Executive Summary Report

Assessments to Prepare and De-Risk Technology Developments

"RAM Electrical Propulsion for Low Altitude Satellites"

ESA RFP/3-15902/19/NL/BJ/va

von KARMAN INSTITUTE
FOR FLUID DYNAMICS

05/03/2020

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1 Introduction

This document summarizes the work achieved during the ESA RFP/3-15902/19/NL/BJ/va project, *Assessments to Prepare and De-Risk Technology Developments:"RAM Electrical Propulsion for Low Altitude Satellites"*. It is not intended to be an exhaustive list of the results; An interested reader should read the project deliverables outlined below.

[1] TN01 - Mission definition - *RAM Electrical Propulsion for Low Altitude Satellites* - ESA RFP/3-15902/19/NL/BJ/va
[2] TN02 - Intake preliminary requirements - *RAM Electrical Propulsion for Low Altitude Satellites* - ESA RFP/3-15902/19/NL/BJ/va
[3] TN03 - Intake preliminary design and optmization - *RAM Electrical Propulsion for Low Altitude Satellites* - ESA RFP/3-15902/19/NL/BJ/va
[4] TN04 - Prototype and Testing assessment - *RAM Electrical Propulsion for Low Altitude Satellites* - ESA RFP/3-15902/19/NL/BJ/va
[5] TN05 - Strategic implementation plan - *RAM Electrical Propulsion for Low Altitude Satellites* - ESA RFP/3-15902/19/NL/BJ/va

2 Study overview

2.1 Mission definition

A **mission concept** was introduced in order to investigate the limit case of the thrust over drag force ratio equal to one. The concept considers only descent phases interrupted by three thrusting arches during which constant altitude shall be maintained. The corresponding selected altitudes are respectively: 250km, 200km and 180km. The altitude variation phases consist in free-falling phase. In Figure 1, the design reference mission is shown.

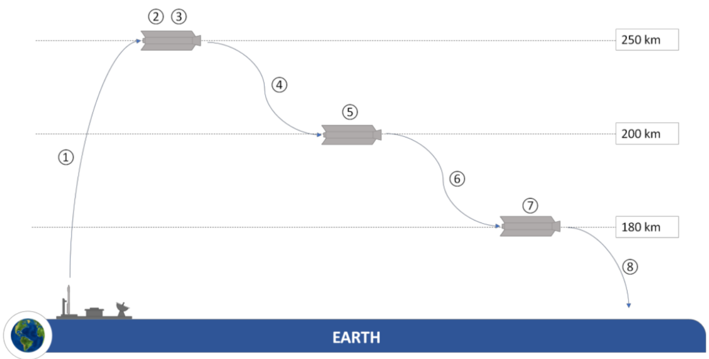


Figure 1: Design reference mission.

2.2 Environmental requirements

We simulate the **atmospheric properties** encountered by a satellite during its orbit, in order to estimate the margins for the design of the operational conditions. We propagate the satellites trajectory using Cowells method accounting for the effect of Earths oblateness. The composition, density, temperature and atmospheric winds of the atmosphere are all parameters that will influence the performance of the ABEP system. These parameters are highly variable, not only on the altitude, but also for instance on the geographic position, the relative position of the sun, the solar activity and the season. The use of NRLMSISE-00 is suggested to determine atmospheric temperature and composition while JB-2008 is suggested to compute the total atmospheric density. The HWM14 model is used to compute the horizontal wind variation in the atmosphere.

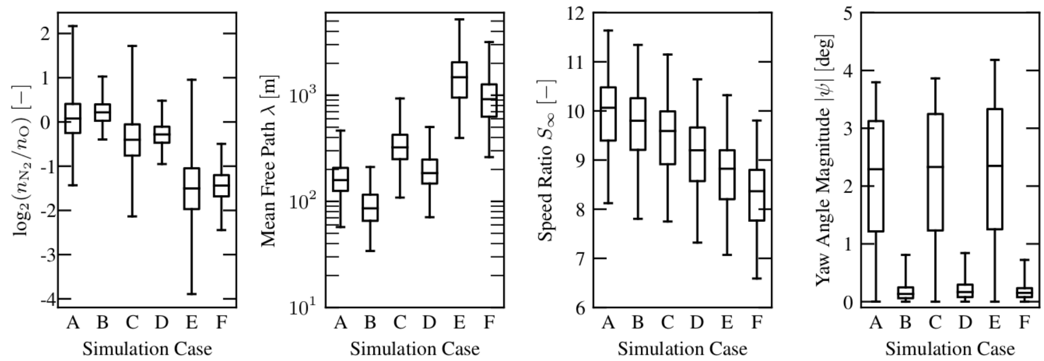
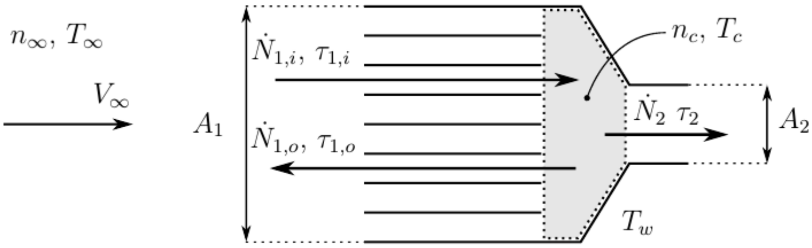


Figure 2: Box and whisker plots of the results from orbital simulations. Shown from left to right: the relative presence of the main constituents N_2 and O, the mean free path λ, the gas speed ratio S_∞, and the magnitude of the yaw angle Ψ. The ends of the box are the upper and lower quartiles, the line inside the box is the median, and the ends of the whiskers are the maximum and minimum observations. Simulation cases from A to F are in order: 180 km SSO, 180 km equatorial, 200 km SSO, 200 km equatorial, 250 km SSO, 250 km equatorial.

2.3 Preliminary design

An **Lumped Parameter Model** has been developed for the investigation and preliminary design of a passive intake. The model:

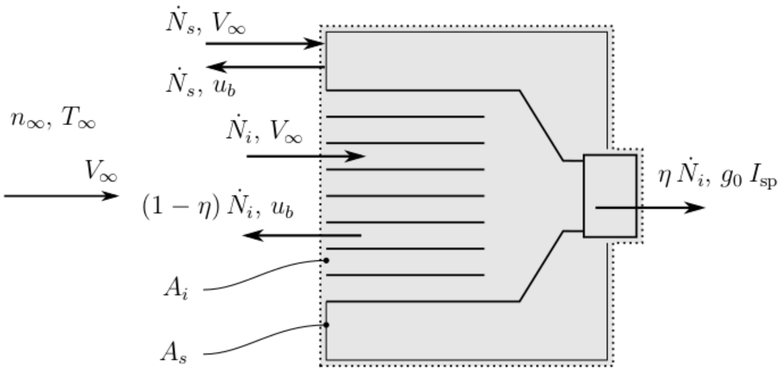
- Captures the behavior of the intake in a wide region of the design space;
- Provides precious information for the optimization of the intakes geometry;
- Allows to infer the scaling laws for the two important performance parameters, η and ν;



$$\nu \equiv \frac{n_c}{n_\infty} = \frac{V_\infty}{\frac{1}{4}\langle C_c\rangle} \frac{\tau_{1,i}}{\tau_{1,o} + \frac{A_2}{A_1}\tau_2} = 2\sqrt{\pi}\, S_\infty \sqrt{\frac{T_\infty}{T_c}} \frac{\tau_{1,i}}{\tau_{1,o} + \tau_2^\star}, \tag{1}$$

$$\eta \equiv \frac{\dot{N}_2}{n_\infty V_\infty A_1} = \frac{\tau_{1,i}}{\tau_{1,o} + \tau_2^\star}\tau_2^\star \tag{2}$$

- Relates the performance of the intake with that of the thruster and, finally, with that of the complete system.



$$\sum F = D - T = \dot{N}_i m\left[V_\infty + (1-\eta)u_b - \eta g_0 I_{\text{sp}}\right] + \dot{N}_s m\left[V_\infty + u_b\right] \tag{3}$$

or, in non-dimensional form:

$$C_F = \frac{\sum F}{\frac{1}{2}\rho V_\infty^2 (A_i + A_s)} = 2 + 2\,(1-\eta^\star)\,\frac{u_b}{V_\infty} - 2\,\eta^\star\,\frac{g_0\,I_{\text{sp}}}{V_\infty} \tag{4}$$

where $\eta^\star = \dfrac{A_i}{A_i + A_s}\eta$ can be regarded as a “reduced” collection efficiency.

2.4 Performance and optimization assessment

SPARTA Direct Simulation Monte Carlo (DSMC) Simulator has been employed to to investigate complex flow effects. The degree of rarefaction of the gas has an effect on the performance. For realistically low densities, increasing the amount of collisions obstructs the particles incoming from the freestream, causing a decrease of the performance. Moreover, the misalignment of the incoming flow causes a performance degradation. It can reach 20% for a 5° misalignment angle and exceed 40% for a 10° misalignment. Increasing the amount of specular reflections increases the collection efficiency and decreases the density ratio, by as much as 5% for an accommodation coefficient α of 0.9.

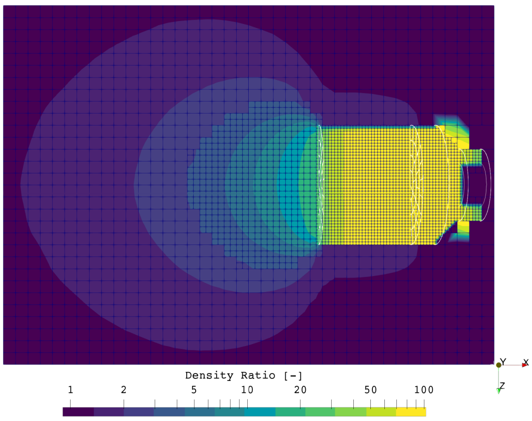


Figure 3: Number density ratio contours (3D DSMC simulation).

RAREFIED (Radiosity Analog for Rarefied Flows Simulation) is an open-source solver for the internal or external flow of a collisionless gas that is diffusively reflected by solid surfaces. The software was originally developed at the *von Karman Institute for Fluid Dynamics* as a part of Pietro Parodi's M.Sc. thesis.
The emission or scattering of molecules at surfaces by a cosine law for characterizing diffuse reflection and consequently the view-factor analogy between gas transport in the free molecular flow regime and thermal radiation has been known since the very first studies on rarefied gas flows. The problem can be reduced to the solution of a system of linear equations. When written in the appropriate form, the boundary conditions can be modified for a given geometry and it is possible to re-compute the solution with little additional computational cost. This provide an advantage if the same geometry has to be simulated in a wide range of flow conditions. On the contrary, DSMC requires a completely new simulation when a change in the boundary conditions is applied.

In the realization of the **optimization process**, the parametrization of the geometry of the intake has been achieved. From the automatically generated CAD model and surface mesh, the optimal design is going to be achieved with a multi-point, multi-objective optimization method whose kernel is already developed at the von Karman Institute mainly

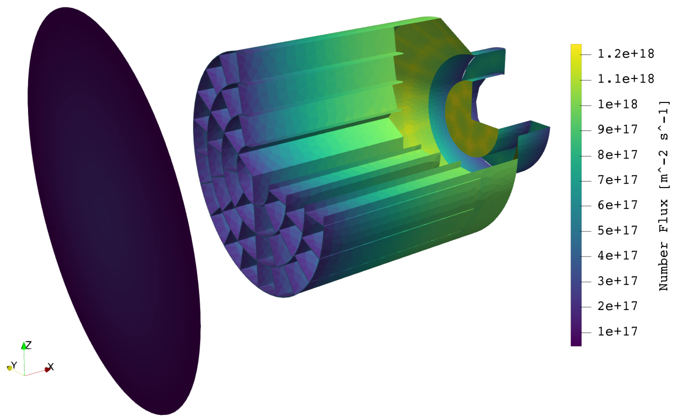


Figure 4: 3D Surface flux simulation based on the view-factor method.

for turbomachinery and aeronautics applications.

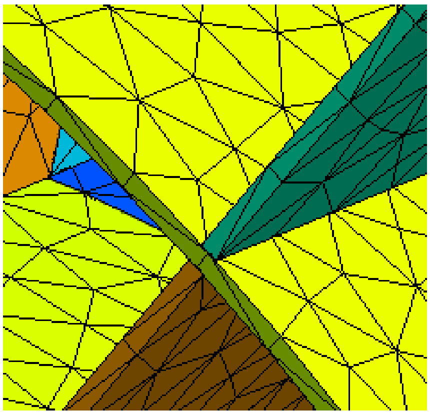


Figure 5: Mesh detail.

2.5 Qualification assessment

A metal prototype has been manufactured using the CAD design reported herefater. Relevant instrumentation has been identified to evaluate the compression ratio and the collection efficiency.

A conceptual **test-bench for the qualification** of an intake-collector system has been proposed based on a Particle Flow Generator developed at ThrustMe. The geometry of the chamber and the vacuum system have been tested using Monte Carlo simulations to ensure that the flowfield is not affected by gas phases collisions and that surface reactions with the walls are predominant.

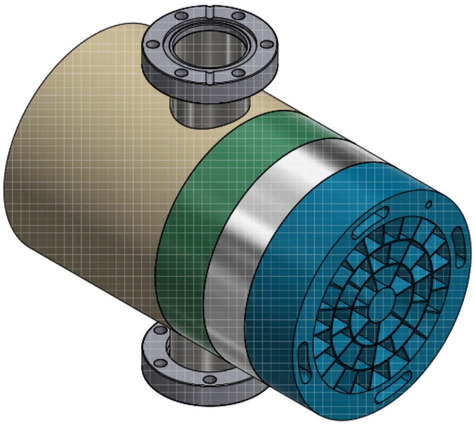


Figure 6: Intake assembly.

3 Conclusion

A roadmap for the development of the intake collector system has been proposed in TN05. The development of high fidelity models will prove to be a precious tool for the design of the PFG, the characterization of the plume, the simulation of the intake-thruster interface and the experimental qualification of the intake-collector device.
Duplicating the orbital flow conditions on the ground is necessary to support air-breathing electric propulsion technology. VKI is willing to host a small-scale low-density facility to qualify the performance of the intake-collector system. In addition, the investigation of gas-surface interactions would permit to make the design evolving.