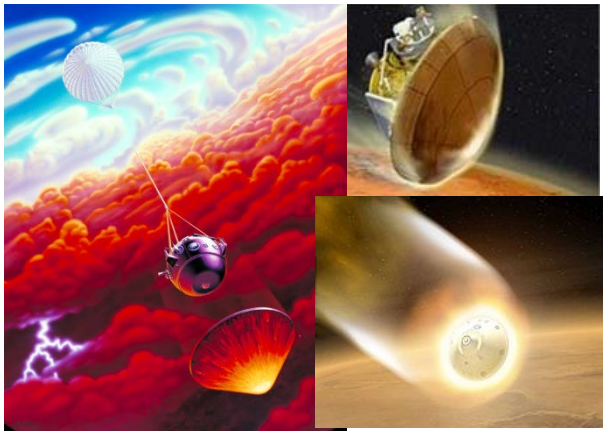
International Planetary Probe Workshop - 11
20.06.2014
Pasadena, CA, USA

von Karman Institute
Université de Liège

Atmospheric Entry Problem



A must for safety and efficiency of future manned/unmanned space missions

When approaching a planet with atmosphere..

→ Extreme aerodynamic heating
→ High Gas-Surface Interaction
→ Real gas effects and lots of chemical reactions
→ Thermal Protection Systems
→ Different stability regimes
→ Telecommunications blackout
→ Different and complicated attitude control requirements
→ …

What is missing?

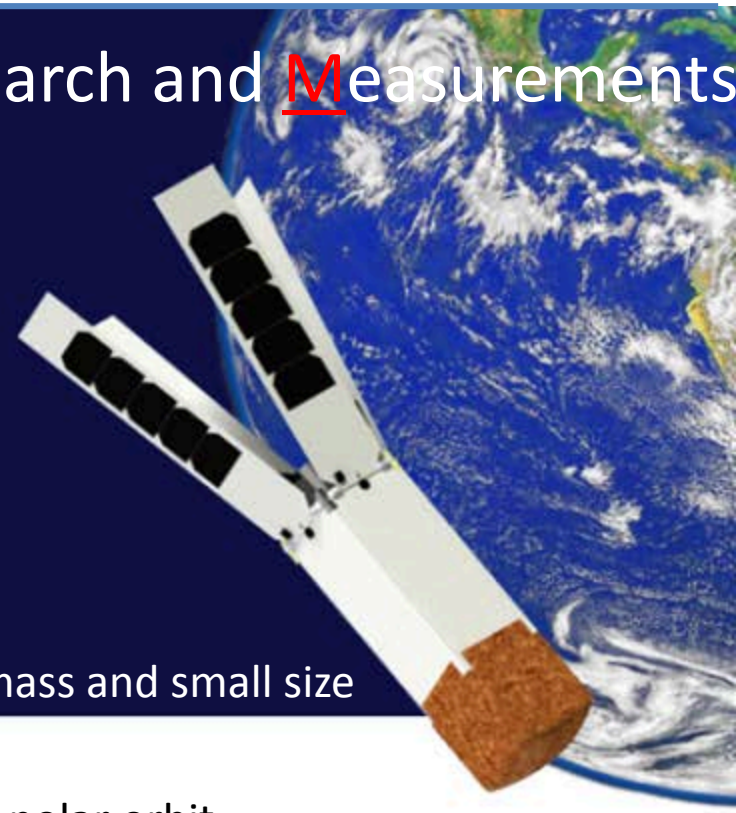
- Accurate **Flight-to-Ground Extrapolation Methodology** for simulating spacecraft on Earth
- **Real Flight Data** for validation of Ground Tests and Numerical Simulations

What is proposed?

- Part 1: Ground test methodology
- Part 2: QARMAN, the re-entry experiment vehicle <u>fully developed and launched by VKI&ULg</u>

QARMAN: A Real Flight Experiment

QubeSat for Aerothermodynamic Research and Measurements on AblatioN



Why a Re-Entry "CubeSat"?

- Affordable **Flight Data**
- Standard subsystems and launch adaptors
- **"Science"** missions with its current high technology
- Opportunity of 'Technology Demonstration'
- Key role in future interplanetary mission thanks to low mass and small size

Mission:

- First VKI mission to be launched in early 2016 to 380 km polar orbit
- Triple Unit CubeSat: 34x10x10cm, 3kg
- Objectives: Atmospheric Entry to Earth for Flight-to-Ground Extrapolation Methods Validation

Part 1: Flight-to-Ground Extrapolation

Stagnation Point Heating by Fay&Riddell, 1958

$$q_w = 0.763\,\mathrm{Pr}^{-0.6}\left(\rho_e\mu_e\right)^{1/2}\left(\frac{dU_e}{ds}\right)_{edge}^{1/2}\left(\frac{\rho_w\mu_w}{\rho_e\mu_e}\right)^{0.1}\left(h_e - h_w\right)$$

Local Heat Transfer Simulation

Thermo-chemical equilibrium

at stagnation point:

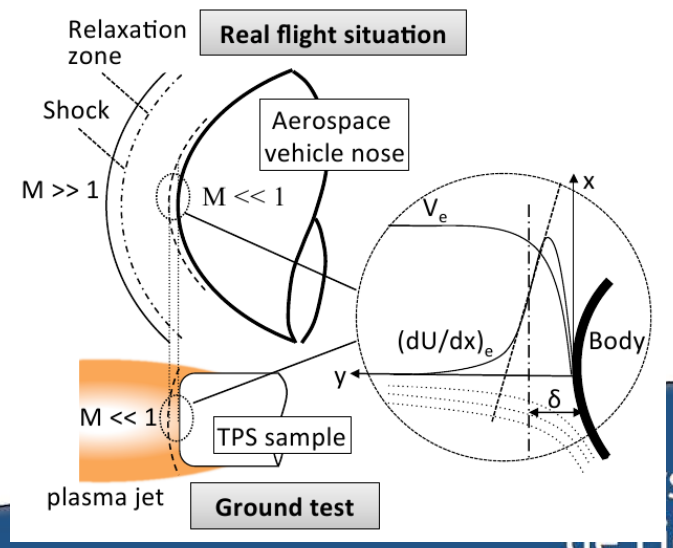
$$H_e^f = H_e^t \quad p_e^f = p_e^t \quad \beta_e^f = \beta_e^t$$

→ Subsonic plasma

Full simulation of stagnation region

Current Status: Effort put only in **p** and **H**

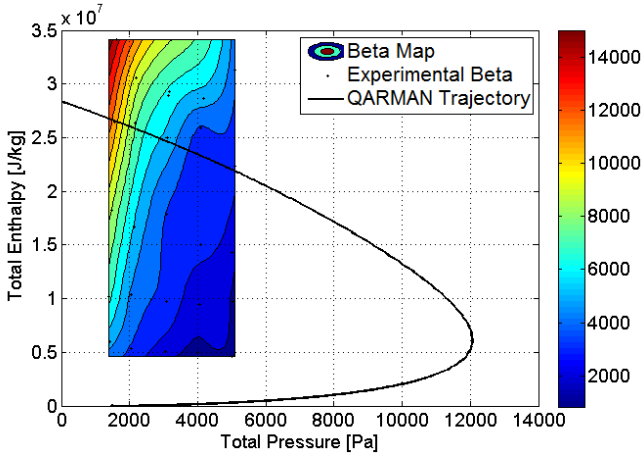
To be investigated: β



Part 1: Flight-to-Ground Extrapolation

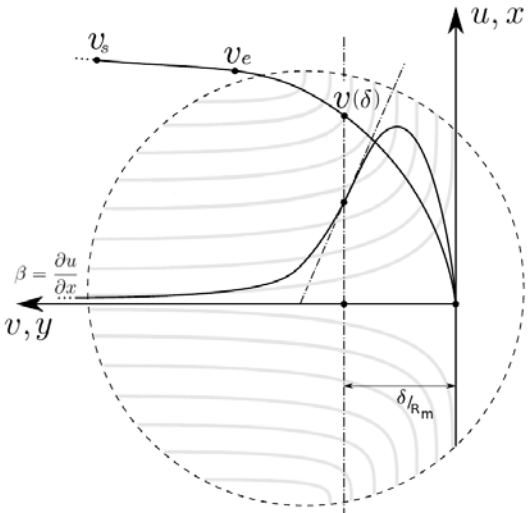
Velocity Gradient β

1. Unique value for **each geometry** and **each point on the trajectory**
2. No expression exists in literature for blunt and non-axisymmetric vehicles
3. Existing expressions are in terms of **velocity gradient** and a **spherical radius** and defined either **at the wall** or **along the stagnation line**



$$\frac{1}{\beta} = \frac{1}{R_{eff,H}} \times \sqrt{\frac{8}{3}\frac{(P_s - P_\infty)}{\rho_\infty}}$$

Lunev, 1975



Subsonic velocity gradient

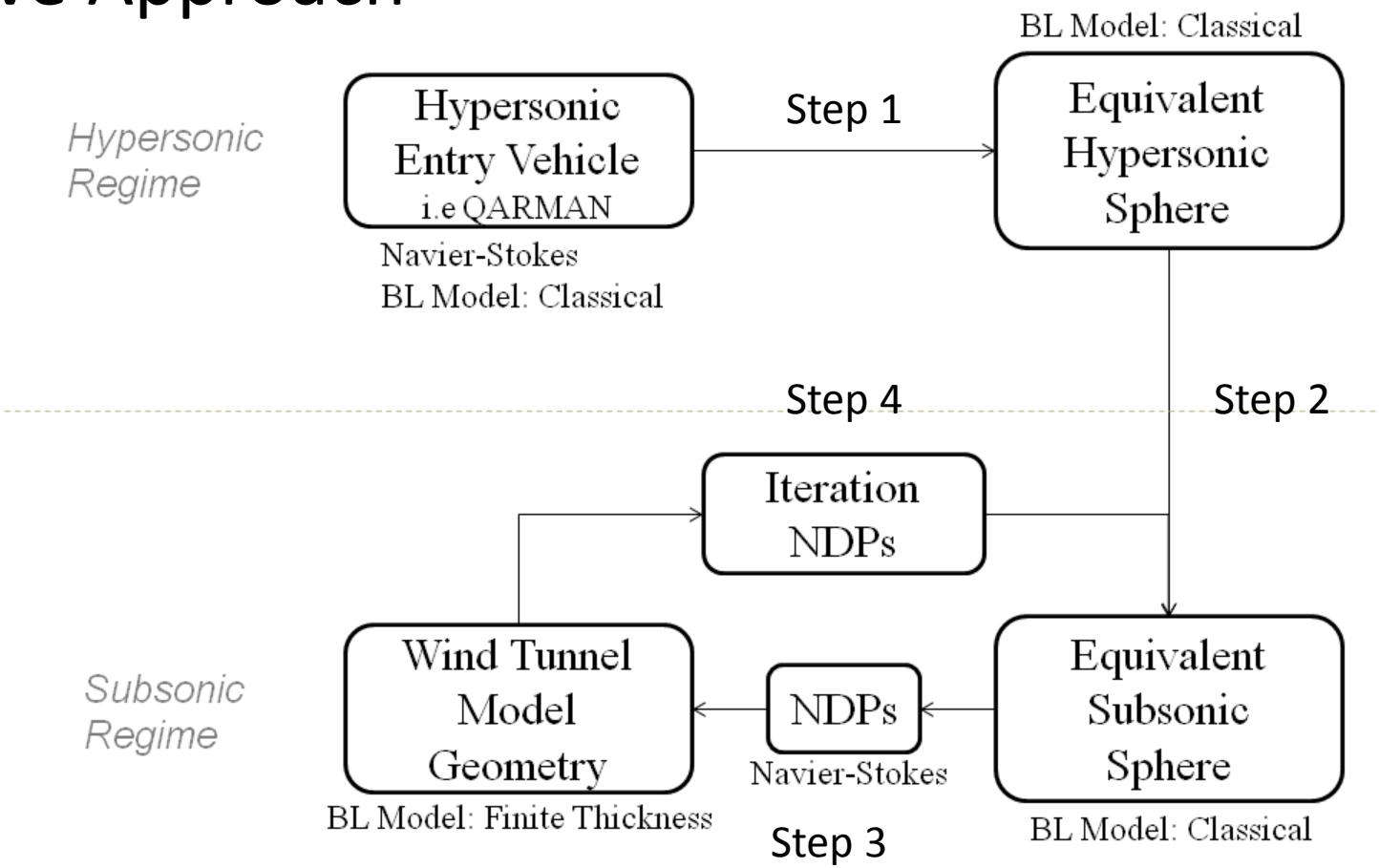
For QARMAN-like non conventional vehicles:

Problem: One equation - Two unknowns; $R_{eff,H}$ and β

→ ***<u>Proposed Solution: A 4-step Iterative Method</u>***

Part 1: Flight-to-Ground Extrapolation

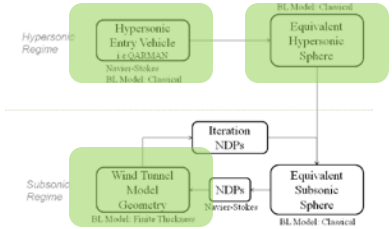
Iterative Approach

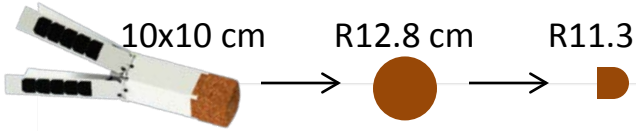


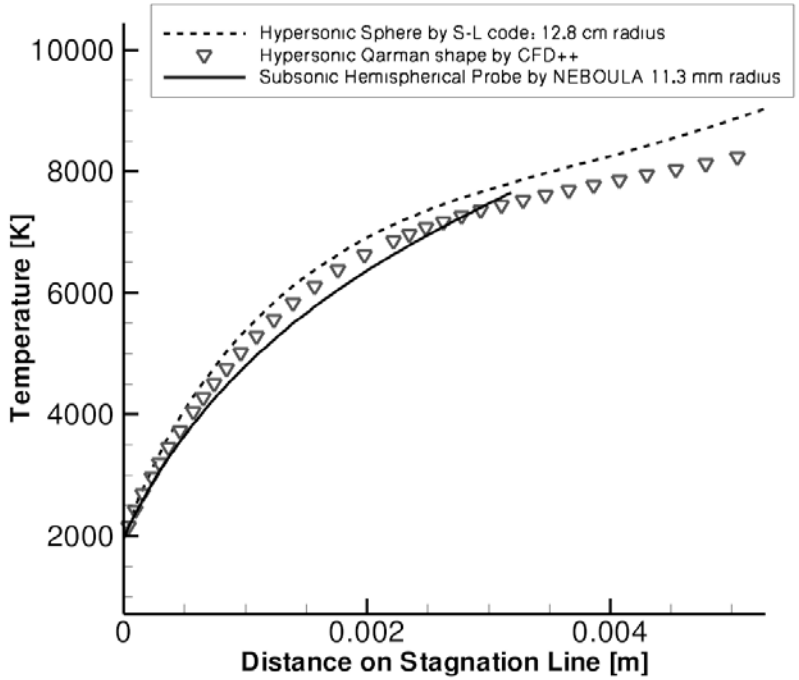
Part 1: Flight-to-Ground Extrapolation

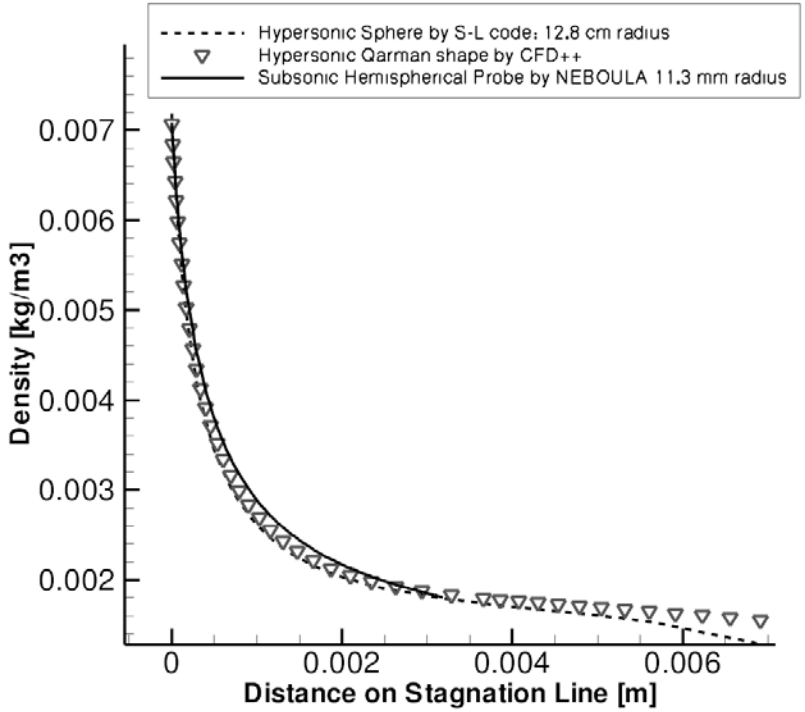
Results for QARMAN@66km

- Very good agreement in temperature and density
- Same good agreement in Species as well









Results shown for 66 km altitude

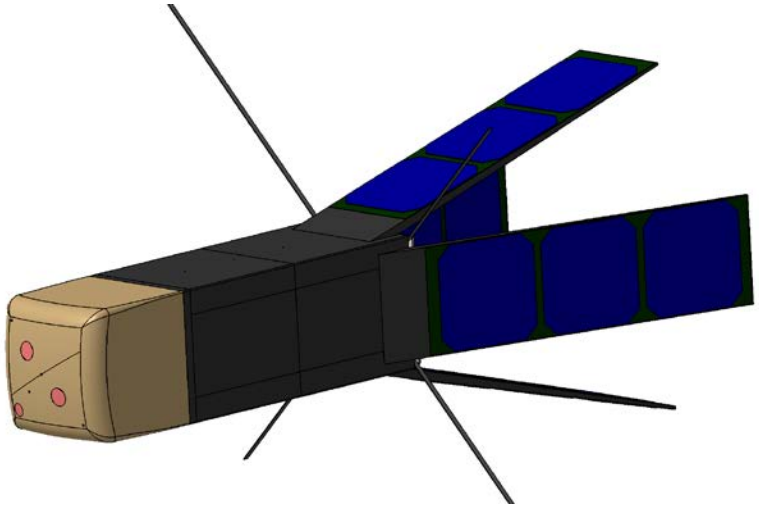
Part 2: QARMAN In-Flight Experiments

Part 2: QARMAN: In-Flight Experiments

Overview

Payload	Objective	Sensor
XPL01	**TPS Efficiency**	**Temperature**
XPL02	**TPS & Environment**	**Pressure**
XPL03	Stability, FADS	Pressure
XPL04	Laminar to Turbulent Transition, FADS	Pressure
XPL05	Off-Stagnation Temperature, FADS	Temperature
XPL06	Aerothermodynamic Environment and Radiation	Spectrometer

**Spectrometer payload was presented on Tuesday AM by Gilles Bailet*



Part 2: In-Flight Experiments Design

I. Stating the Problem and Defining the Payload Objectives

II. Subject Trades: Measurement Parameters/Magnitudes

III. Preliminary Investigation: CFD, Experiments and Determining the 'Performance Thresholds'.

IV. Measurement Techniques: Mass, Volume, Power Consumption, Accuracy, Data Size, TRL, Cost and Feasibility in a CubeSat platform

V. Preliminary Configuration and Operations Concept

VI. Ground Testing Methodology and Extrapolation to Flight

VII. Risk Analysis

VIII. Success Criteria: Considering the previously defined 'performance thresho

IX. Docum

Payload Head Design

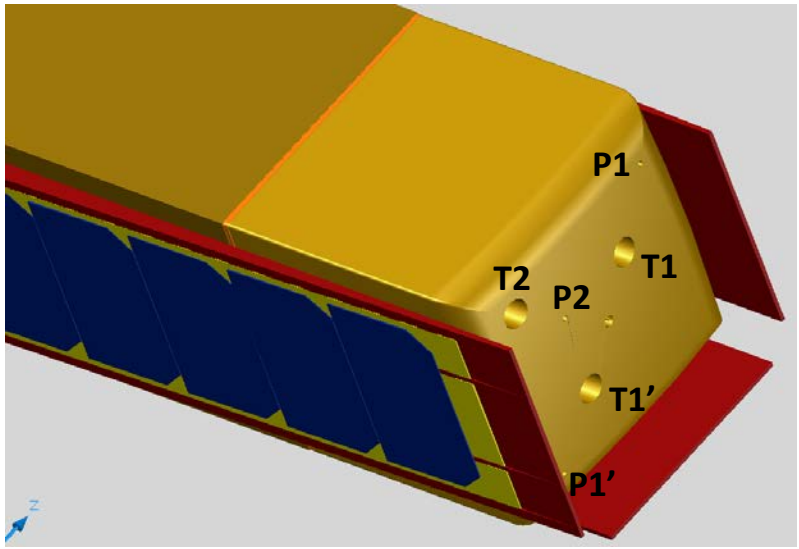
Measurement Chain Design

PL Design: TPS Scenarios XPL01 & XPL02

Selection Criteria

- Scientific Contribution
- Redundancy
- Weight
- Mission Risk
- Dependency
- Integration Simplicity
- DAQ Simplicity

Selection: ***Scenario 4***

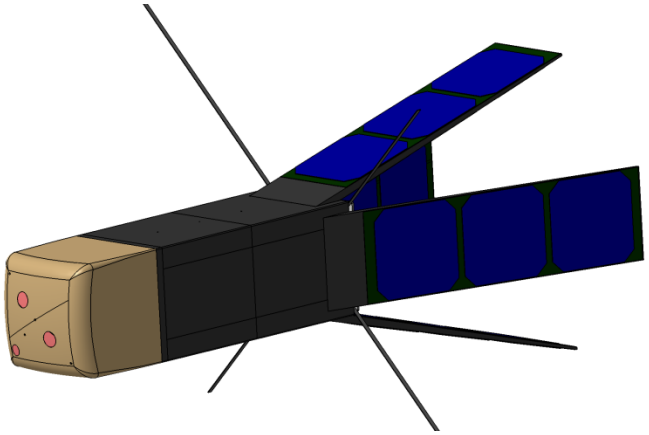


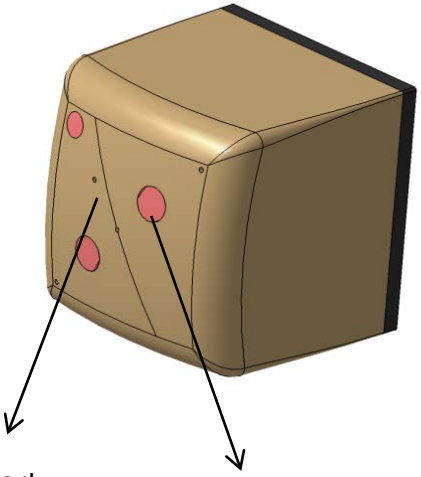
1- Thermal plug center locations:
z1=22mm and **z2=46mm**

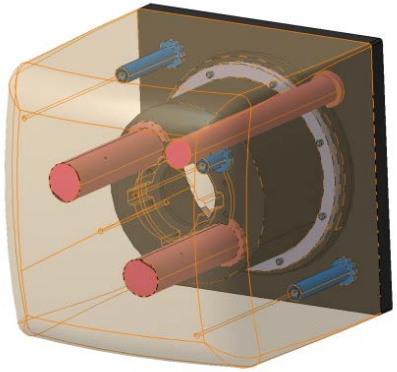
2- Pressure port center locations:
z1=15mm and **z2=40mm**

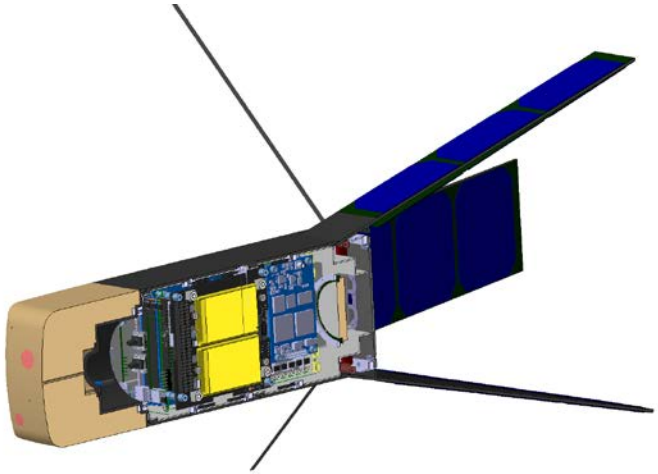
3-Spectrometer optical path at z=0

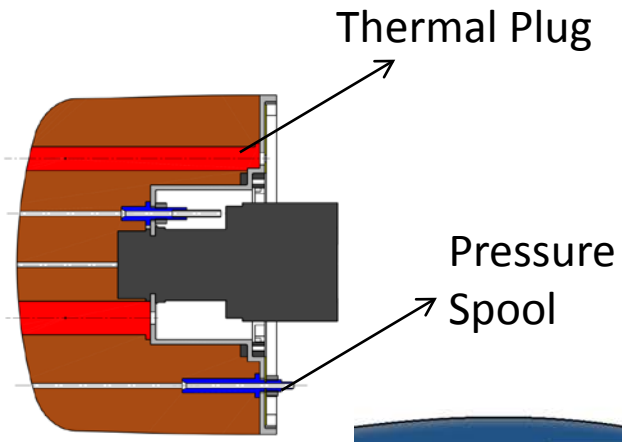
XPL01 & XPL02 Configuration







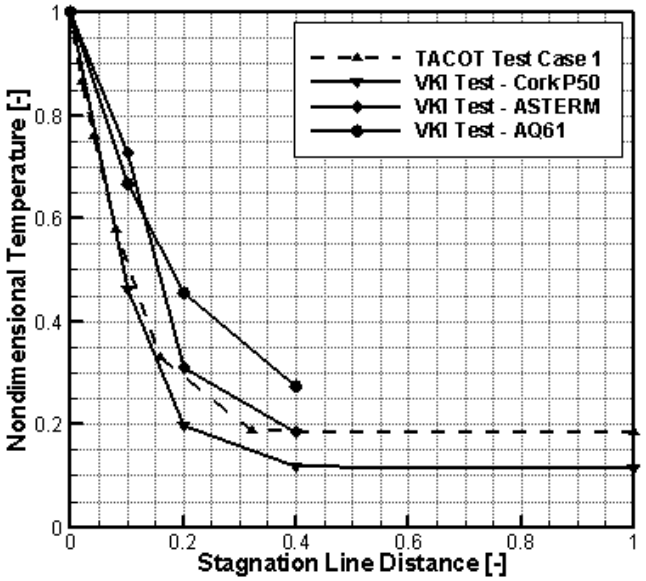


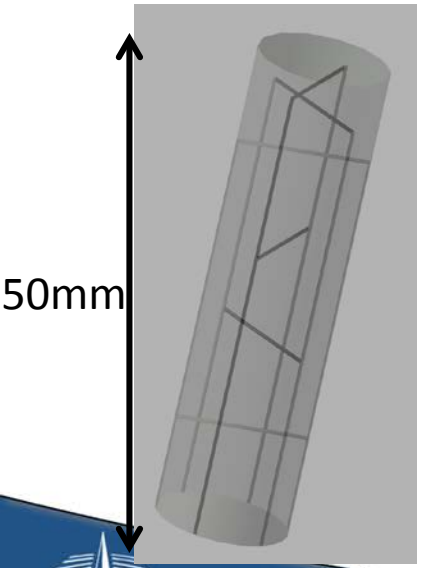


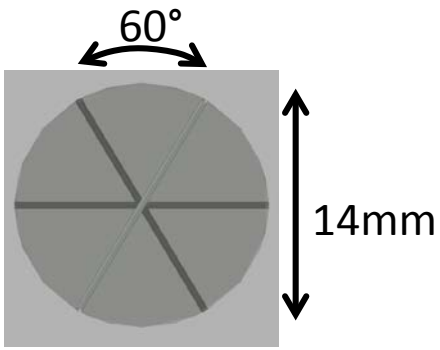
XPL01: Thermal Plugs

Payload Objectives:

- Ground Test Methodology Validation
- Characterize&Qualify TPS material
- Rebuild the free stream flow condition (FADS)
- CFD Validation







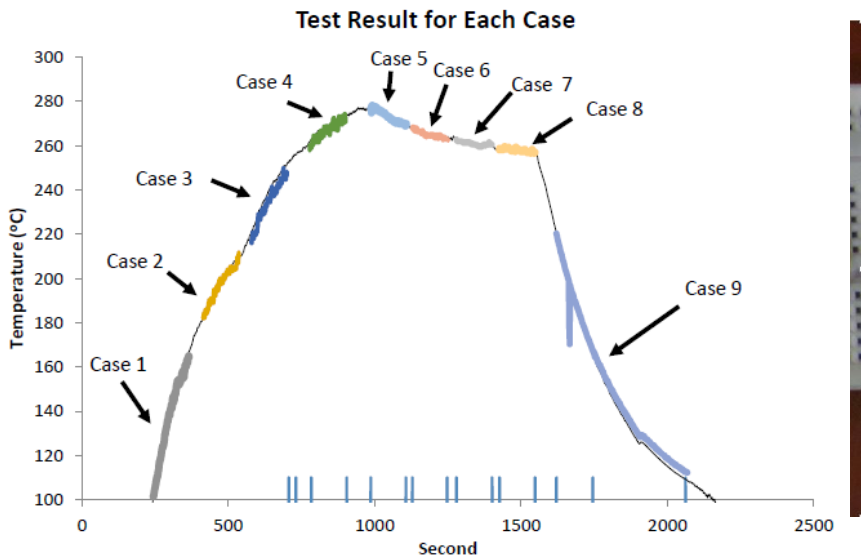
- 5 Thermocouples at 2.5, 5, 11, 18, 25 mm
- At 60° apart
- 2 thermocouple per side trail
- TC Type K in U-shape

XPL01 Measurement Chain Design & Qualification

Breadboard Tests

Launch: 19 June 2014
Payload: 6 Type K TCs – Fiber Glass Insulated + Teflon Insulated

- TRL 3 to TRL 4



Type K circuitry including

- CJC
- RFI Filter
- ADC

Flight Model of the satellite
VKI Engineering Model

Hopefully TRL 9 for the circuitry after 19 June 2014

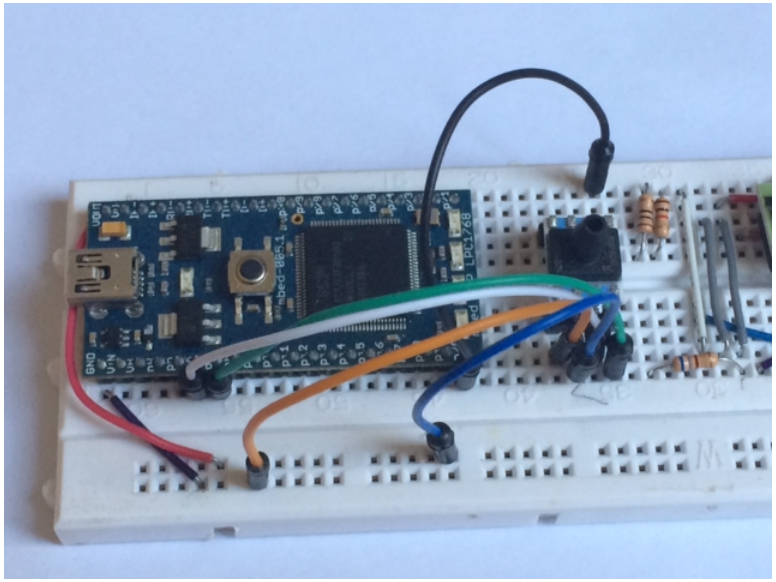
XPL02: TPS Pressure

Breadboard Tests

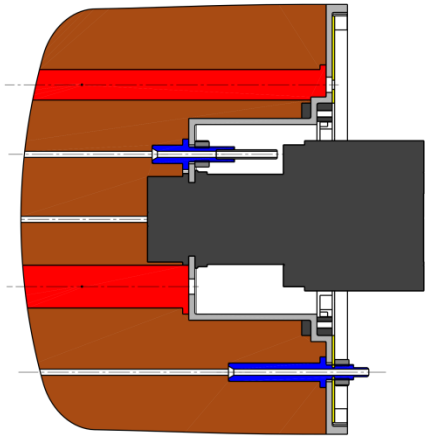
- TRL 3 to TRL 4

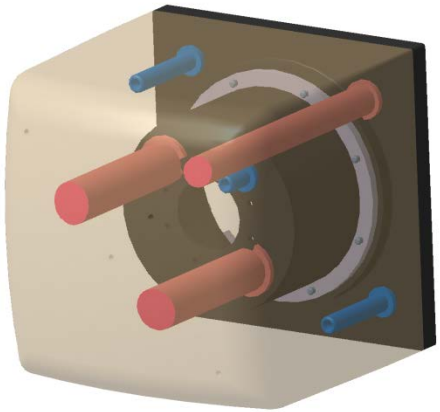
Optimized for Absolute Pressure Senso

Tested at VKI Minitorch Facility



Pressure Spool Design





Bare Pressure Port-No tubing

Hole in TPS:	2mm
Spool diameter:	3 mm inner
	6 mm outer
Pipe:	Stainless Steel

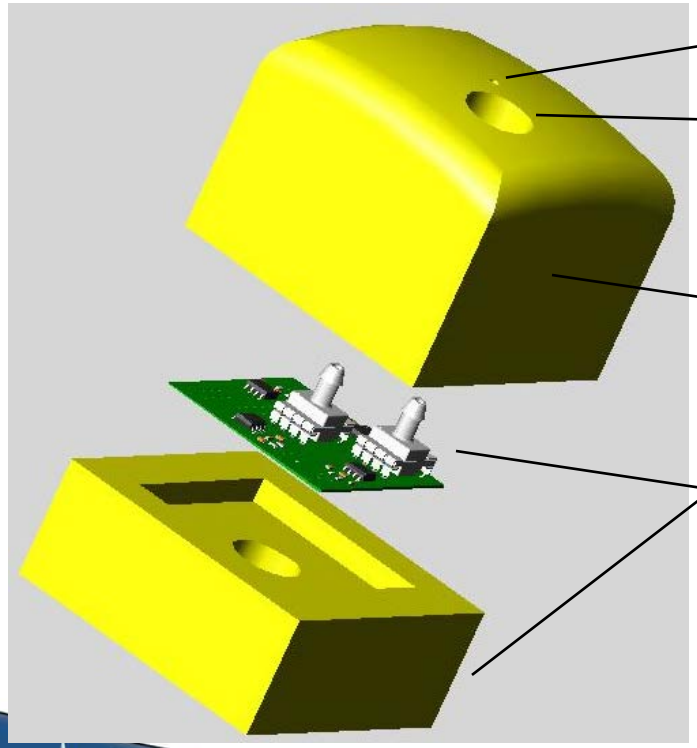
XPL01 & XPL02: Testing

Engineering Model at VKI Plasmatron – 25 March 2014

Objective: Make autonomous measurements inside Plasmatron chamber

- TRL 4 to TRL 7

  Scale 6/10 Model



Pressure Hole

Thermal Plug with 3 TCs at 8, 15, 22mm

Cork P50

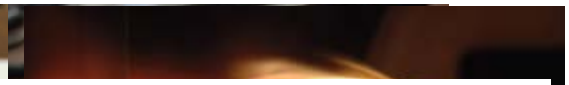
1 Microprocessor including memory
2 Absolute Pressure Sensors
4 Thermocouples Type K → 2 thermal plugs

XPL01 & XPL02: Testing

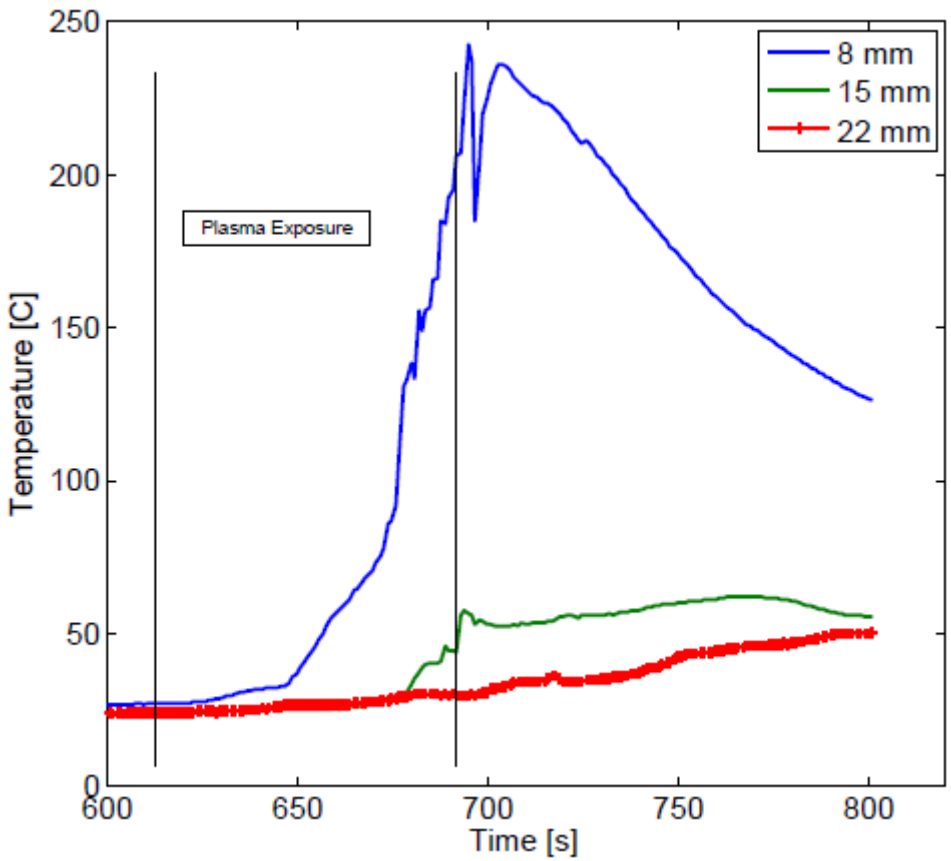
Engineering Model at Plasmatron – 25 March 2014

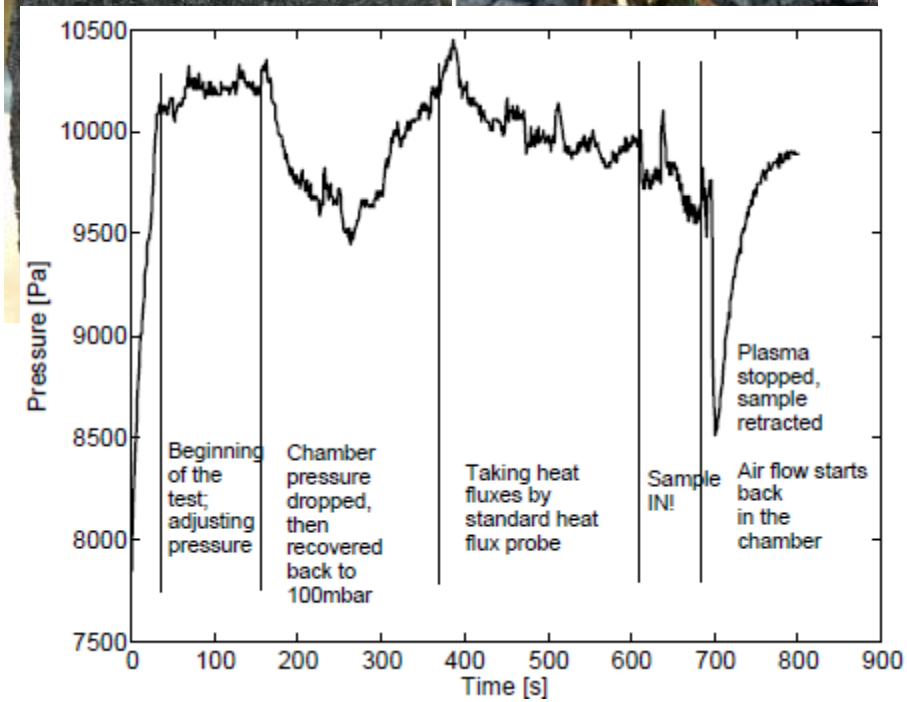
Before Test

During Test



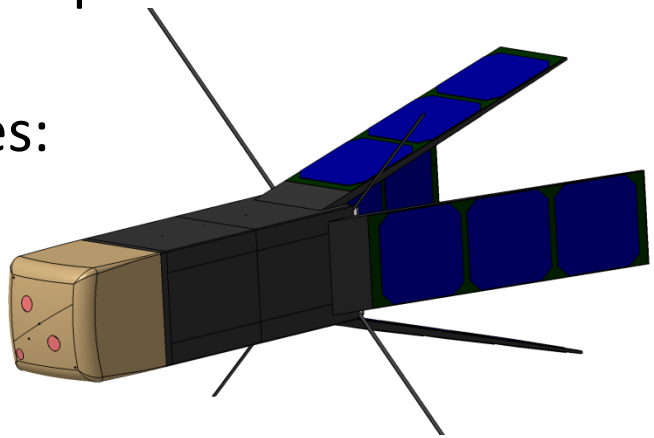
After Test

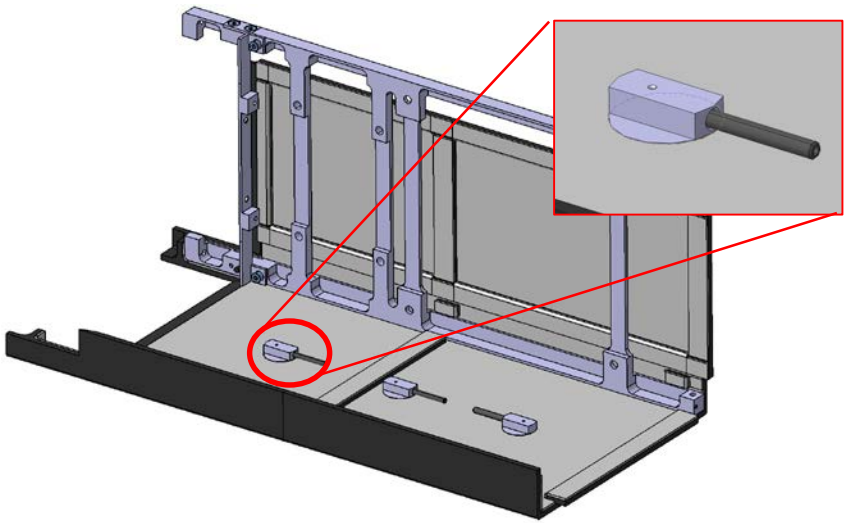




XPL03-04-05 Configuration

Pressure and Temperature Measurements





Main Objectives:

XPL03: Stability

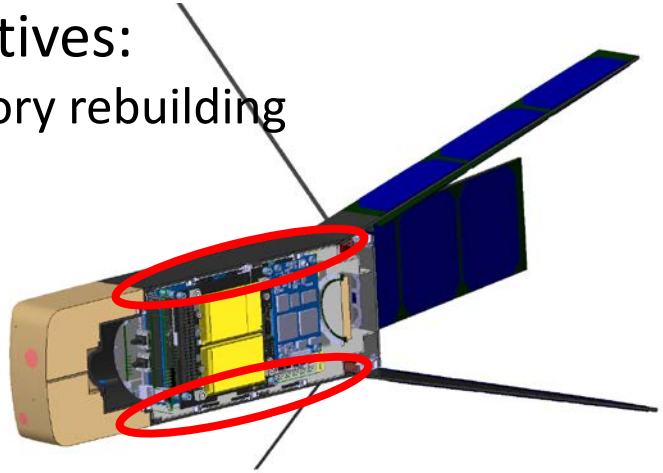
XPL04: Transition

XPL05: Temp.

Common Objectives:

1- FADS for trajectory rebuilding

2- CFD Validation



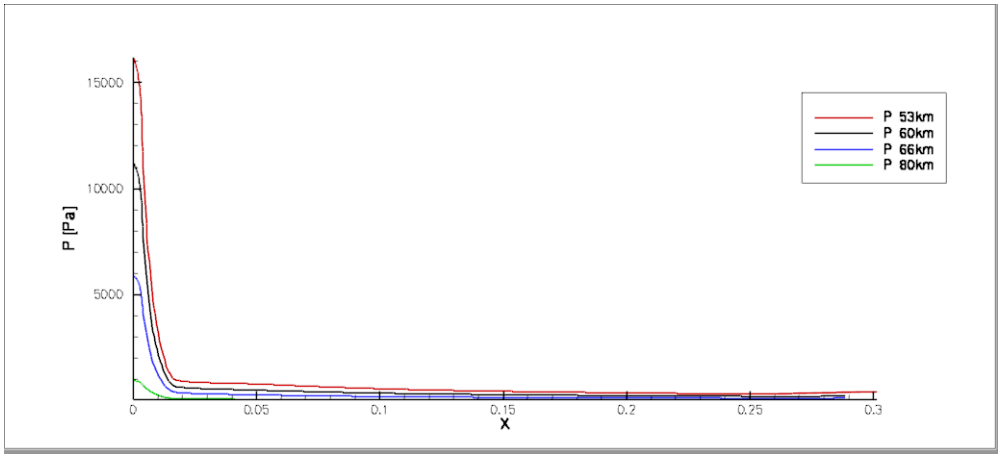
Pressure Port

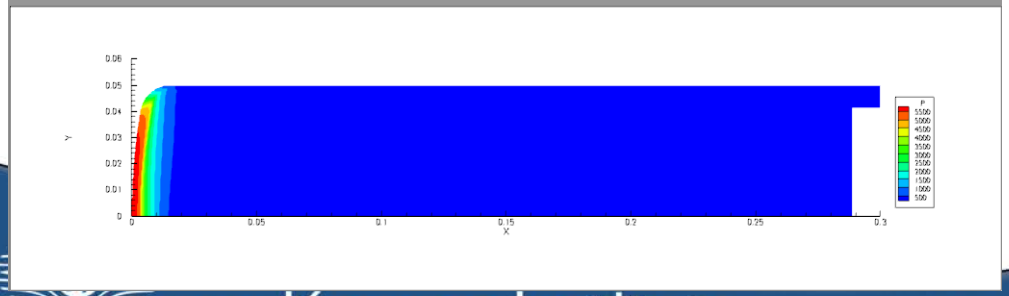
TC Port

XPL03: Stability and FADS

Payload Objectives:

- Rebuild the stability attitude of the spacecraft during re-entry by **pressure** measurements
- Rebuild the free stream flow condition (FADS)
- Ground Test Methodology Validation
- CFD Validation

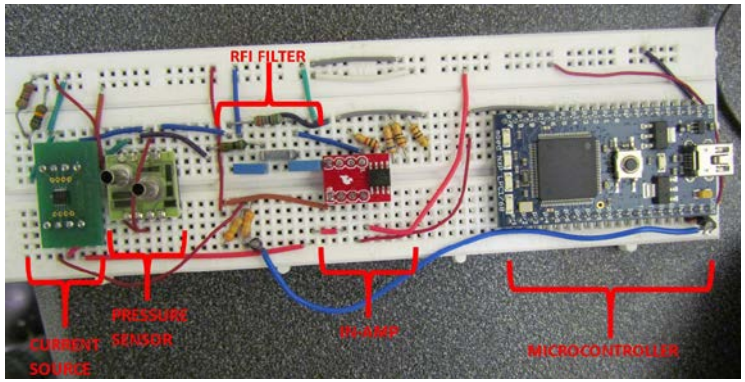




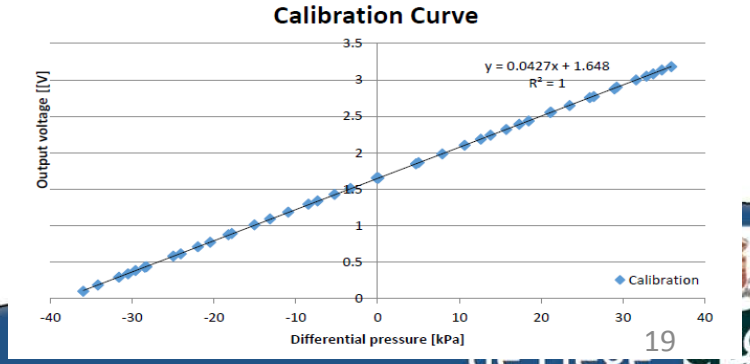
Breadboard Tests

- TRL 3 to TRL 4

Measurement Chain Optimized for Differential Pressure Sensor
with 34 Pa sensitivity



Tests at VKI Minitorch Facility



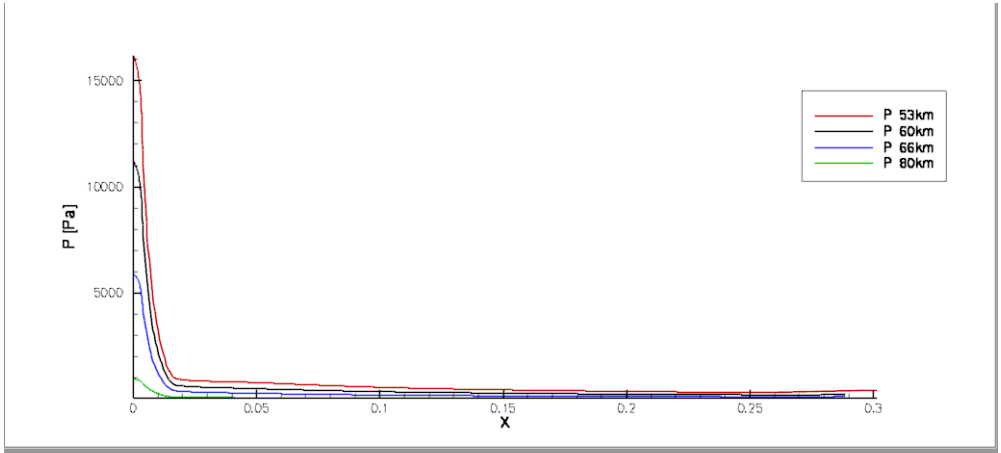
XPL04: Laminar to Turbulence Transition

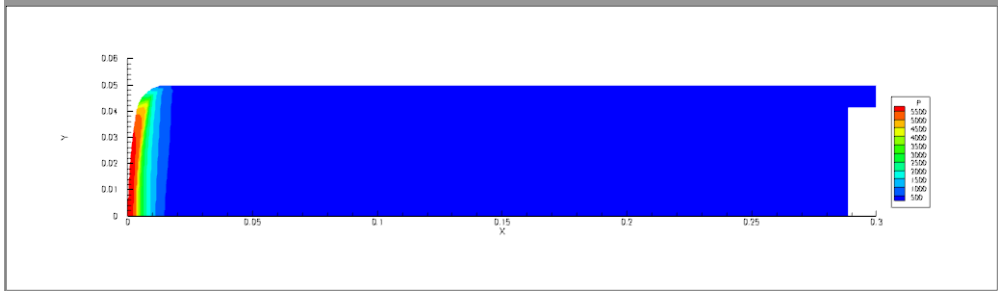
Payload Objectives:

- Determine laminar to turbulent boundary layer transition location (if any, since Reynolds ~300-600)
- Provide input for FADS with additional pressure station
- CFD Validation

Specifications:

- Combination of absolute and **differential pressure** sensors along the middle line + **temperature** sensors (XPL05)
- y = 15; 20; 25 mm
- Pressure spool attached to the side panel ceramic structure
- Measurement chain identical to XPL02 and XPL03

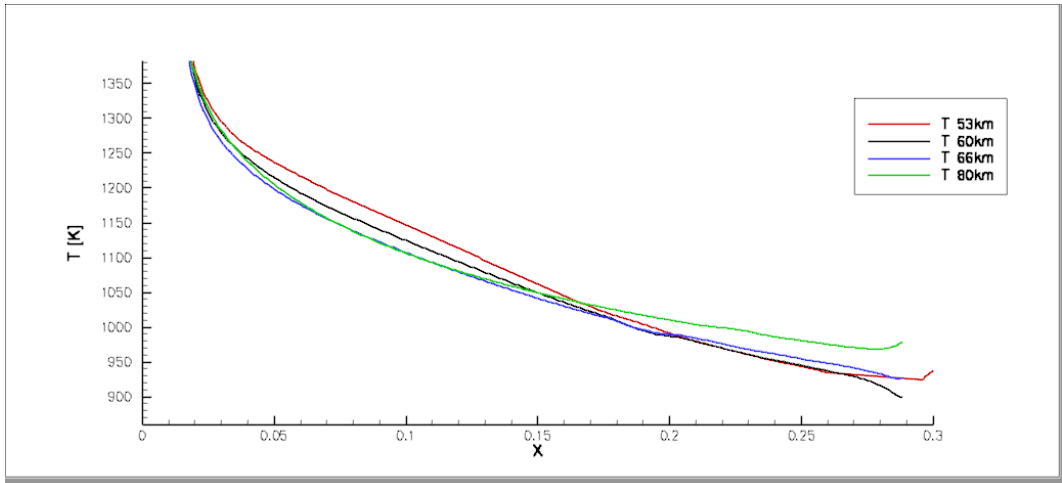


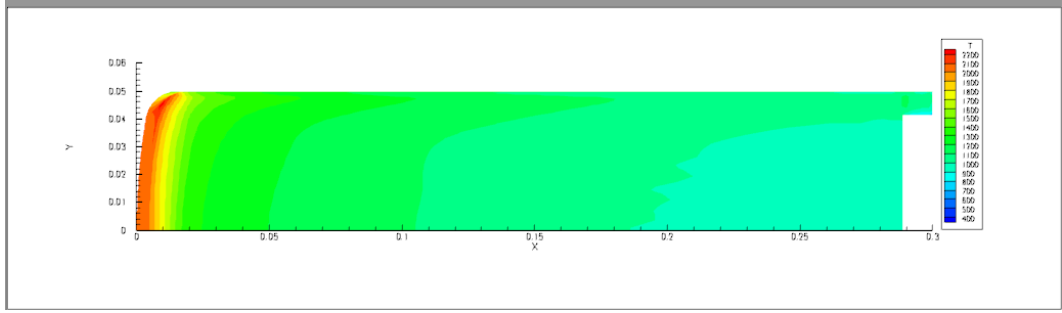


XPL05: Off-Stagnation Temperature

Payload Objectives:

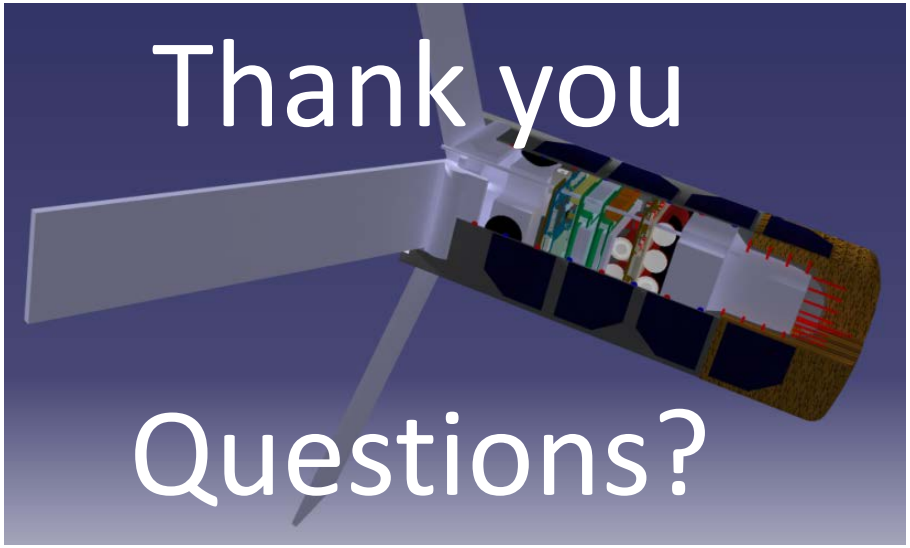
- Monitor the **temperature** evolution
- Monitor the density evolution (combined with XPL03)
- Contribute to FADS
- Plasmatron Off-Stagnation Methodology Validation for TPS Characterization
- CFD Validation





Specifications:

- 8 Type K thermocouples
- Faces +X –X
- y=15; 20; 25 mm
- Data Acquisition System identical to XPL01



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QARMAN Team,
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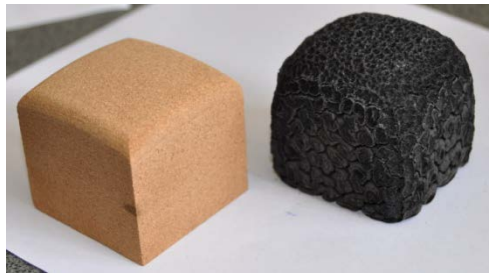
Cem O. Asma,
Amorim
Airbus Defence

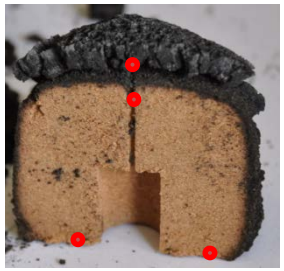
Part 2: QARMAN – TPS Selection

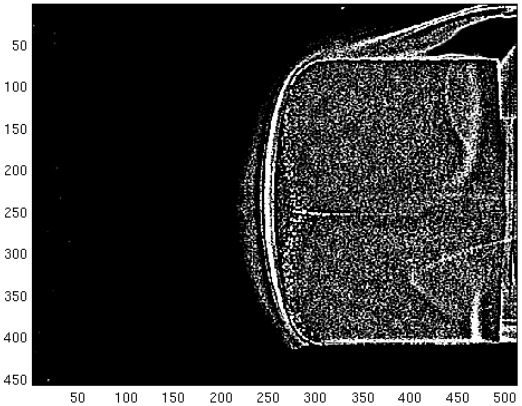
Cork P50

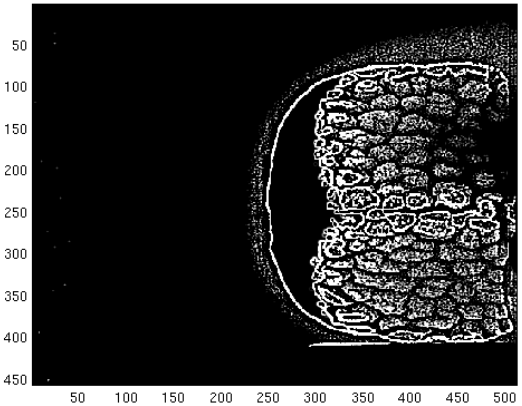
Stag. Point: +1mm

Corner: -7.4 mm









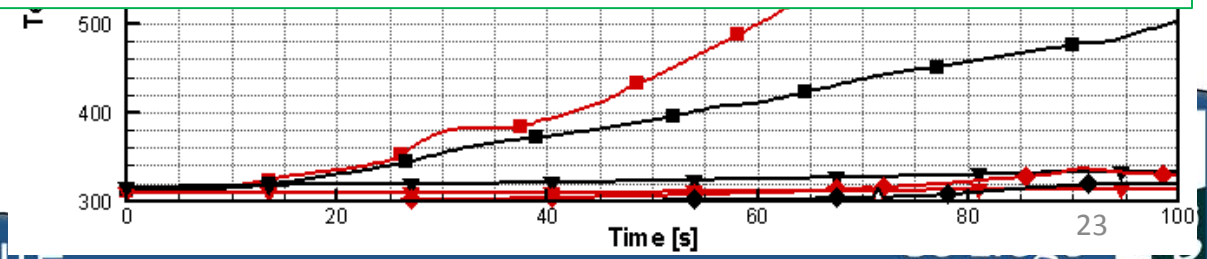
Selection

-It is decided by VKI to continue design and manufacturing with both P50 and TPS3L

-Ablator producersAstrium/Amorim agrees to provide material free of charge

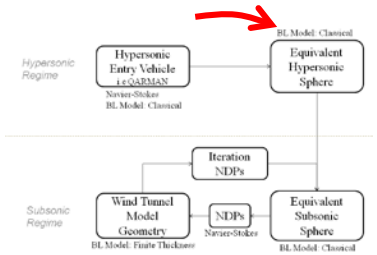
- Insulation in the back; mass loss and recession/swelling of P50 and TPS3L are comparable.

-TPS3L is lighter than P50

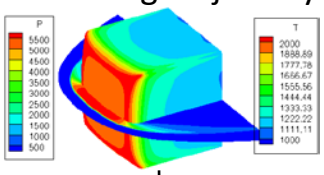


Part 1: Flight-to-Ground Extrapolation

Iterative Approach - Step 1



CFD Along Trajectory



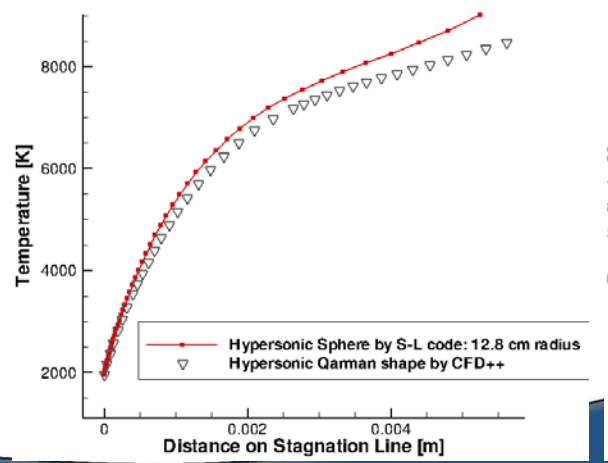
Stagnation Line Profile

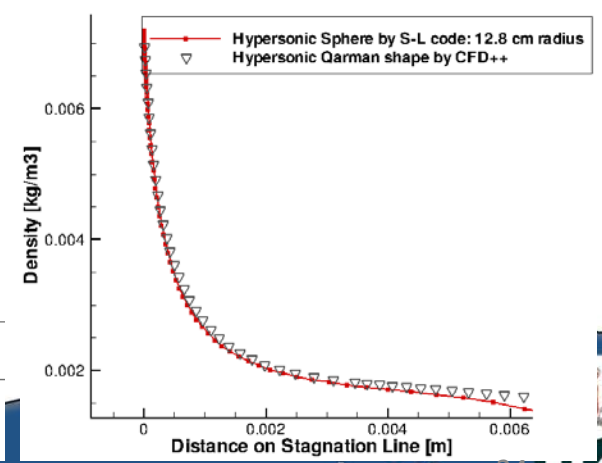
- Inviscid Comp.: β at the wall
- Temperature profile stops being linear: β @ δ
  - ➢MNT is used to find $R_{eff,H}$

Are shown to be **equivalent**

$$R_{eff,H} = \frac{1}{\beta}\sqrt{2\frac{(P_e - P_\infty)}{\rho_e}}$$

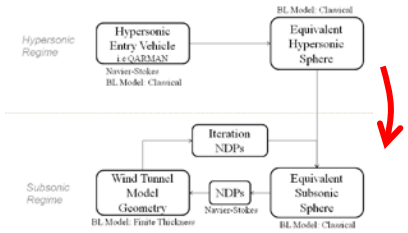
VKI Stagnation Line Code for the sphere of $R_{eff,H}$ at 66km





Part 1: Flight-to-Ground Extrapolation

Iterative Approach - Step 2



Fay-Riddel equation

$$q_w = 0.763\,\mathrm{Pr}^{-0.6}\left(\rho_e\mu_e\right)^{1/2}\left(\frac{dU_e}{ds}\right)_{edge}^{1/2}\left(\frac{\rho_w\mu_w}{\rho_e\mu_e}\right)^{0.1}\left(h_e - h_w\right)$$

Hypersonic Regime

$$Q_w\sqrt{\frac{R_{eff,H}}{P_s}} = K_H\left(H_e - h_w\right)$$

Subsonic Regime

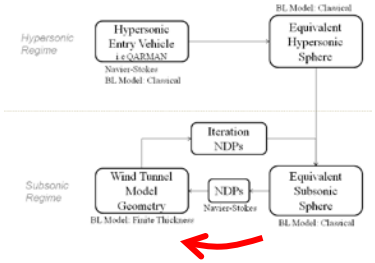
$$Q_w\frac{\sqrt{R_{eff,S}}}{\sqrt[4]{P_e.\Delta P}} = K_S\left(H_e - h_w\right)$$

$$R_{eff,S} = R_{eff,H}\frac{\sqrt{P_e.\Delta P}}{P_s}$$

- Subsonic Sphere
- Classical BL Model

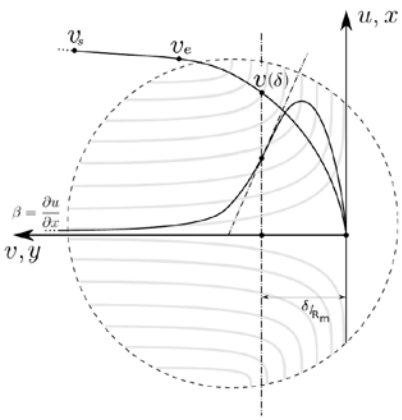
Part 1: Flight-to-Ground Extrapolation

Iterative Approach – Step 3



Plasmatron simulation by ICP

- Conversion needed from Classical BL to Finite Thickness BL



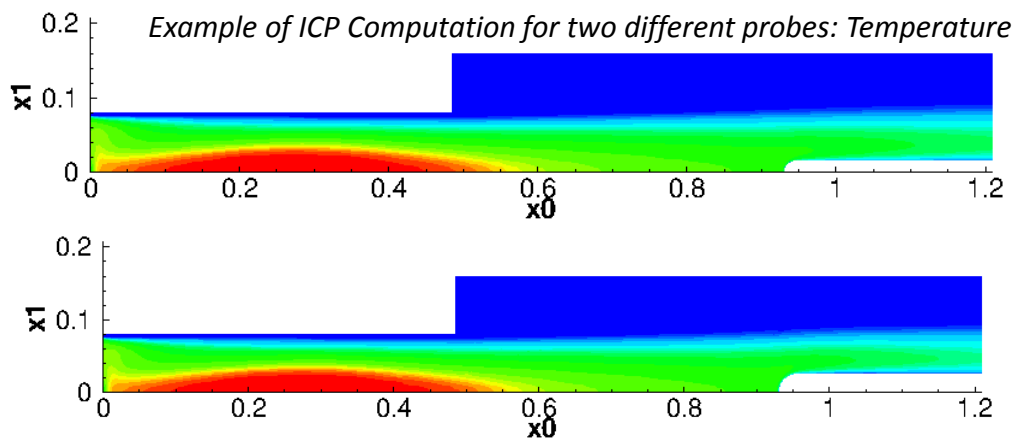
$$NDP1 = \delta = \frac{\Delta}{R_m}$$

$$NDP2 = u_{1e} = \frac{\partial u}{\partial x} \cdot \frac{R_m}{v_s}$$

$$NDP3 = u_{1y} = \frac{R_m{}^2}{v_s} \cdot \frac{\partial}{\partial y}\left(\frac{\partial u}{\partial x}\right)$$

$$NDP4 = \overline{v} = \frac{v(\delta)}{v_s}$$

$$NDP5 = \frac{v(\delta)}{v_e}$$

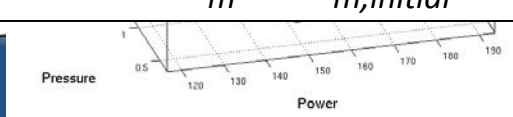


- Momentum equation gives:

$$R_{eff,s} = \frac{R_m}{NDP2 \cdot \left(1 + \frac{NDP5 \cdot NDP3}{NDP2^2}\right)} = \frac{R_m}{f(NDP)}$$

- *Rm is the radius of the hemispherical probe to be used.*
- ***Step 4:** Iteration on ICP & geometry*

  Check: R_m vs $R_{m,initial}$

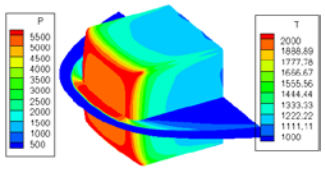


Part 1: Flight-to-Ground Extrapolation

Tools for each step and summary

Step 1:

- Hypersonic CFD++ computation: viscous and inviscid
- Grid convergence study
- VKI SL code for vehicle-hypersonic sphere comparison



Step 2:

- Experimental Plasmatron Campaign to determine

1. Correct free stream conditions: enthalpy and pressure
2. Dynamic Pressure at the correct conditions

$$R_{eff,S} = R_{eff,H} \frac{\sqrt{P_e.\Delta P}}{P_s}$$

Step 3:

- Run VKI ICP Code

1. With an initial radius of hemispherical probe $R_{m,initial}$
2. For the entire test matrix

- Compute NDPs
- Compute Rm

Step 4: Iteration:

- Repeat Step 3 with the *Rm found* until it matches the ICP *Rm where the NDPs are found*