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ARIANE 6 CRYOGENIC UPPER LIQUID PROPULSIVE MODULE MULTI-BOOST MISSION DEVELOPMENT, A SYSTEM INTER DISCIPLINARY CHALLENGE

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Ariane 6 Cryogenic Upper Liquid Propulsion Module currently under development is a real game changer thanks to the mission versatility it will offer. Based on two propulsive systems (VINCI Main engine and Auxiliary Power Unit) using liquid Hydrogen / liquid Oxygen propellant, , it will have a capability of four Main Engine ignitions with long coasting phase in-between. The present paper will provide an overview of the definition of these specific flight phases, the encountered difficulties and the way they have been managed.

Nomenclature

ULPM	=	Upper Liquid Propulsion Module
LLPM	=	Lower Liquid Propulsion Module
ESR	=	Equipped Solid Rocket
APU	=	Auxiliary Power System
GOX/GH2	=	Gaseous Oxygen/Hydrogen
LOX/LH2	=	Liquid Oxygen/Hydrogen
CGRS	=	Cold Gas Reaction System
GNC	=	Guidance Navigation Control
LEO	=	Low Earth Orbit
GEO	=	Geosynchronous Orbit
GTO	=	Geosynchronous Transfer Orbit
MEO	=	Medium Earth Orbit
MEOP	=	Maximum Expected Operating Pressure
CoG	=	Center of Gravity
MCI	=	Mass Centering & Inertia
FU	=	Functional Unit

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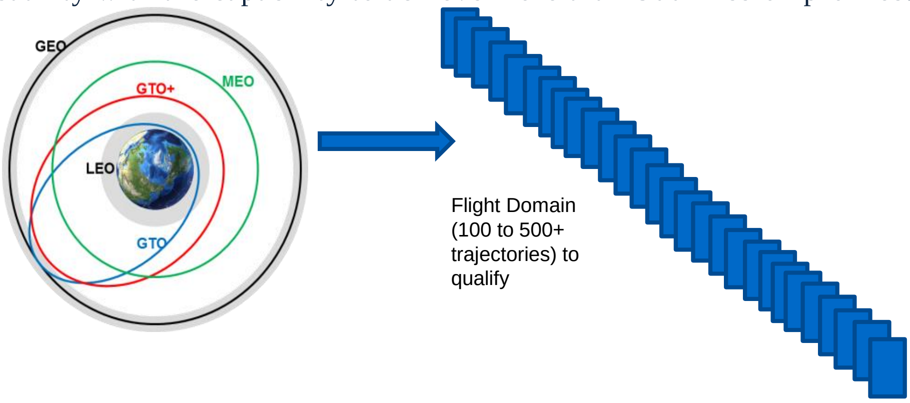
I. Introduction

Ariane Group carries the legacy of Ariane 5 operation and Ariane 6 development. As successful and reliable Ariane 5 has been, it has long been apparent that its cryogenic upper stage was limited to mono-boost missions. One basic objective of Ariane 6 is to offer a full versatility with the capability to achieve more than 500 mission profiles.

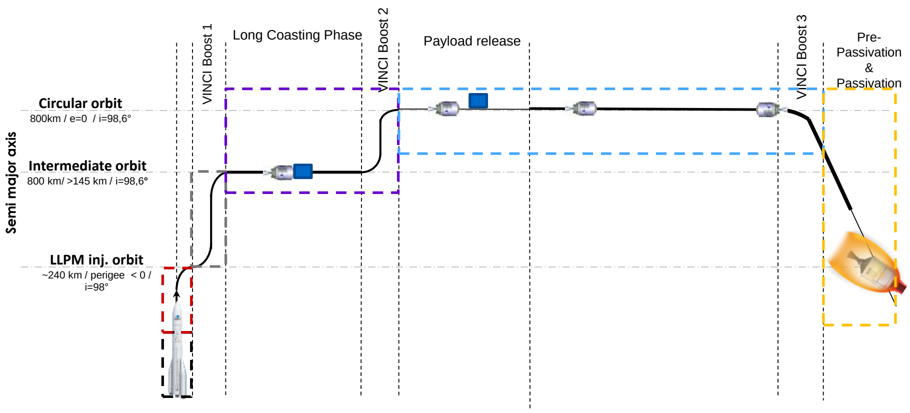


At the eve of Arinae 6 program, the way to manage the complete mission domain (more than 400 possible different missions) in a coherent manner was clearly an issue.

Although firsts Ariane 6 flight phases (ESR, LLPM, ULPM first Boost) are quite classical when compared to Ariane 5,the versatility requested on Ariane 6 for orbital phase is a game changer ! This versatility mainly relies on two following elements:

- ULPM design which uses innovating system called Axillary Power Unit (APU) combined to re-ignitable VINCI Main Engine, allows ensuring overall flight domain with a single HW definition
- Flight sequence modular architecture defined in such a way to reach the flight domain with mastered qualification effort and limited tuning effort from one mission to another

Among this mission domain, some of them have been pictured here below to highlight the diversity of sequences we have to face.



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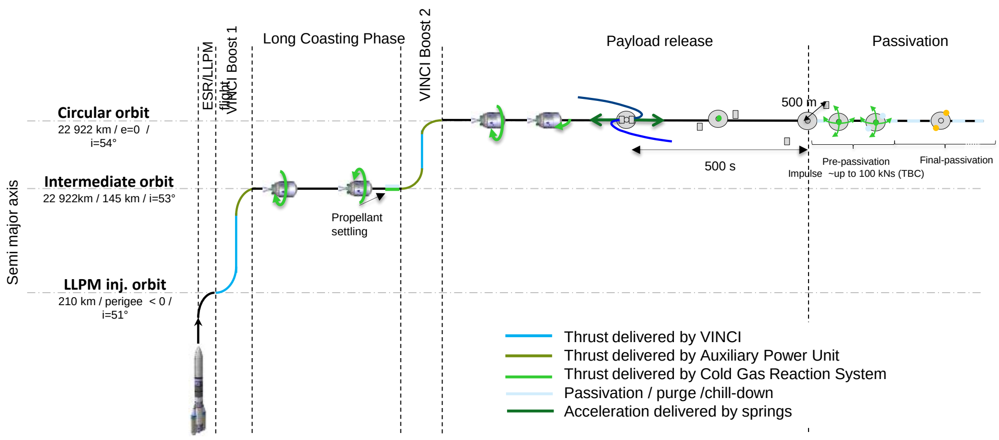

Per definition, all operations made post ULPM first boost are part of the "Orbital Phase"

- It encompasses all the phases up to fall-out or to graveyard orbit final state
- In particular, payload release phase and ULPM Main Engine (VINCI) re ignition preparation and re boosts are part of the orbital phase.

The main technical difficulties related to this phase are:

- Mastering of propellant thermodynamic conditions and hydraulic motion in consistency with
  - Engines needs (APU, VINCI)
  - Orbital control needs (CGRS feeding)
  - Missions constrains depending on the Payloads/Launcher : Sun Aspect Angle, Launcher Spin Velocity, Thermal…
  - Consumptions allocation compatible with the launcher definition (Propellant, Helium, power budgets)
- Keeping the proper mastering of orbitals parameters and especially targeted accuracy (attitude, attitude angular rate) and associated scatterings.

II. Main constrains/drivers of the orbital phase

Ariane 6 ULPM functional architecture is based on:

- One Main Engine (VINCI) with two operating point 180kN or 130kN thrust. It provides also GH2 (tap off) for LH2 Tank pressurization
- An Auxiliary Power Unit (APU) providing different level of thrust (from 110N up to 300N) GOx for Lox Tank pressurization (during VINCI boost and during orbital phase), GH2 for LH2 Tank pressurization (only during orbital phase)
- Cold Gas (GH2) Reaction System for Orbital control connected to the LH2 Tank (ten thrusters dispatched on 4 plates)

The firsts and main constraints are related to Engines (APU, VINCI):

- need to have propellant in front of the pump during engines ignition preparation and when they are running ➔ constraints on orbital control, longitudinal thrust using APU to get sufficient settling of the propellant

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- Mastering of propellant thermodynamic conditions (pressure, temperature) in order to avoid any cavitation risks when engines are running :
    - Mastering of Lox propellant positioning in the tank areas subject to very low incoming fluxes (rear bulkhead) when VINCI is not running to keep acceptable temperature for re boost ➔ constraints on orbital control, longitudinal thrust using APU to get sufficient settling of the propellant
    - Management of LH2 tank pressure to master properly LH2 temperature before engines re ignition preparation
    - Mastering of LH2 propellant positioning in the tank areas subject to very low incoming fluxes (rear bulkhead) when VINCI is not running to keep acceptable diphasic ratio at APU Moto pump inlet ➔ constraints on orbital control, longitudinal thrust using APU to get sufficient settling of the propellant
    - Mastering of LH2 Tank stored impulse in order to feed all orbital Control need ➔ constrain on LH2 pressure management using GH2 pressurization capability of the APU

Not forgetting, all other constraints such as:

- In orbit injected mass which implies the mastering at the minimum level of consumptions (so called “non-propulsive propellants”): LH2 boil-off, Tanks re pressurization prior VINCI re ignition, VINCI chilling down, geometrical residuals (dependent on longitudinal acceleration so on upper composite MCI)…
- In orbit accuracy which could be affected by forces/torques induced by propellant motions, by IMU drift (which implies for some cases to perform full zero g short phases for recalibration) or by VINCI shut-down tail-off scattering
- Payload constrains which could implies spin mode or not, specific Sun Aspect Angle,

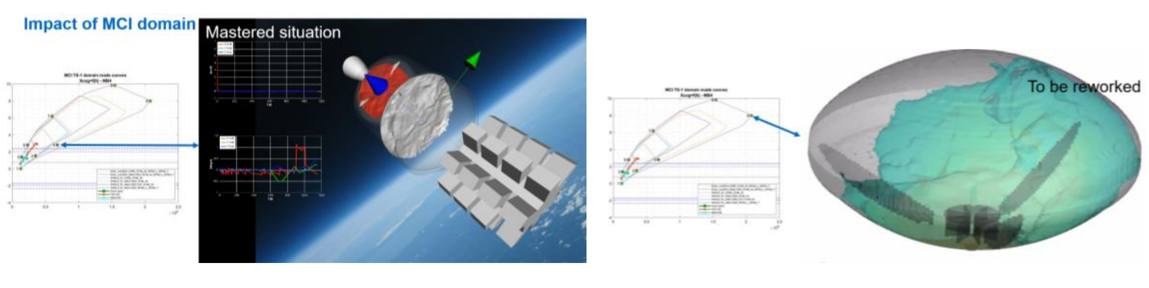
Obviously, all these constrains have to be considered in front of the whole MCI possible range.
Indeed, the upper composite CoG positioning with regards to LOX/LH2 propellant is:

- dependent of Payload mass
- Moving all along the mission

Therefore orbital control strategy has to be adapted in order to :

- Insure effective control
- Insure mastering of propellant behavior under induced disturbances

it could lead to fully mastered situation…or not !



Depending on the Upper Composite MCI and on mission scenario, the consumption of the CGRS in GH2 and the number of thruster activations could vary. Indeed, the CGRS insures during Orbital Phase several functions:

- Attitude control of the Launcher

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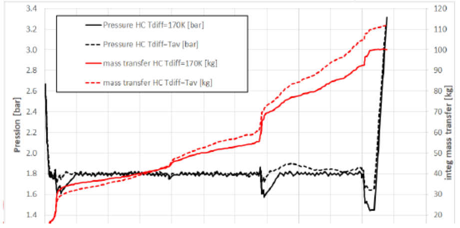
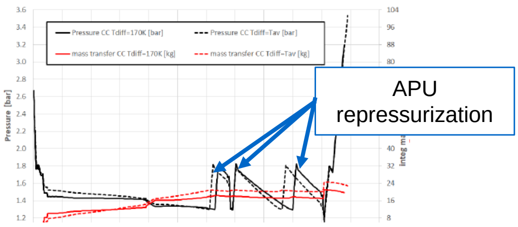
- Propellant settling before APU re-ignition
- Distancing of the Launcher w.r.t. P/L or Dual Launch System
- LH2 tank depressurization
- Passivation of LH2 tank when power is available

Therefore, GH2 resources availability is key to keep upper composite control. It implies:

- Proper management of tank pressure
- Proper management of LH2 boil-off (which contribute to GH2 re generation)
- APU availability and capability to re pressurize the LH2 tank in case of need



Hot case ➔ important boil-off – no need of APU repressurization



Cold case ➔ Low boil-off – need of APU repressurization

III. Solution found : Multi-disciplinary system functional analysis

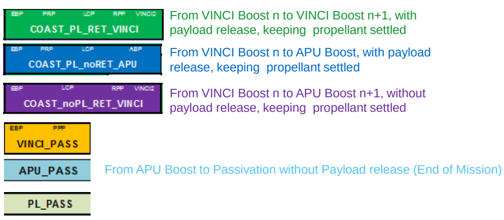
In front of such challenge, in 2018 we went through a system functional analysis. This exercise was fruitful providing surprising outcomes.
Indeed, it appears rapidly that from a system point of view all missions are a pure sequencing of a low number of different macro phases defined by the couple: from where are you coming, where do you want to go

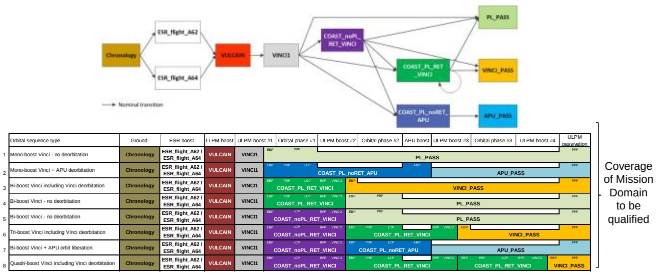
- From one VINCI boost to an another one
- From one VINCI boost to an APU one
- From one VINCI boost to the passivation (end of mission)
- From one APU boost to the passivation (end of mission)

For each of them, the sequencing of elementary operations is always the same and just dependent of:

- Payload release or not during the phase
- Continuous settling of propellant or not

At the end, we were able to demonstrate that with only 6 macro phases, the complete mission domain could be covered !





Declination to Macroblocks concept

Macro phases identified through the functional analysis have been renamed "Macro-Blocks" with the following definition

- A Macro-block is a part of the Launcher flight sequential in which Main Functions realize actions in a pre-defined and coordinated manner, to implement functions requested during the phase. Therefore, it is a succession of standard modes for different domains (Control, propulsion, …) always in the same order.

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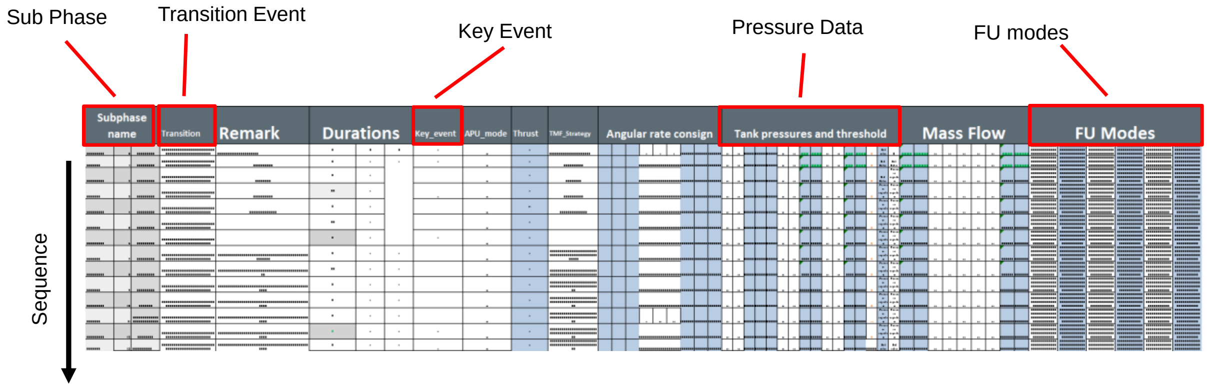
- A Macro-block is generic. It can be used for several mission as it is tunable via simple rules, mission data without impact on qualification
- Depending on the characteristics of the mission, these Macro-block have to be tuned, either by variant (finite number of possibilities) or by optimization (boost duration for instance).
- The customization of the Macro-blocks depends on: Launcher MCI, amount of propellant remaining, duration of coasting phase…
- An orbital Macro-block always starts at an engine (VINCI or APU) extinction

A Macro-block is described by a succession of bricks (elementary types of operations). For each brick, the following elements are defined within the Macro-blocks:

- Duration of each brick (nominal, min, max)
- APU mode
- Longitudinal thrust insured
- GNC mode
- Thruster management function strategy (use of longi thruster, all thrusters,…)
- Angular rate consign for CGRS (maneuvers, accuracy of roll control)
- Functional pressure in LOX and LH2 tanks pressurization mode LOX (MEOP protection, pressure regulation, force depressurization)
- Pressurization mode on LH2 side (MEOP protection, pressure regulation, force depressurization)
- Thresholds for LOX tank depressurization
- Thresholds for LH2 tank depressurization using CGRS
- Number of thrusters for LH2 tank depressurization
- Safety limit for LH2 tank depressurization
- Thresholds for activation of LH2 tank re-pressurization by APU



Many Stake-holders are involved in the definition/justification/qualification of the different Macro-blocks :

- Phase A/B1(Pre-Project)

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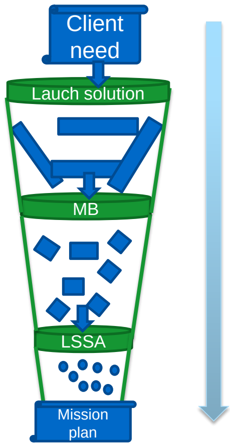
- Mission preparation
- GC orbital
- Pressure budgets
- Propellant budget
- APU Power budget
- Thermal analyses
- APU fatigue
- APU inlet conditions
- Propellant stratification
- Performance
- Functional Units / Flight Software
- Failure mode assessment
- Mission qualification



Leading to a complex but necessary RACI matrix…involving all disciplinary

***R (Responsible)* :** Those who **do the work** to complete the task.

***A (Accountable)* :** The **one ultimately answerable** for the correct and thorough completion of the deliverable or task, the one who ensures the prerequisites of the task are met and who delegates the work to those *responsible*

***C (Consulted)* :** Those whose opinions are sought. There is a **two-way communication**

***I (Informed)* :** Those who are kept up-to-date on progress, often only on completion of the task. There is just **one-way communication**

(1) For multi-disciplinary studies coordination
(2) Until MF Constraints are not formalized
(3) For ULPRO justification. Analysis
(4) For multidisciplinary tool
(5) To be nominated at BTC
(6) Depending on validation needs
(7) For new MB only
(8) If sequence related

…nted by :	Phase … L. Nguyen Duc	Main … Frapsauce, B. Heese	… Fontaine, A. Romet	Technic … Piquemal	Technical … Peyraud, R. Cheve,	Functionnal architec … P. Casiez	Tools develope … J. Albrieux	enforcement responsible … J. Giroux	enforcement responsible (… V. Coipeau	compliance responsible (quality … F. Tisseyre	Sequential-Launcher manageme nt … M. Ducamp	MB	Mission analysi	PM … Condamnet	Mission prepara … der Ricour	Launch solutio … Antoine Joulot	Trajectory responsi	Configuration … Gurau Tudoran	Data managemen … Catherine Vatel	Technical … G. Pignie
Specifying the need with the MB requester	R	C										A								
BTC	A	C	I		I (5)	C		C	I	C	I	C		I		C / I (7)	C	C	C	I
- Preliminary conception and definition	R	I, currently C (2)			C (6)				A											C (6)
Phase by Phase definition	A, R	R	C		R (7) / I (5)	R				I	C									R (7) / I
BTC complementary study	C	A		R						C				C						
Justification analysis	C (1)	A	R (for GNC)	R (3)																
ETC complementary study	C	A		R						C				C						
- Global justification	A, R	C		R (4)	C (7)	C					I (8)									C (7)
- Redaction	A, R																			
- Review loop	R	R	I	I	R (5)	R		R	A	R	I	I								R
- ETC	A	C	I		I (5)	C		C	I	C	I	C		I		C / I (7)	C	C	I	I
- Finalization of DF/DJ and Dataset publication	A, R																			
- Signature loop	A							R	R	R										
- MB Key event issuing	A										I									
- DF and DJ issuing	A, R	I	I	I	I	I		I	I	I	I	I	I	I	I	I	I		I	I
- CR delivering	A, R	I	C			C					I (8)									
- MB Dataset issuing	A, R										I (8)									

IV. Conclusion

In front of Ariane 6 versatility challenge, the concept of Macro-blocks has been setup. It gathers all stakeholders (multi-disciplinary network) in order to ensure a system consistency. This new way of thinking answers to most of technical leaders questions such as:

- Where can I find what is requested for my software?
- How is used my product in flight?
- What is happening to my system on this phase? What is ongoing on the launcher at the same time?
- What the sequences of event in flight?
- What should I use for trajectory computation?
- …

Therefore, Macroblocks concept became a backbone of Ariane 6 mission solution and according definition and justification files