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TRAJECTORIES / MISSIONS MULTI-OBJECTIVES GLOBAL OPTIMIZATIONS

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ABSTRACT

The space sector is experiencing rapid evolutions and launchers / launch solutions are getting increasingly capable to satisfy large variety of destinations in space (For example while embarking multiple payloads and possibly delivering them towards multiple destinations within a single launch).

With re-ignitable upper stage engines, usage of KickStage(s) in addition to an upper stage, and with reusability of lower stages, the overall mission of a "launch solution" no longer consists in a single branch that aims for a single destination. The mission analysis work changes in some way and more and more becomes a work that consists in optimizing multiple branches addressing multiple destinations.

This document first identifies generic situations that are encountered when treating these type of problems; in particular 2 main situations are identified: "serial" problem and "Y" problem. General missions made of multiple "Y" situations and multiple "serial" situations may then be built while aggregating these two generic situations.

This document then illustrates through examples different application cases of mission where serial problems and / or Y problems are used to define a global mission.

Eventually, and based on examples, some guidelines and best practices are identified to solve globally these kind of multi-branches / multi-purposes / multi-destinations missions.

Ultimately, performance aspects and ways to present the maximum capabilities of a launch solution when addressing the various branches is also discussed (ie maximum reachable domain).

ACRONYMS

APU	Auxiliary Power Unit
ASDS	Automatic Spaceport Droneship
KS	KickStage
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MLS	Multi Launch System
MTO	Medium Transfer Orbit (Elliptic)
RAAN	Right Ascension of the Ascending Node
RTLS	Return To Launch Site
SSO	Sun Synchronous Orbit
ULPM	A6 Upper Stage

1. INTRODUCTION

This paper provides:

- Generic encountered situations of multi-purpose missions:
  - <u>Serial problem</u>

    Consists in one "vehicle" addressing several destinations sequentially one after the other.
  - <u>"Y" problem</u>

    Consists in 2 "vehicles"/elements of a launch solution first evolving together before separating from each-other at a certain point in space and having part ways towards their respective destinations from then on.
- Examples:
  - **A6-MLS** (Multi launch services)
  - Combined {**Ariane 6+ KickStage**} launch solution. "Serial" problem on a Multi-SSO is considered as well as a "Y" problem – HEARTED case - with KickStage and Ariane 6 having part ways towards their respective destinations in space from a certain point in space and onwards.
  - Eventually, case of reusable launcher is also discussed with **THEMIS** preparatory program
- Best practises to solve a multi-purpose mission with several branches satisfying multiple constraints / destinations.
- Establishing performance and reachable domain of multi-purposes and multi-branches launch solutions.

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2. GENERIC ENCOUNTERED SITUATIONS ("SERIAL" AND "Y" PROBLEMS)

2.1. Elementary "Serial" Problem

The serial problem consists in a single branch problem that addresses several destinations. In this case, the launcher would deliver the destinations one after the other (ie on an optimisation point of view the constraints are satisfied and resolved one after the other).

2.2. Elementary "Y" Problem

The "Y" problem is a generic situation where 2 components of a launch solution first evolve together on a common branch before separating and having part ways from a certain point in space onwards.

This generic "Y" problem typically applies to:

- Launch solution with 2 upper stages (eg 2nd stage and a KickStage)
- Reusable launcher: during a first phase the launcher climbs towards orbit, then when 2nd stage and 1st stage separate, the 2nd stage would continue on its way to orbit whereas the first stage would aim for a point on the globe specified by its longitude and latitude and null velocity as it lands which represents a certain orbital job to perform / DeltaV to produce.

2.3. Combinations of Multiple "Y" & serial situations

There can be optimization problems that would consist in treating multiple "Y" situations with each sub-branches that could also be addressing at their level and in "serial" multiple destinations.

3. REFERENCE – "One branch" Mission

Before going into more details of extended launch solutions that would satisfy multiple constraints while delivering multiple payloads at multiple destinations, figure below reminds reference "one-branch-like" missions addressing one destination (LEO/MEO/GTO).

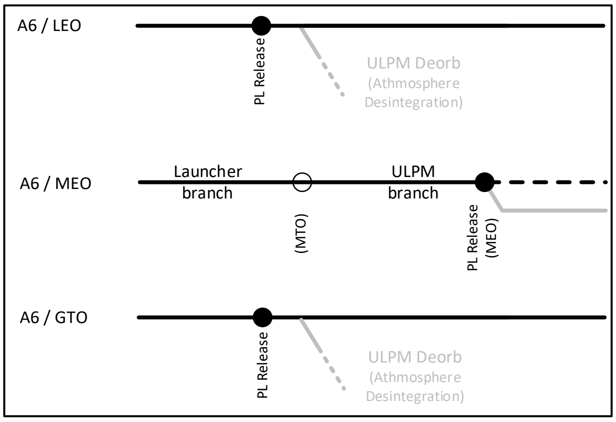

Figure 1: Reference single branch launcher addressing one orbit as destination – (Metro plan)

4. EXAMPLES / APPLICATIONS MULTI-PURPOSES MISSIONS

This section provides examples of extended missions addressing multiple orbits / destinations within a single launch and while delivering multiple payloads.

4.1. One launcher branch / multiple destinations and multiple releases

Introducing Ariane 6 MLS (Multi-Launch-Services):

*Multi-launch services is a service offered/proposed by Ariane6 => more info on this refer to **[2]**.*

The mission considered here is a Multi payload release in the LEO region (typically for constellations). It consists in one branch with payloads being released sequentially one after the other.

Ariane6 - when in service – will have extended capabilities for in-orbit operations thanks to the re-ignition capabilities of its main engine VINCI and thanks to its APU.

- With Vinci re-ignition capabilities, Ariane6 ULPM is able to change orbit and release payloads / group of payloads at these various destinations.
- With its embarked systems and in particular its APU, A6 ULPM will be capable to deliver, separate and organize (*) clouds of payloads. For example, ULPM may deliver payloads in such a way that released payloads would gradually increase their relative distances up to occupying the orbit entirely with time while payloads being potentially equally spaced or spaced according to client wishes.

  Remark:

  The relative movement between payloads is initiated by the ULPM launcher. This relative movement would then have to be stopped by the payloads themselves as they would approach their "anomaly" slot on the orbit via stabilizing themselves at their operating altitude.

  (*) A6 ULPM will indeed be capable to separate payloads as well as capable of organizing proper separation of the orbit parameters of these payloads (for example separations of semi-major axis, orbital period, inclination, RAAN drift, apogee, etc …)

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The typical MLS mission is a "serial" problem where the deliveries of payloads are performed one after the other.

Picture below illustrate schematic view of a mission releasing multiple payloads on 2 different altitude levels sequentially one after the other. Ariane6 will be able to change orbit either via usage of its VINCI re-ignitable engine and/or via usage of its APU, and may organize proper separation of clouds of payloads.

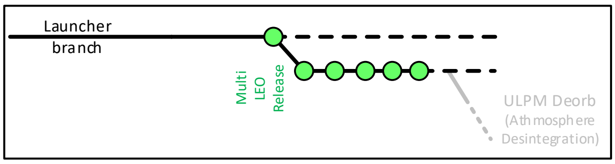


Figure 2: A6 – Multiple Payload Release (schematic)

The next coming simulation results show Ariane 6 capability to release and initiate spacing between payloads of a constellation.

The simulation case consists in 4 packs of 4 payloads each being radially released via four by four radial release.

⇨ Picture below illustrates case of 2 payloads being radially released at the same time (angle 180° between the 2 radially released payloads) - although the considered example in simulation case described below will actually consider 4 payloads radially released (angle 90° between these 4 radially released payloads).

Figure 3: A6 ULPM – Delivering 2 payloads via radial release

⇨ Figure below provides the separation strategy; it consists in separating the semi major axes of the packs of payloads with some separation within a pack being also ensured.

This strategy of release leads to progressive increase of relative distances (payload have slightly different period). This eventually leads to progressive occupation of a median orbit as shown next column-page.

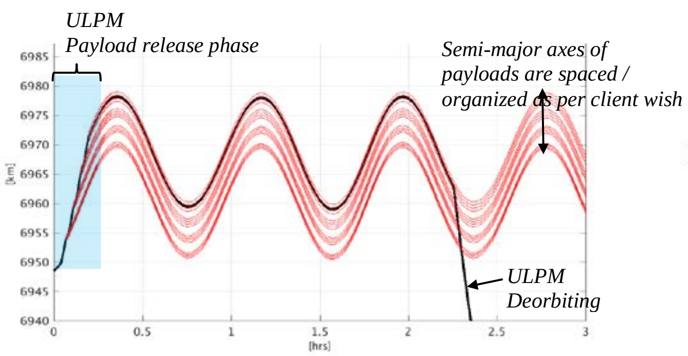


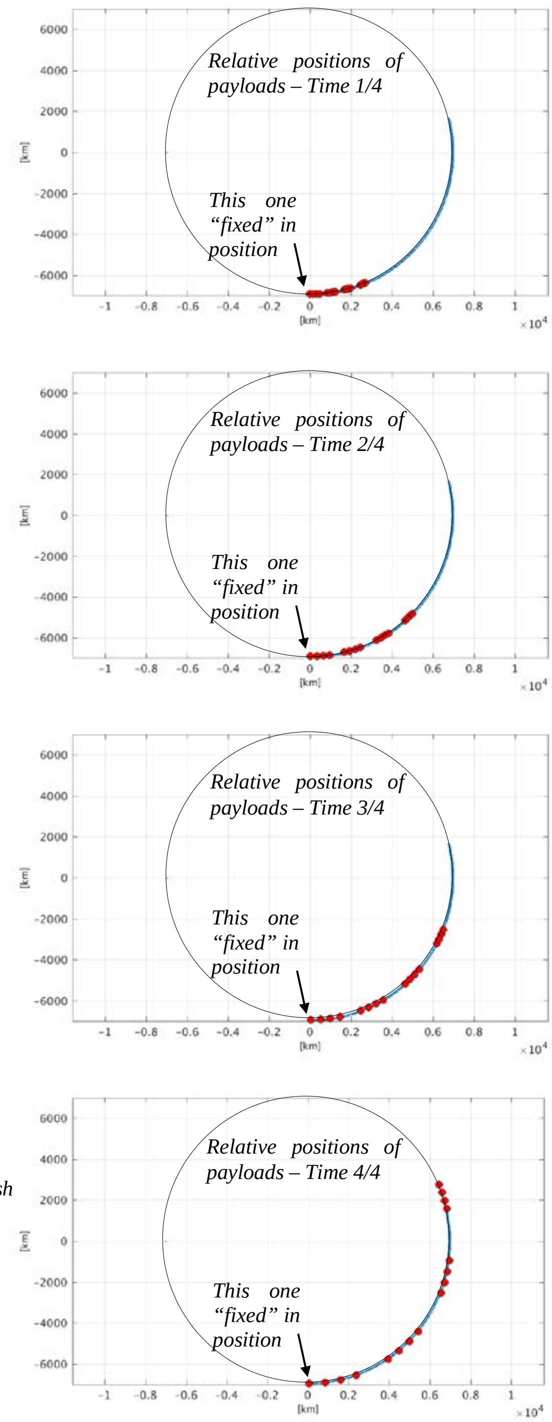
Figure 4: Spacing of Semi-Major axes to organize payloads relative movement

Remark:

It is clear that the relative movement between payloads is slow (depends on the spaced semi-major axes) in comparison to the orbit period of each payload (approx. 1h-1h30 for LEO). The thus-delivered and thus-created "train" of payloads will increase its relative distances through time (through numerous orbit periods) with this train and each of its constituted payload passing-by their anomaly slot every period (ie every 1h-1h30).

This delivery strategy may be useful to facilitate next-coming operations from each payload as they aim to join their final destination/slot.

This may be discussed with clients in order to deliver most suitable payloads organization that would facilitate next-coming operations performed by the satellites.



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4.2. Combined launch solution made of launcher + KickStage {A6+KS}

Introducing ASTRIS KickStage:

ASTRIS is an ESA project of KickStage for Ariane 6 for which ArianeGroup-Germany is the main contractor. More info on this project => refer to ***[3]****.*

Example ASTRIS-Multi-SSO (Serial problem)

One of the ASTRIS mission specified by ESA consists in delivering multiple payloads on multiple orbit planes.

- A6 gets to a first polar orbit 300x300km inclination 90°, and a first set of payloads is delivered at this orbit as well as a KickStage which has 2 sets of payloads.
- The KickStage then takes over the mission from then onwards and performs orbital changes (increasing altitude by 300km each time and inclination by 5°).

The mission consists in 2 branches of the combined {Launcher + KickStage} launch solution with payloads being released sequentially one after the other on the various delivered orbit planes.

This is a “serial” problem with constraints being applied one after the other.

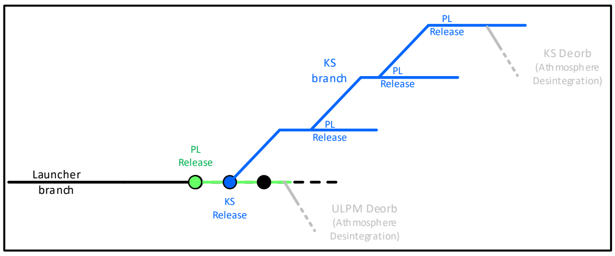


Figure 5: {A6+KS} – Multi SSO – (Metro plan)

Results of simulation are provided below:

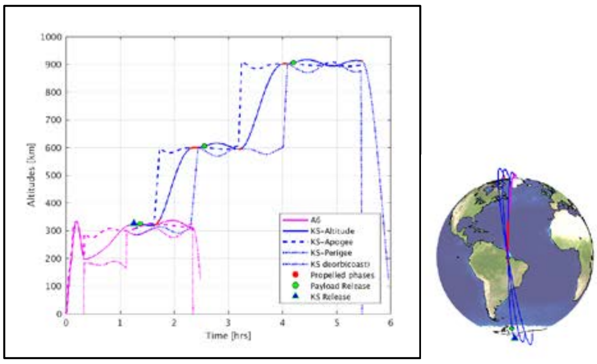
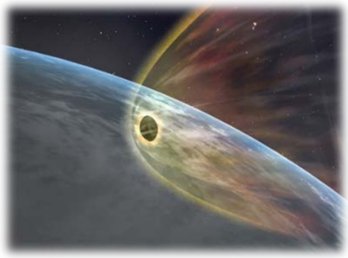


Figure 6: {A6+KS} – Multi SSO

Introducing HEARTED:

HEARTED is re-entry demonstrator led by ESA and aiming at testing critical technologies for high speed reentry (it prepares future sample returns from the Moon or from Mars). More info on this project => refer to ***[4]****.*



Example HEARTED – MEO shared, HEARTED deorbitation WOOMERA (“Y problem”)

For this demonstration exercise, a shared launch may be considered; and the example here illustrates a combined MEO-mission mission with another branch that would perform relevant manoeuvers to perform a high speed re-entry aiming for Woomera-Australia as deorbiting and recovery area of the tested probe.

The here-proposed mission consists in the following:

- At MTO KickStage and ULPM separate from each other.
- ULPM continues on its way to the MEO orbit whereas the KickStage engages a set of 3 maneuvers in order to organize a deorbitation of the HEARTED probe at high velocity over the Woomera region in Australia.

  The KickStage branch is highly constrained, because it is preferable to enter the Woomera region with a certain azimuth of arrival from the NorthWest. Therefore the KickStage branch was constrained by Latitude Longitude, Slope, velocity and azimuth of arrival. In order to organize such transfer for the KickStage branch with such amount of constraints, it is necessary to have the necessary amount of freedom parameters to solve this problem with multiple constraints. To achieve such mission, ARIANEGROUP has considered non-classical way of delivering MEO (with in particular unusual departure: south instead of north) and to consider also unclassical perigee argument of the MTO.

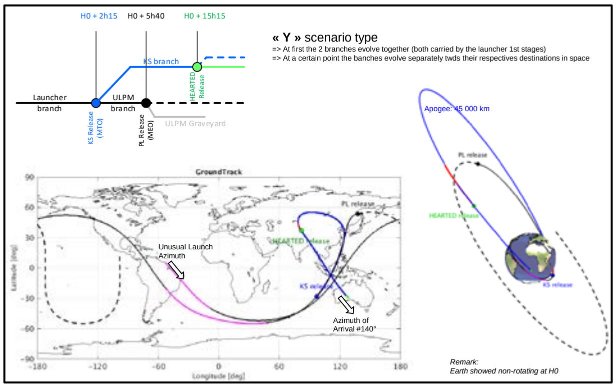


Figure 7: {A6+KS} – MEO GALILEO + HEARTED

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Illustration of perigee argument variation at MTO => see picture below.

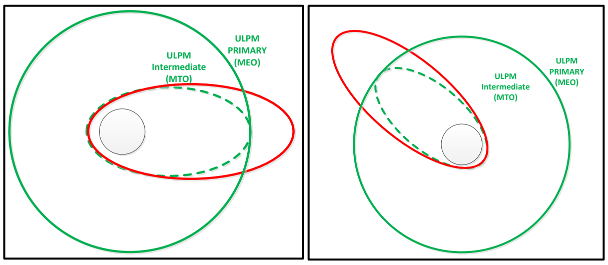

Figure 8: HEARTED MEO shared / Perigee Argument at MTO principles

The perigee argument at MTO (see previously shown MEO-share + HEARTED mission) has no importance for payloads being delivered at MEO, they will still get to their final destination whatever this perigee argument at MTO may be, but it is of importance for the KickStage branch that aims at deorbiting towards Woomera region. Therefore on this "Y" type dual mission, the perigee argument and the unusual hour of launch to meet a certain RAAN at MTO have been "decided" by the KickStage branch because the ULPM branch heading for MEO was indifferent to these choices.

This example provides guidelines and best practices to solve a highly constrained and multi-purposes / multi-branches mission in order to find a solution to it and then optimize the overall mission. The best practise consists in identifying the proper degrees of freedom that each branch has (common branches and derived ones) and to pose the problem adequately in order to:

- Reach a solution that satisfies all constraints of the various branches and make it possible to be solved
- Optimize globally the mission. In particular identification of optimal separation point in space associated with orbital job of each sub-branches as well as their respective loadings lead to advantageous overall performance optimizations of such combined missions.

4.3. Reusable launcher

The reusable launcher is another example of "Y" situation where 2 branches first evolve together before separating from each-other and then heading towards their respective destinations. (Second stage would aim for orbit while stage1 would return to the ground with aimed-null velocity as it lands.

<u>*Introducing THEMIS:*</u>

*THEMIS is a reusable launcher demonstrator and is a consortium of ESA-CNES-Arianegroup through Arianeworks. More info on this project => refer to **[5]**.*

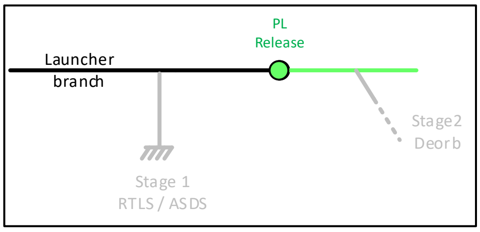

Figure 9: Reusable Launcher – (Metro plan)

Figure below provide simulation results of a double branch consisting of the ascending branch heading for orbit destination and a returning stage 1 branch returning to the ground with aimed-null velocity as it lands.

Cases of Return-To-Launch-Site and Landing on a barge at sea are shown below.

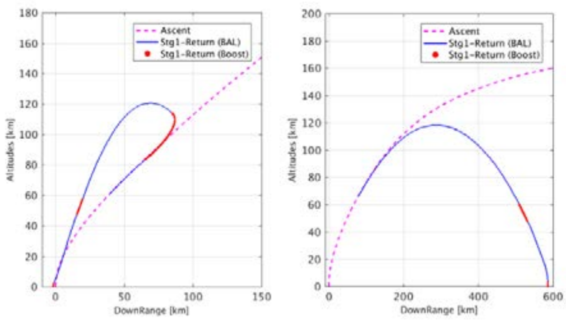

Figure 10: Reusable Launcher – RTLS/ASDS

5. ESTABLISHING PERFORMANCE

When establishing performances of launch solutions that have several branches and may deliver several orbits, the way performance is presented (abacus) changes dimensions:

- If 2 destinations are addressed, then 2D abacus payload mass 2nd region vs payload mass 1st region may be provided. If more than 2 regions are addressed then the visualisation of reachable domain may extend its dimension by as many delivered destinations, or may consist in imbricated domains.
- If a reusable launcher is used, then this may lead to several abacuses being issued considering different cases of usage of the launcher (so-called Expendable, ASDS, RTLS)

Remark:

The combination of the 2 previous points is also possible.

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6. SYNTHESIS AND BEST PRACTISES

Ariane 6 MLS Multi-LaunchServices)

Ariane 6 will have extended capabilities for in-orbit operations with capability to change orbits and capability to release and organise large amount of payloads in space.

ArianeGroup has the relevant tools to produce proper missionisation of the upper stage flight software which will lead the launcher to perform such extended tasks.

This is the result of multi-constrained problem solving and optimization capabilities.

Highly constrained "Y" problem

A best practise for such situation – that may be encountered via combined usage of upper stages and KickStages - consists in identifying the proper degrees of freedom of each branches and to pose the problem appropriately in order to:

- Reach a solution that satisfies all constraints of the various branches and make it possible to be solved.
- Optimize globally the mission. There are indeed important performance stakes in determining the proper separation point in space of two branches as well as in defining the loading of the thus-obtained sub-branches as they head towards their respective destinations from this separation point onwards.

7. CONCLUSION

Having the capability to perform global optimization of a launch solution that is composed of several stages addressing several destinations as they separate from each other is of real benefit for the overall mission definition and overall performance of the mission.

Elementary multi-optimization problems that are generically encountered are:

- Serial problem

  Consists in one "vehicle" addressing several destinations sequentially one after the other. One application of this case is the type of services Ariane 6 will be able to provide when addressing multiple orbits as well as when releasing multiple and potentially large amount of payloads while also organizing these release according to client needs.
- "Y" problem

  Consists in 2 "vehicles"/elements of a launch solution first evolving together before separating from each-other and having part ways towards their respective destinations. When solving this kind of problems, it is important to treat it and pose the problem adequately, having some initial thinking about that in order to provide the relevant degrees of freedom of the flight sequence (in particular that of the common branch, and each of the derived branches after separation) this in order to ensure feasibility of the overall mission and feasibility of an optimizer to find an overall solution that satisfies all the constraints of the various branches (common branches and derived sub-branches).

8. REFERENCES

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[2] **Ariane 6** Users's Manual for **Multi-Launch-Service** – iss0 – rev0 – July 2021.
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Hearted activity is funded by ESA under TDE 4000129154
ESA ESTEC technical officer Luca Ferracina - Luca.Ferracina@esa.int

[5] Reusable Launcher / **THEMIS**
https://www.esa.int/Enabling_Support/Space_Engineering_Technology/ESA_plans_demonstration_of_a_reusable_rocket_stage