ROCKET ENGINE DIGITAL TWIN

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ABSTRACT

The study aims to present the modeling and simulation activities foreseen on an upper stage rocket engine, the RL10A-3-3A expander cycle engine. Firing test transient results [1] have been used to validate the transient behavior of the model. Once the detailed engine model is validated, this engine is coupled with a flight dynamic launcher model. A typical mission profile of Delta IV, a geostationary transfer orbit (GTO) is selected. This plant model framework integration can help engineers to assess the engine start-up in real flight conditions as well as tackling other technical challenges of interest.

NOMENCLATURE, ACRONYMS, ABBREVIATIONS

DOF	Degrees of Freedom
GTO	Geostationary Transfer Orbit
IR	Infrared Radiation
MBWR	Modified Benedict Webb Rubin
PLF	Payload Fairing
SECO	Second Stage Engine Cutoff
GNC	Guidance, navigation, and control

INTRODUCTION

The space industry has evolved significantly in recent decades as evidenced by the many ambitious projects under consideration or emerging today. Among the challenges proposed, one could name the manned space flights in the thermosphere but also towards planets such as Mars, or the possibility of reusing launchers, the use of additive manufacturing for the design of parts, etc. To reach these goals, modeling and simulation means are more and more used and useful all along the product development and its lifecycle. It helps engineers early in the design cycle, making and securing architectural choices, and finally maturing the design all along the development cycle. It serves the development of controllers by providing a transient detailed model of the plant, while supporting the validation and verification process. During the product lifecycle, it provides key capabilities for health monitoring among others.

The study aims to present the modeling and simulation activities performed on the Simcenter Amesim platform for what concerns multi-domain system simulation. A first model of the engine is depicted, showing the complete expander cycle engine from tanks to the nozzle, including a detailed model of the regenerative circuit and therefore covering the two-phase flow transition of the cryogenic fluid. Both oxidizer and fuel feeding circuits are also detailed as well as actuators, pumps, turbine and mechanical transmission. Combustion chamber and associated chemical reactions are included. The engine transient performance results are compared to experimental results from firing tests rig [1]. A second model is built to simulate part of a launcher mission, including the detailed engine, flight dynamics and orbital heating. It extends the use of simulation to evaluate the impact of real mission conditions on the engine start-up. This approach is applied on an existing launcher to illustrate the benefits of the integrated model. Further analyses are finally proposed, discussing how this integrated framework could be extended to steer performance, stability and control studies.

RL10 ENGINE MODELING

RL10A-3-3A is a rocket engine used for the upper stage vehicles. It was developed by Pratt & Whitney, under contract to NASA. RL10 engine is based on an expander cycle using liquid hydrogen (LH_2) and liquid oxygen (LOx). In an expander cycle, shown in Figure 1, heat dissipated by the combustion chamber is used to gasify and raise the gas temperature of the hydrogen. In this way, it can be used to drive the turbine, which in turn drives a single-stage liquid oxygen pump (through a gear case) and a two-stage liquid hydrogen pump, before being injected into the combustion chamber and burned [2]. Finally, the products of the combustion are accelerated in the rocket nozzle to generate thrust.

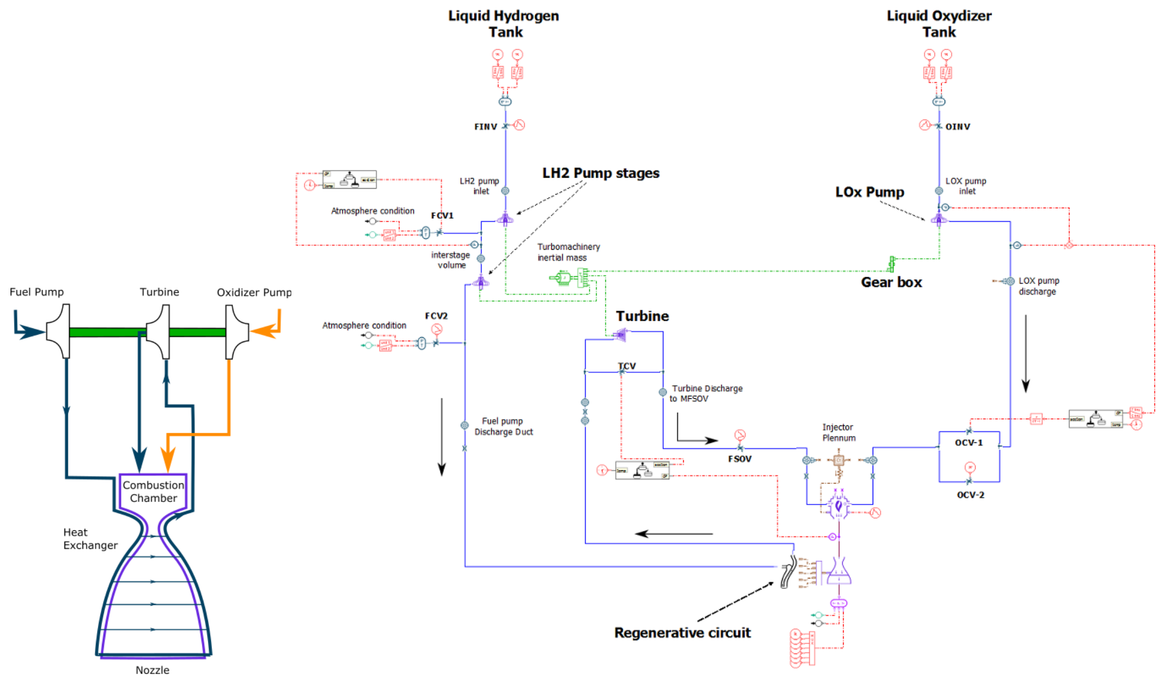

Figure 1: Expander cycle schematic (left hand side) and Simcenter Amesim model (right hand side)

The RL10A-3-3A engine is modeled using the Liquid Propulsion library in Simcenter Amesim software. The Liquid Propulsion library consists of a set of specific components for cryogenic engines as pump, turbine, combustion chamber and nozzle. This library is an extension of the Two-Phase Flow and Gas Mixture libraries which addresses the physical phenomena linked to dynamic gas mixture, combustion and phase change transition (supercritical, boiling, condensation...). Components from other libraries such as shafts, accounting for mechanical dynamics, gearboxes, electrical generators, heat exchangers can be combined with this library components to allow the modelling of any rocket engine configuration and any integrated systems.

This engine model is shown in Figure 1 and is based on the information found in [1]. Para-hydrogen (LH_2) and Oxygen (LOx) are modeled using a two-phase flow fluid model. The equation state used for LH_2 is Helmholtz and for the Oxygen is Modified Benedict-Webb-Rubin (MBWR). The gas mixture of the combustion products is considered in this model for the nozzle performance computation. The fluid properties are calculated according to the reference [3].

In this model, most of the icons represent a physical or a functional model like pumps, volumes, orifices or pressure losses, etc. To ease model understanding or to re-use some assembly of models or submodels, super-components are useful: they allow to organize the model, gathering some submodels together and so creating your own model to be re-used in another context. In the model presented above for instance, the regenerative circuit is modeled thanks to a super-component depicted in Figure 2.

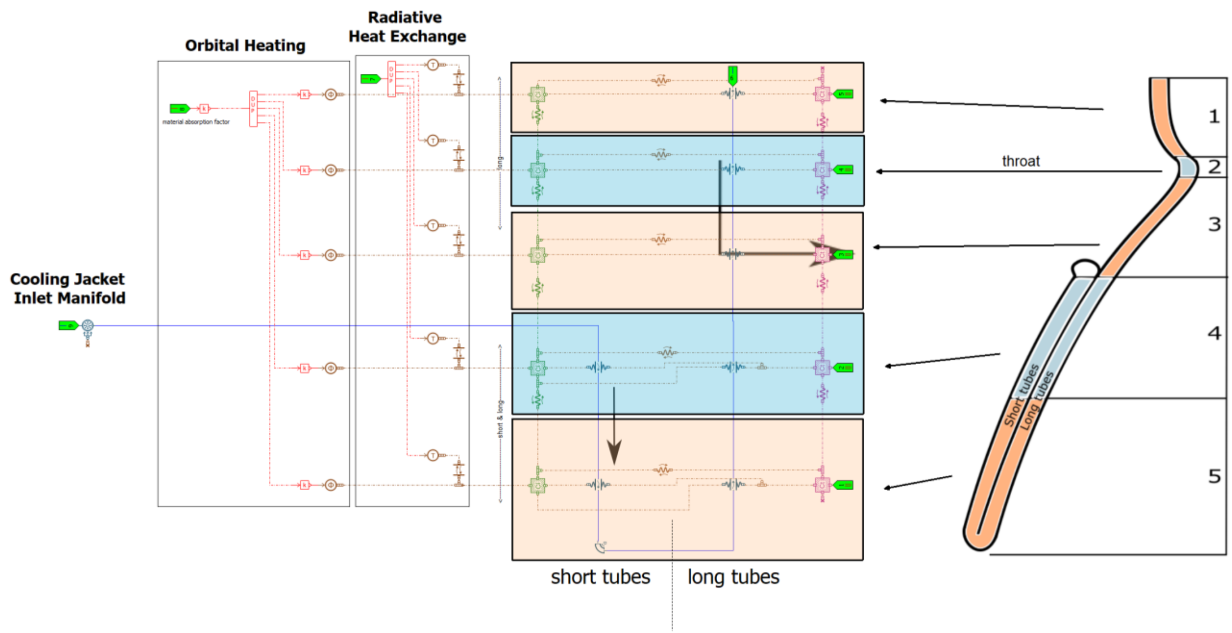

Figure 2: Simcenter Amesim model – regenerative circuit super-component

Inside the super-component, one can identify all the different parts of the regenerative cooling jacket (short and long tubes, wall masses, tubes masses). It also includes orbital heating and radiative heat exchanges with the environment.

<u>Validation RL10 start-up vs NASA results</u>

Firing test transient results have been used to validate the dynamic behavior of the model. The following Figure 3 compares measured data on a ground firing test [1] with Simcenter Amesim results and simulation results available in [1].

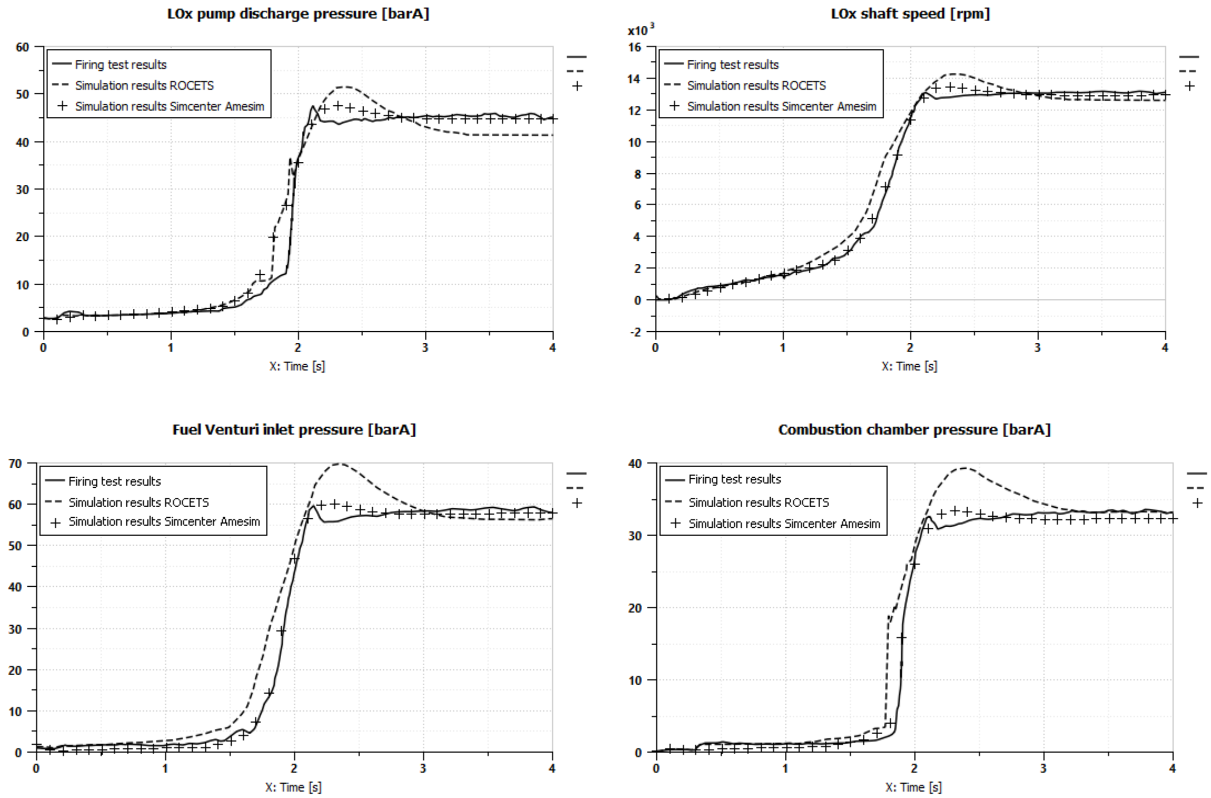

Figure 3: Results comparison – LOx pump discharge pressure (top left), LOx shaft speed (top right), Fuel Venturi inlet pressure (bottom left) and combustion chamber pressure (bottom right)

Figure 3 shows a very good agreement between simulation results either from ROCETS either from Simcenter Amesim compared to firing test results. Differences between simulations means are likely to come from different assumptions or different model granularity (and associated parameterization), thus it is not feasible to further analyze these results as we are not knowledgeable on the simulation model developed by NASA on ROCETS. Looking at the comparison of Simcenter Amesim results and on ground firing tests, a relative error of less than 3% is observed on steady state results, once rated operating point is reach. One can note the very good agreement observed on transient behaviors as well, as illustrated on the oxidizer pump acceleration or on the evolution of the pressure in the combustion chamber for instance.

<u>Start-up engine operation</u>

One of the main important factor in the start-up transient of the RL10 engine expander cycle is the cooling jacket temperature: the heat stored in the metal of the cooling jacket helps to warm and vaporize the oxidizer before going to the turbine. This evaporation helps to start the turbine and pumps rotation, which drive more propellant into the system.

In the dynamic validation shown in the above Figure 3, the ambient temperature has been used to define the initial cooling jacket temperature which is assumed to be uniform [1]. However, the initial temperature at the engine start-up can have a big impact on its time-to-accelerate. As an illustration, the Figure 4 presents, on the left-hand side, the evolution of the liquid hydrogen fuel consumption as a function of the initial cooling jacket temperature during the start-up, exactly at 1.9 seconds. As the initial temperature increases the fuel consumption increases too, even though it is not linear, it indicates a slower stat-up of the engine, confirmed by the LOx pump shaft speed time evolution on the right-hand side plotted for different initial temperature of the cooling jacket and compared to the ground firing test result. One notes that the rated operating point of the engine is not reached yet for the lowest initial temperature “virtually tested”.

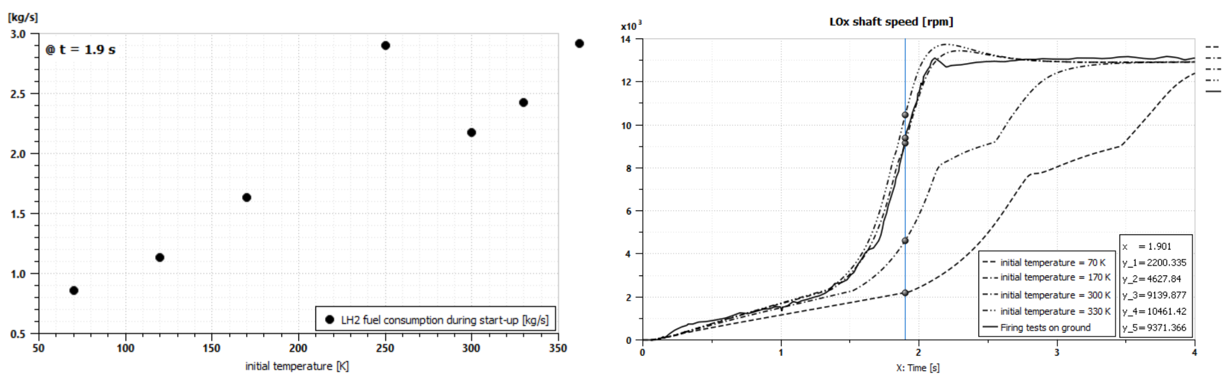

Figure 4: transient results at different cooling jacket’s initial temperatures

As RL10 engine have several start up during a launcher flight (as in the example of Delta IV), the initial temperature of the cooling jacket needs to be computed to validate the correct performance of the engine operating in real conditions. For that point, an integration of flight dynamics, atmospheric model and rocket engine has been done.

INTEGRATED FRAMEWORK FOR MISSION ANALYSIS

In that section we simulate the RL-10 engine startup in real flight conditions. The objective is to evaluate the impact of environmental conditions on the startup sequence and complement the previous analysis performed at ground conditions. We will specifically focus on the cooling jacket thermal behavior during a long ballistic phase, as its temperature can impact the engine transient behavior at startup.

Framework overview

During the flight the cooling jacket is exposed to environmental conditions that will vary depending on the spacecraft position and the launch time. To conduct this analysis, we have developed a framework that combines models of spacecraft flight dynamics, environmental conditions and engine.

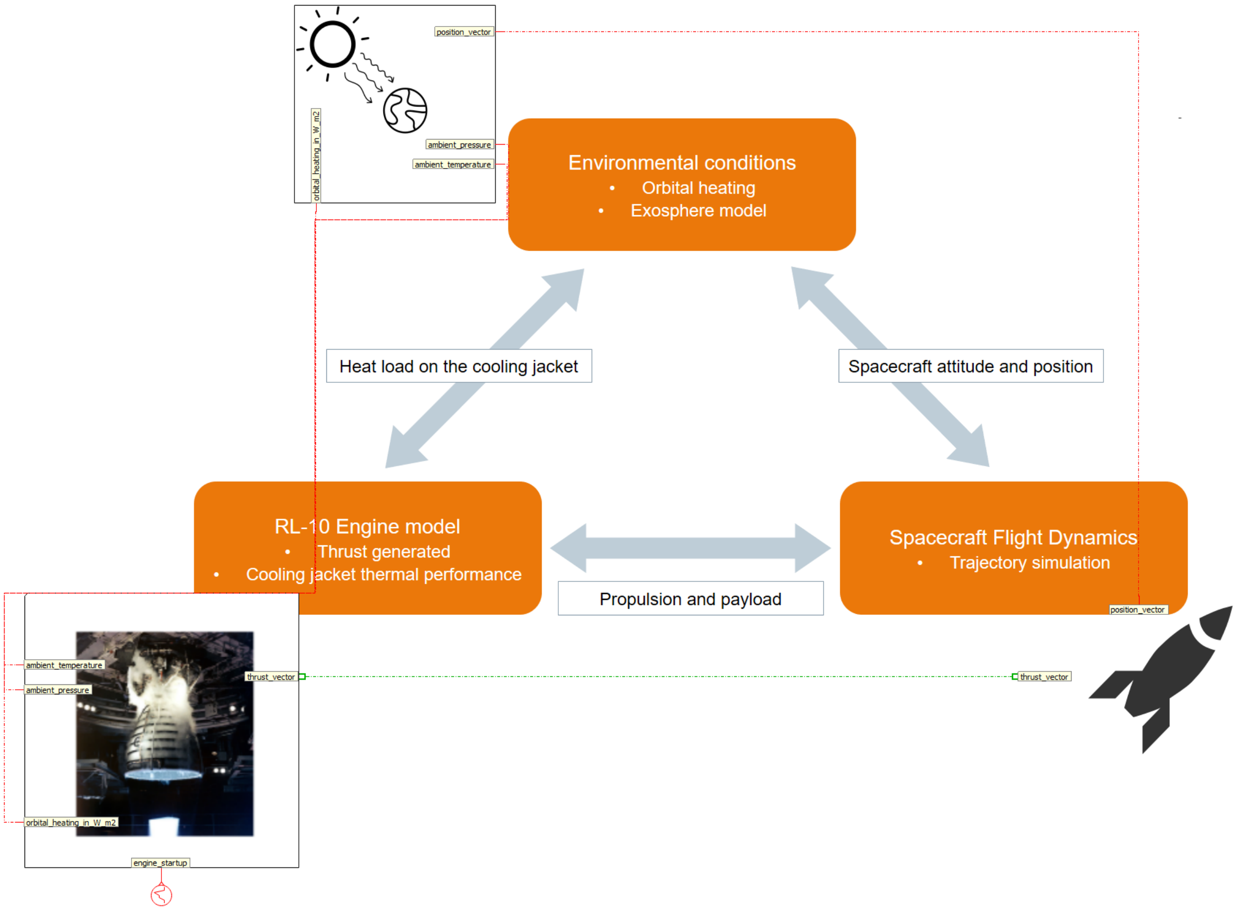

Figure 5: Framework for real flight conditions simulation in Simcenter Amesim

<u>Flight dynamics</u>

Thanks to the Aerospace and Marine library, the Newton's 2nd law and the Euler's law are written and solved to compute the vehicle's trajectory. The Aerospace and Marine library consists of a set of specific components for launcher's mission simulation and analysis. It provides the user with flight dynamic models for rigid bodies (point mass, 3 and 6 DOF) with variable mass and inertia. Sensors allow to keep track of vehicle's attitude, position and forces applied to it during the complete mission. A useful set of frames are made available: fixed in the space, to the Earth, to the spacecraft or to the aerodynamic velocity. Each of them ensures a specific goal, to write the fundamental equation of dynamics or to express forces and torques applied to the launcher's upper stage.

The linear dynamics of the body is described by Newton's 2nd law [4]:

$$\sum \overrightarrow{F} = m \cdot \overrightarrow{a}^{I}_{G}$$

$$\sum\vec{F} = \mathrm{m} \cdot \overrightarrow{\mathrm{a}_\mathrm{G}^\mathrm{I}}$$

The linear acceleration of the body center of gravity can be written:

$$\overrightarrow{a_G^I} = \left(\frac{d\overrightarrow{v_G^I}}{dt}\right)_{R_{gal}} = \left(\frac{d^2\overrightarrow{O_rG}}{dt^2}\right)_{R_{gal}} = \frac{\sum\vec{F}}{m}$$

With:

- $\overrightarrow{a_G^I}$ body center of gravity linear acceleration (absolute)
- $\overrightarrow{v_G^I}$ body center of gravity linear velocity (absolute)
- $\overrightarrow{O_rG}$ body center of gravity linear position (absolute)
- m total body mass
- $\vec{F}$ external forces applied to the body

The angular dynamics of the body is described by Euler's law:

$$\sum\vec{M} = I_b \cdot \left(\frac{d\,\vec{\Omega}_{R_b/R_{gal}}}{dt}\right)_{R_{gal}}$$

The angular acceleration of the body center of gravity can be written:

$$\dot{\vec{\Omega}}_{R_b/R_{gal}} = \left(\frac{d\,\vec{\Omega}_{R_b/R_{gal}}}{dt}\right)_{R_{gal}} = I_b^{-1} \cdot \sum\vec{M}$$

With:

- $\dot{\vec{\Omega}}_{R_b/R_{gal}}$ body angular acceleration (absolute)
- $\vec{\Omega}_{R_b/R_{gal}}$ body angular rate (absolute)
- I_b body inertia tensor
- $\vec{M}$ external moments applied to the body center of gravity

Dedicated post-processing such as 3D trajectory visualization can be generated from simulation results.

Environmental Conditions

Environmental conditions component contains the atmosphere model and computes the orbital heating as a function of the trajectory followed by the launcher.

Gravity and Atmosphere model, Earth representation

An implementation of the U.S. Standard Atmosphere model 1976 [5] is used to compute air pressure and temperature as well as the gravity field as function of altitude given as an input from the simulated spacecraft trajectory. The earth representation is round rotating with a spheroid geometry based on the WGS84 standard.

Space thermal environment - orbital heating calculation

Overall thermal behavior of the spacecraft is achieved by balancing the infrared radiation (IR) emitted by the spacecraft against the heat generated by the internal components and the heat absorbed from the environment.

The heat sources coming from the environment are:

- Direct solar radiation (referred as 1 in Figure 6) - major source of environmental heating on most spacecraft. Varies slightly due to Earth's elliptic orbit and it is maximum during the winter solstice.
- Albedo (referred as 2 in Figure 6) - sunlight reflected of a planet or moon. Expressed as the fraction of incident sunlight that is reflected to space.
- Planet IR (referred as 3 in Figure 6) — incident sunlight not reflected as albedo is absorbed by the planet and re-emitted as IR energy or blackbody radiation.
- Free Molecular Heating (FMH) — results from the collisions of individual molecules in the outer reaches of the atmosphere. It is more noticeable in low perigee orbits or when aerobraking is used.

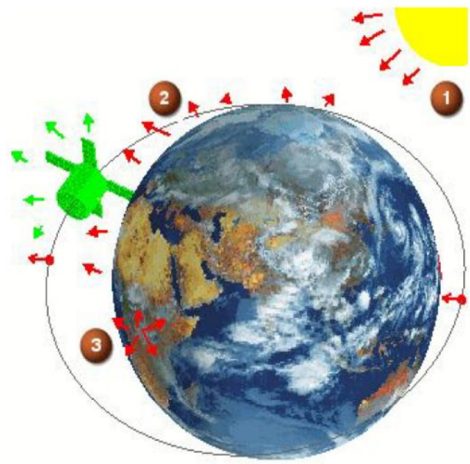

Figure 6 : schematic of orbital heat sources, extract from the Simcenter 3D Space Systems Thermal documentation

Simcenter 3D Space Systems Thermal for Orbital Heating calculation

How the spacecraft is affected by these heat sources depend on the orbit, season, attitude, and location over the planet. The spacecraft attitude and position calculated by the trajectory simulation in Simcenter Amesim are fed to a Space Thermal Module. It computes heat loads resulting from direct solar flux, albedo and planet IR using a radiosity approach to determine the reflection and absorption of the incident flux throughout the model. Free molecular heating will be neglected in this study considering the angle formed between the cooling jacket surface and the spacecraft's velocity vector.

Integration of models in Simcenter Amesim platform

Interactions between multidisciplinary systems and complex 3D systems are often needed during the concept and validation development phases. Simcenter Amesim platform allows to be coupled with various external software, such as computer-aided engineering (CAE), computer-aided design (CAD), computer-aided manufacturing (CAM), finite elements analysis / finite elements method (FEA/FEM), or computational fluid dynamics (CFD). These coupling ensure a good dialog between the tools and the simulation software.

Coupling with external software can be done in different ways:

- Weak coupling: this is a one-way coupling when full interface between simulation software is not required. CPU time is an advantage point.
- Co-simulation or strong coupling: a two-way coupling. Simcenter Amesim platform propose two ways to do Software Interfacing, either using Generic Co-simulation or using Functional Mock-up Interface (FMI).

In this case, both options were feasible, a weak coupling has been done to favor results restitution delay or CPU time performance. Therefore, a look-up table with the orbital heat flux

[W/m^2] has been generated thanks to Simcenter 3D and imported into Amesim. The look-up table is a function of the altitude, latitude and longitude of the spacecraft, previously computed at system level.

APPLICATION CASE: DELTA IV MEDIUM GTO MISSION

We choose to simulate part of a GTO mission of a Boeing Delta IV (medium version) mission. This application case has the advantages that:

- the delta IV upper stage is propelled by a RL-10 engine. In the first part of this study we developed a transient model of the RL-10 that can be reused for the mission simulation,
- the extensive documentation of the launcher and its mission give us access to the parameters required to set-up and run the simulation,
- the flight segment between the upper stage first engine cut-off (SECO1) and the engine re-ignition (between 886[s] and 1452[s] in a typical GTO mission, Figure 7) is a good example of a long ballistic phase followed by a re-ignition.

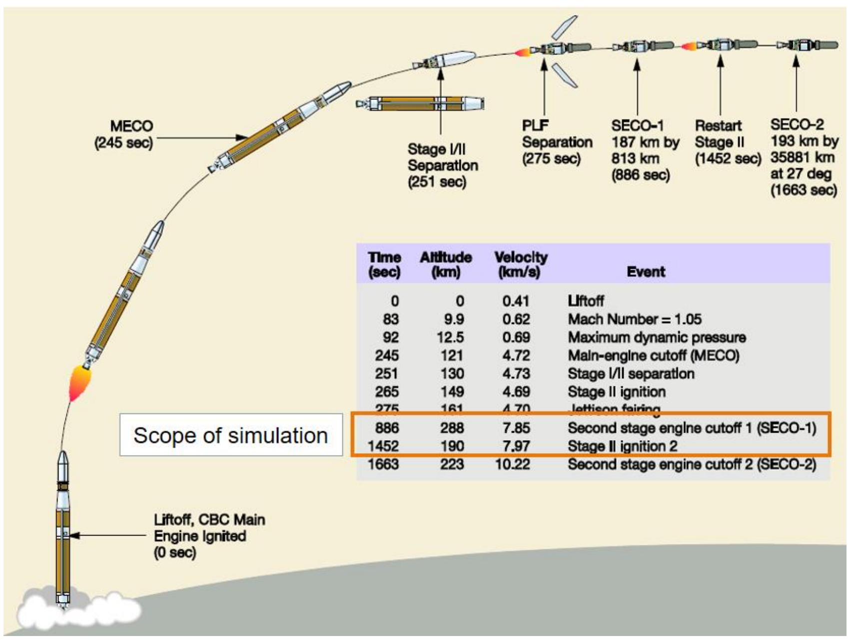

Figure 7: extract from Delta IV users guide [7]

The launch time and date simulated correspond to an illuminated flight segment, with a solar intensity around 600 [W/m^2] (Figure 8):

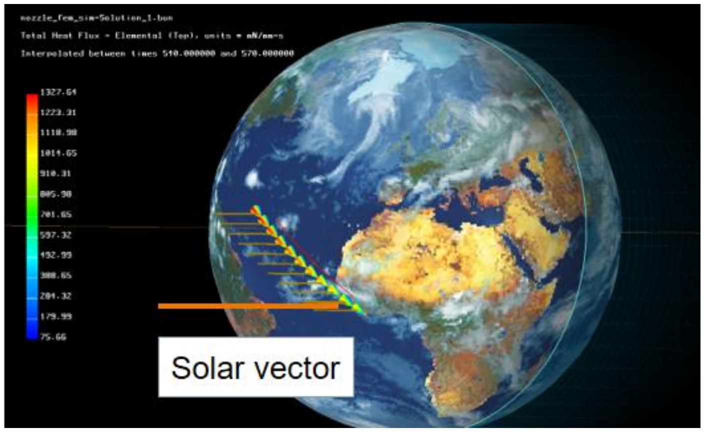

Figure 8: representation on the illuminated region during the delta IV mission

Results – Impact of cooling jacket temperature on engine start-up

The simulation gives us access to the temperature evolution of the cooling jacket during the mission. Figure 9 shows the temperatures of the five zones considered in this study.

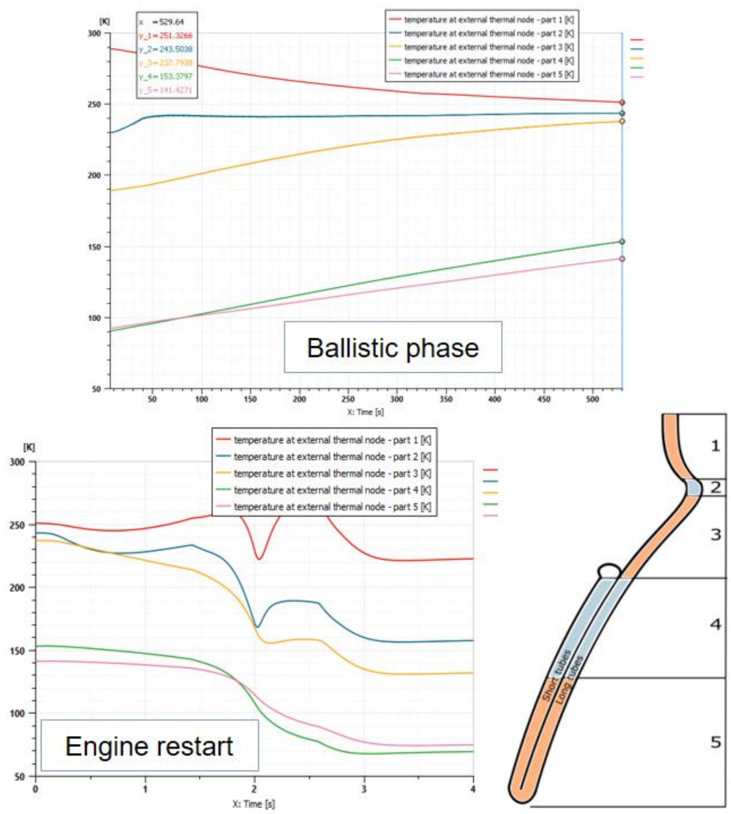

Figure 9: Results – cooling jacket temperature

During the ballistic phase, it reflects the balance between the heat sources (heat accumulated during the first combustion phase and the orbital heat loads) and the heat released by radiation.

Once the engine is restarted, according to the delta IV medium mission profile, additional heat exchanges take place due to the combustion and the propellant passing through the tubes.

Figure 10 shows the engine time to accelerate simulated. On ground firing test results similar the one shown on Figure 3 are kept as a reference even though interest to compare them to simulation results is limited. It is interesting to observe the longer time to accelerate to the rated point, on LOx oxidizer flow rate and pump shaft speed as well as on the combustion chamber pressure increase. In the same time, one can note that the fuel flow rate almost reaches the nominal fuel flow rate with a sharp decrease occurring around 3 seconds after the re-ignition.

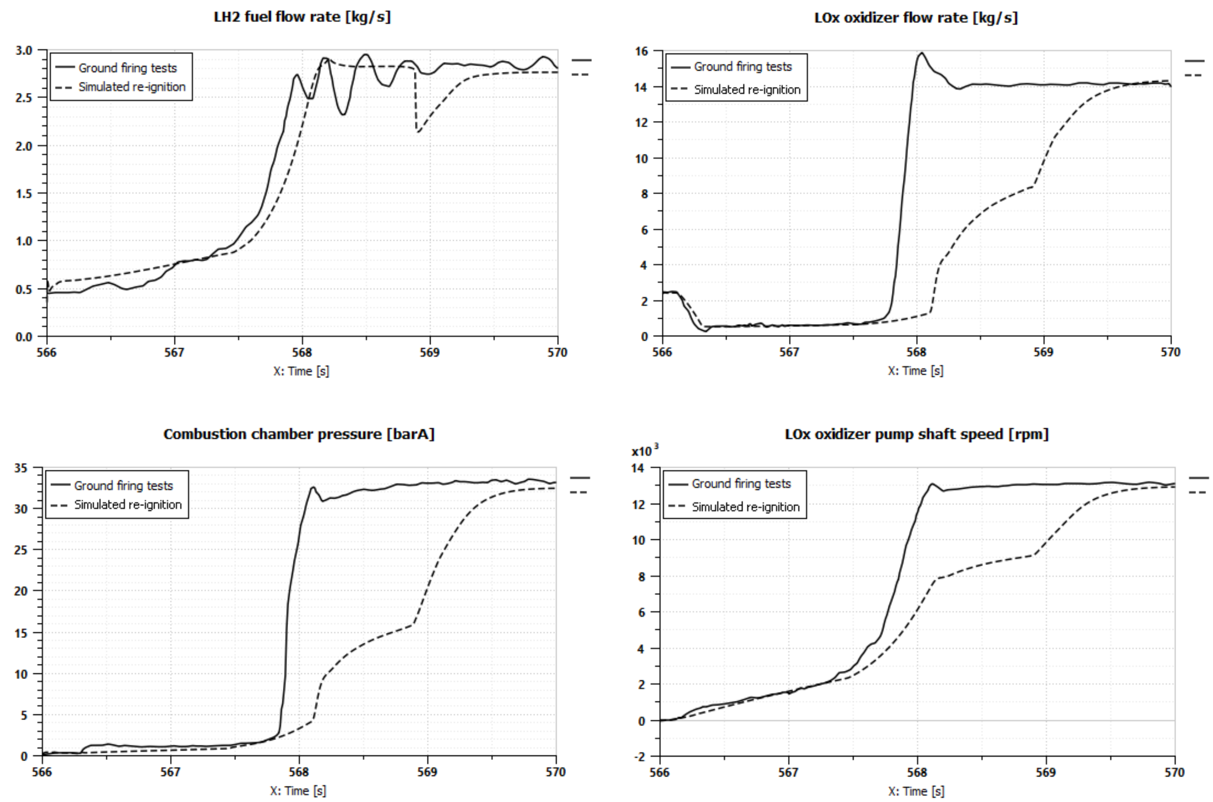

Figure 10: Results - engine time-to-accelerate

The cooling jacket low temperature at restart triggers a delay in reaching the operating point, as expected from the sensitivity analysis abovementioned.

The spacecraft trajectory is also an output of the mission simulation. Figure 11 shows the ground trace and the velocity profile compared to the delta IV theoretical mission profile. At the end of the ballistic phase, the predicted final altitude is of 188.7 km compared to 190 km and the predicted spacecraft speed is equal to 7.967 km/s compared to 7.97 km/s as shown on Figure 7. The agreement of simulation results is quite good with values extracted from literature [7].

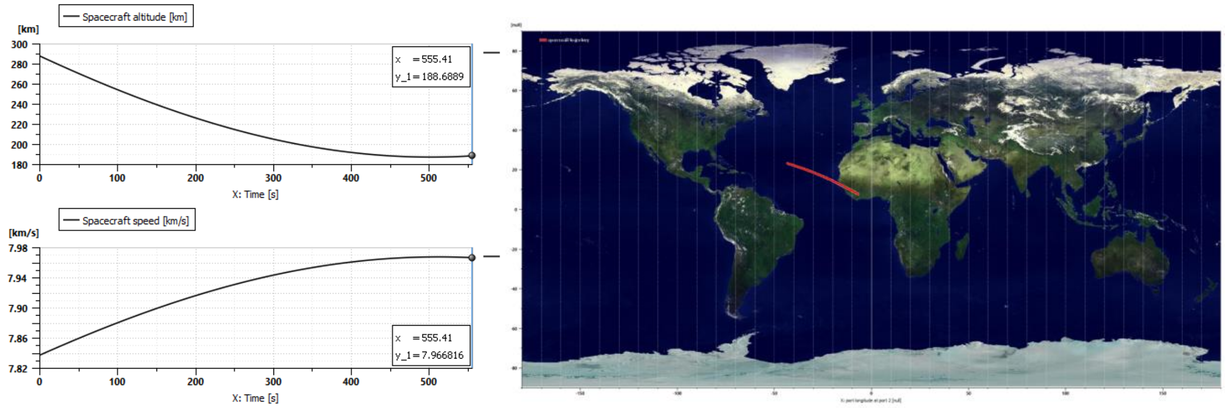

Figure 11: Results – altitude, velocity and ground trace on 2D earth

CONCLUSIONS

The integrated model developed in this study allows a better prediction of the real flight conditions and their impact on the engine start-up. We built it by connecting models coming from different engineering disciplines: thermal analysis in an orbital environment, spacecraft flight dynamics and rocket engine transient modeling.

The Simcenter Amesim platform is used to combine these three models and create an integrated plant model, able to simulate events like ballistic flight segment followed by an engine re-ignition. With this study, we seized the benefits of an integrated model. First it allows to account for systems interactions combining different engineering disciplines. Secondly it allows the simulation of complex missions with operating conditions that are not easily reproducible during ground conditions firing tests. By complex mission we refer to scenario involving stage recovery, the launch of multiple payloads or space exploration tasks. The common point between these examples is that they require to shut down and restart the engines multiple times.

As prospects to this study, extension to other types of mission can be envisaged as well as:

- Upper stage flight dynamics simulation in support of GNC development. In low gravity environment spacecrafts attitude and orbit control is challenging. The controllers for instance must deal with the effects of fuel sloshing, separation mechanisms, thrust vector control (TVC) actuator properties and engine transient behavior. An integrated model assessing the behavior of these systems in real flight conditions would be helpful.
- Stage recovery simulation. To decrease the launch cost some companies are designing reusable stages. Different engineering disciplines are involved in making sure part of the launcher can be recovered: aerodynamics, engine design, flight controls, fuel system, landing gear to name a few.

CONTACTS

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