DOI: 10.13009/EUCASS2022-9613

JWST LAUNCH ON ARIANE 5
ORBITAL MISSION AND UPPER STAGE END-OF-LIFE-MANOEUVRE

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ABSTRACT

JWST has been successfully launched on an Ariane5 rocket from Kourou (French Guiana Space Centre). This launch marked the debut of JWST journey in Space on its way to its halo orbit around L2.

The success of the Ariane 5 launch as well as that of the deployment of JWST that followed are the results of many and in particular the results of close cooperation and partnerships involving USA (NASA), CANADA (CSA) and EUROPE (ESA).

Europe is a partner of JWST project through ESA participation in this project (ie NIRSpec & MIRI instruments as well as launch responsibility).

This paper presents the Ariane 5 launch and some of the specificities that have been put in place for JWST mission.

Among the specificities for this launch were:

- Specific depressurization under the fairing in order to avoid any shock during opening.
- Specific roll manoeuver during EPC and ESCA propelled phases towards injection point in order to protect JWST from the sun.
- Once JWST has been released, the Upper stage has indeed performed a divert manoeuver (with hydrogen cold gas blow down through the main engine) in order to get out of the way from JWST thus providing a clear path to JWST as it travels towards L2 Lagrange point.

This paper focuses on the 3rd point above-described (ie Upper Stage End-Of-Life-Manoeuvre EOLM)

Figure 1: Ariane5 lift-off (with JWST inside)
Kourou French Guiana Space Centre / Christmas day 2021

1. INTRODUCTION

Stakes are high when interfering with JWST and the highest standards, processes, and precautions needed to be applied for any ground or flight operations.

⇨ On the ground JWST could benefit from the know-how of Europe at its Guiana Space Centre.

⇨ For its mission and launch, JWST could benefit from Ariane 5 reliability. The mission and the flight program have been defined in Les Mureaux (France) with involvements of ESA, ARIANEGROUP, ARIANESPACE and CNES.

Figure 2: JWST in “white” clean room
Kourou French Guiana Space Centre

This paper provides insights of:

- Ariane5 mission to deliver JWST orbit
- Orbital sequence (Releasing JWST and upper stage getting out of JWST way)
- Short term and long term non-collision as well as short term non-pollution justifications as the Upper Stage was manoeuvring to get out of JWST path.

2. ACKNOWLEDGEMENTS

The authors wish to thank and recognize ESA for its leadership towards achieving a successful launch while satisfying all NASA requirements and needs to secure JWST and its next-coming operations/observations. This paper is part of Arianegroup launch activities which have been conducted under ESA contract (refer to [1]).

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3. ACRONYMS

EOLM	End-Of-Life-Manoeuvre (ESCA)
ESCA	A5 Upper stage
HM7B	A5 Upper stage – Main Engine
MCC	Mid-Course-Correction (JWST)
RCS	Reaction Control System
RLP	Rotative Libration Point Frame

4. OVERALL MISSION & LAUNCH

The launch occurred on December 25th 2021 at 9h20 AM (local time i.e. UTC-3).

The injection orbit is an undershoot trajectory (apogee 1.06 Million km), and JWST would then perform a set of three burns in a forward direction (MCC1a, MCC1b, MCC2) to gradually increase its apogee and insert itself on to the L2 Lagrange point (More info on JWST MCC manoeuvers => refer to [5] and figure extract below).

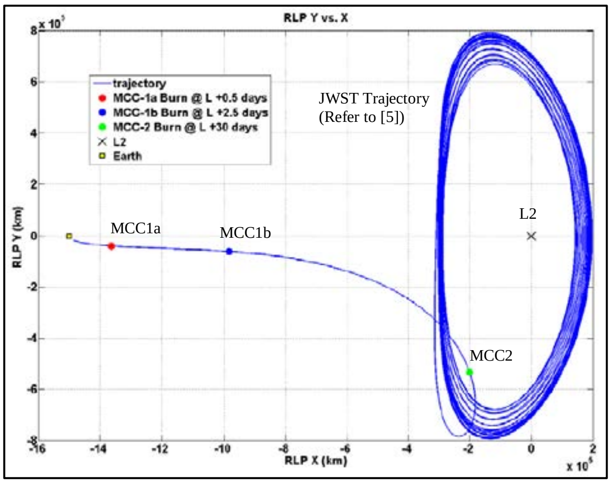

Figure 3: JWST travel towards L2
(with MCC manoeuvres shown) – figure from [5] (NASA Credit)

Ariane5 had already experience in launching towards L2 with Herschel-Planck mission (launch in 2009).

Ariane teams have incorporated some enhancements of the Ariane 5 launcher for the benefit of JWST:

- Roll manoeuvres during ESCA propelled phase to limit effects of the sun on JWST,
- Orbital sequence enhancement with upper stage having extended manoeuvring capabilities after release to get out of the JWST vicinity (End-Of-Life-Manoeuvre using hydrogen blown-down through the main engine)
- Additional depressurization devices have been installed on the fairing to ensure proper depressurization under the fairing in order to avoid any brutal depressurization at fairing separation (which could otherwise have represented a critical risk for the heatshield thin layers of JWST). Damaging the heatshield would have "blinded" JWST and would have jeopardized the whole mission – as it aims for infrared observations which necessitates the heatshield to perform its cooling function properly.

5. ORBITAL SEQUENCE (RELEASE & UPPER-STAGE ESCAPE)

5.1. Releasing JWST

JWST is released with an attitude opposite the sun in the direction of its trajectory path towards L2 Lagrange point. This way JWST is optimally oriented to perform its extra-pushing manoeuvres (MCCs) that will progressively raise its apogee and eventually set JWST on a proper course (proper Lagrange variety) as it heads towards its final destination (halo orbit around L2) – more info on halo orbits and varieties => refer to [4].

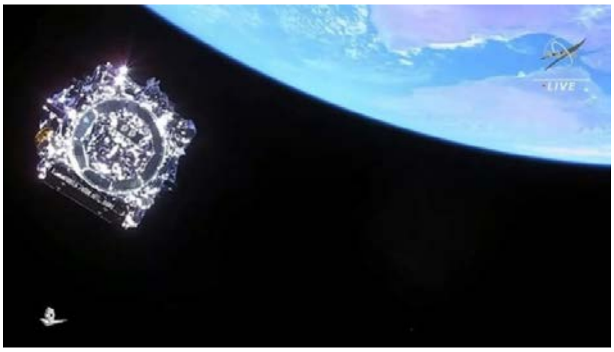

Figure 4: JWST once released
(View from Ariane5 Upper Stage camera)

5.2. A5 Upper Stage Getting out of JWST way

Once JWST has been released, there was two options for Upper stage EOLM (in order to get out of the JWST way):

- Option1: Upper stage could push backwards to stay behind JWST and in order to remain within Earth orbit/gravity below L2.
- Option2: Upper stage could push forward to travel in front of JWST and escape from Earth orbit/gravity as well as from L2 region.

For more info on orbital sequence description, especially when pushing forward then refer to [9].

Option1 - Backward blowdown push

In case Upper stage manoeuvres backward: this provides clear dissociation of paths and clear dissociation of energy between upper stage and JWST on short and long term (because JWST manoeuvres the opposite side ie forward in the direction of L2).

However, this option exposes the Upper Stage to gravitational perturbation and to the risk of an uncontrolled re-entry which limited the allowable launch window. This solution (that consists in pushing backwards opposite L2 direction) has been developed, qualified and implemented into the flight Software as a "safe" back-up plan in case of detected degraded launcher status after JWST release.

Option2 - Forward blowdown push

In case Upper stage manoeuvres forward then the upper stage needs to set itself on an over-energetic path in front of JWST. Meaning that despite of the JWST pushes that come next, the Upper stage would not be caught-up: (the upper stage would keep on increasing its forward distance despite the JWST manoeuvres).

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With an upper stage pushing forward and escaping from Earth orbit, the risk of uncontrolled re-entry disappears and the launch window acceptances increase with it (launch window opens-up). But a non-equivalence of push had to be demonstrated with robustness in order to qualify this manoeuver.

This solution has been developed, qualified and implemented into the flight Software as the nominal scenario if launcher health status was assessed OK.

A rigorous demonstration was conducted of the minimal Upper Stage DeltaV ensuring dissociation of path between Upper stage and JWST on short and long term.

This solution has allowed to open-up the JWST launch window and analyses across a whole year (*) of launch with minimal Launcher penalty.

(*) JWST MCCs as well as attitude to aim-for at JWST release depend on the day of launch (effect of inclination of the Earth wrt ecliptic plane: more info refer to [4] & [9])

GO-NOGO Health Status

The GONOGO is a software gate event occurring during the orbital sequence where the launcher assesses its proper healthiness before allowing to continue the forward push.

At this moment the Upper stage has monitored and assessed its attitude control healthiness as well as its capacity to provide the right amount of DeltaV.

⇨ If a GO status is obtained then the EOLM continues until its end.

⇨ In case of attitude control issue is detected or improper DeltaV is being delivered, then a NOGO status would be triggered leading to abortion of the forward manoeuvre and reversion into a BKUP scenario where the upper stage would have changed directions and would have ended-up pushing backwards to set itself behind JWST according to XRLP "forward" axis which would have set the Upper Stage on an under-energetic trajectory (ie a trajectory that would not have reached JWST halo orbit).

5.3. Ensuring "Short-Term" JWST protection from Upper stage manoeuvres

Once the Upper stage releases JWST, the manoeuvre of the upper stage to get out of JWST way has been defined taking into account highest constraints of non-collision and non-pollution(*) guarantee versus JWST.

(*)
As the Upper stage manoeuvres towards a safe position in space and to dissociates its path from that of JWST it ejects propellant from its main engine and from its RCS thrusters. Pollution risk mitigation consists in ensuring that the ejected propellants from the upper stage are not oriented towards JWST within a close range.

Short Term / Mid-Term non collision

A Criteria / requirement consisting of a growing sphere around JWST (fictive protection sphere) was considered as keep-out zone for short-term / mid-term analysis (up to Payload release + 12h => i.e. up to JWST MCC1a).

In fact the keep-out zone first consist in a growing sphere when considering short term non-collision analysis, but once the upper stage orbital sequence ends, then the keep-out zone becomes a semi-sphere oriented in XRLP direction (e.g. upper stage being in front of JWST is given a more severe requirement than if setting behind JWST because JWST is manoeuvring forward).

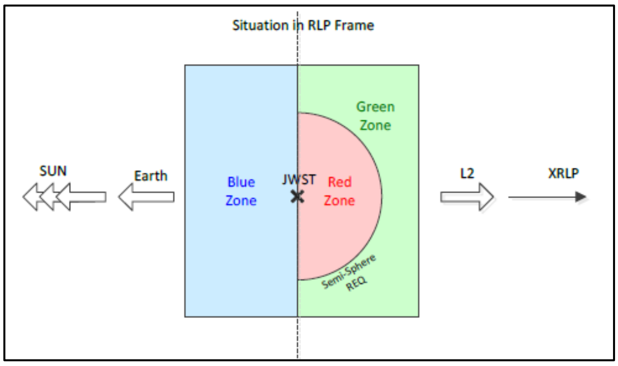

Figure 5: Protective Semi-Sphere Requirement (oriented towards L2)

Figure below provides status of Upper stage position at release +12h versus JWST and its surrounding fictive protective sphere (Requirement).

Result of MonteCarlo with Upper stage having performed its EOLM after JWST release – ie its forward push to escape from Earth gravity.

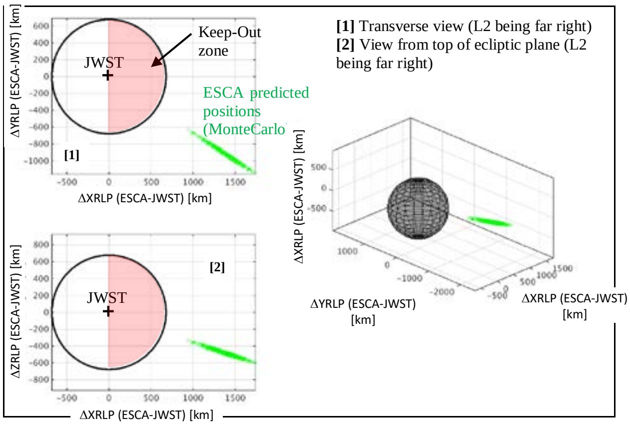

Figure 6: UpperStage situation vs keep-out zone around JWST (situation at release +12h ⇔ at MCC1a)

Non pollution

The orbital sequence also ensured that the ejections of gas coming from the upper stage as it was manoeuvring after release would limit pollution risk on JWST.

- When performing attitude change the upper stage uses lateral RCS thrusters and ejects gaseous hydrogen; a minimum distance 100m was guaranteed with JWST when using these thrusters (for this case the angle between upper stage longitudinal axis and direction of JWST is 90°).
- When performing the EOLM some gas/liquid hydrogen are ejected rearward from the upper stage through its main engine as well as some gaseous oxygen through T35 nozzles. A minimum distance 200m was guaranteed with JWST when using these thrusters (for this case the angle between upper stage longitudinal axis and the direction of JWST is 180°).
- Figure below provides result of MonteCarlo of the flight sequence and shows compliance to the red protected zones to mitigate pollution risks.

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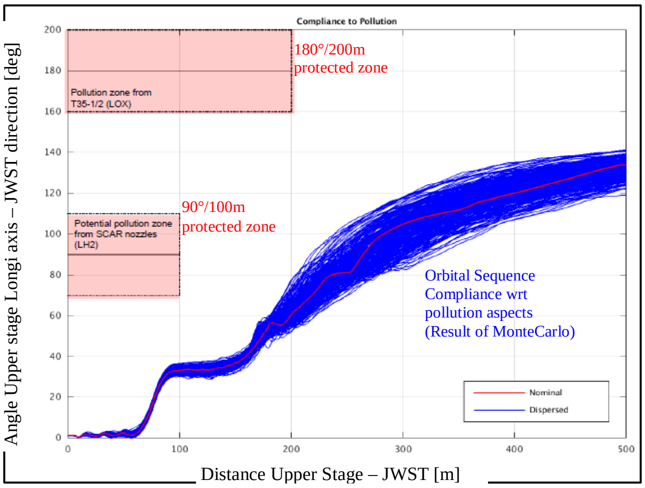

5.4. Ensuring "Long-Term" dissociation of paths between Upper stage and JWST

In order to evaluate the long term relative distances between the upper stage and JWST, models of manoeuvres and propagations while taking into account gravity of Earth + sun + moon have been checked and evaluations performed in Europe have been ensured consistent with the ones established and published by NASA (in particular [5]). This preliminary check of JWST trajectory and MCCs was important before evaluating distances and relative positions between A5 upper stage and JWST on the long term towards L2.

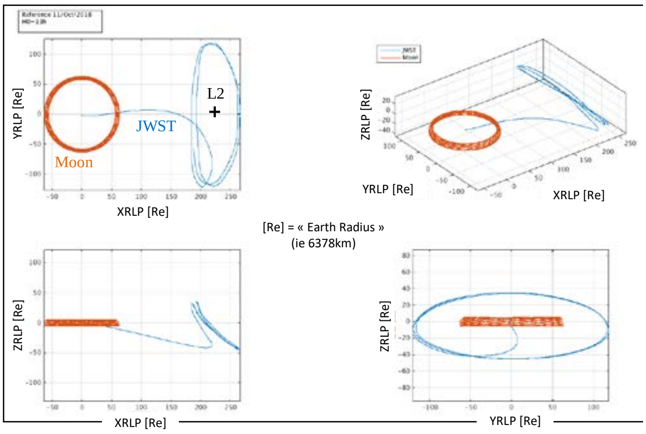

Figure 7: JWST trajectory up to L2
(ArianeGroup evaluation checked with NASA [5])

Non-equivalence of DeltaV & Dissociation of paths between Upper Stage and JWST

Manoeuvres performed by JWST and Upper stage though not occurring at the same time needed to be ensured non-equivalent in order to guarantee proper dissociation of paths.

The upper stage manoeuvre occurs early (after separation) at this moment, a manoeuvre is efficient and leads to efficient increase (resp. decrease) of the apogee depending on if the push is done along orbital speed (resp. opposite).

Next figure provides analysis of relative distances evolution through JWST travel towards L2.

- In case the upper stage is set to and "under-energetic" trajectory, then it remains within Earth orbit and the relative distances between upper stage and JWST keep on increasing
- In case the upper stage is set on an over-energetic trajectory, then the upper stage leaves forward, keeps on increasing its forward distance vs JWST and is not deviated by L2.
- In case of equivalence of pushes, then this would have led the upper stage to evolve along a variety close to that of JWST, with both vehicles ending-up travelling at the same pace up to L2 which potentially leads in such case to dramatic reduction of relative distances between the two vehicles as they would approach from L2 region (cases in green on Figure 8). Such situation of equivalence of pushes needed to be avoided and guaranteed as such.

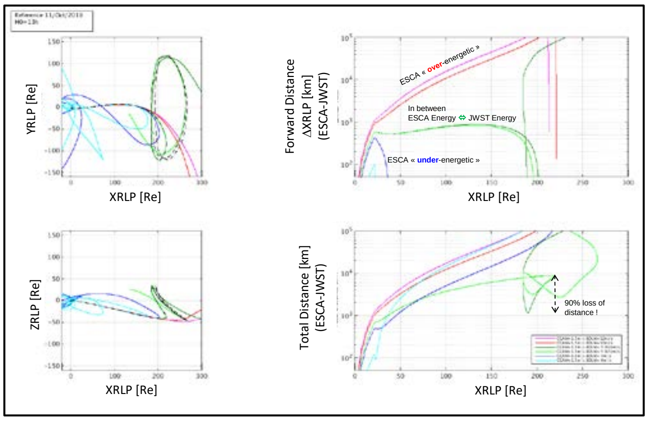

Figure 8: LongTerm Analysis /
JWST vs ESCA relative distances & positions

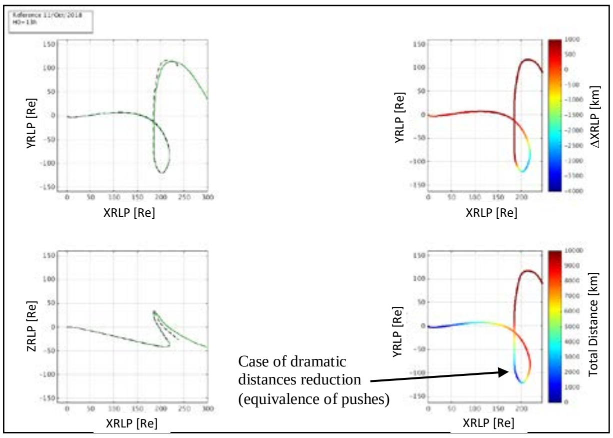

Figure 9: LongTerm Analysis /
Equivalent DeltaV case (Not to be encountered)

6. PROPULSION MODEL & FLIGHT EXPERIENCE

<u>Ariane 5 - Flight proven Experience in performing Upper Stage EOLM</u>

It was clear that for JWST the flight software needed to be flight proven and recurrent. The flight software had been upgraded in this respect since 5101 (Enhanced flight software includes the additional functionalities to perform EOLM).

The ESCA end-of-life manoeuvre (EOLM) is performed without re-ignition of the HM7B, meaning that the engine is used as cold gas thruster, which is outside its nominal application domain.

At first, remaining liquid hydrogen is expected to be pushed out through the main engine (via sole pressure as source of energy), then once liquid propellant becomes

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insufficient gaseous hydrogen is ejected leading to rapid depressurization of the tank and loss of energy for the manoeuvre (manoeuvre nears its end).

In addition to LH2 blow-down through the main engine, gaseous oxygen is evacuated through the oxygen relief valves (T35) to increase the total thrust and to facilitate propellant settling inside the tanks during and before the EOLM. The combined usage of T35 and Main engine to deplete the tanks through this EOLM manoeuvre has been introduced in [8].

To validate this usage of HM7B, which was not tested on ground, a model was developed to predict the thrust and DV quantity we could get form it.

The model of thrust through the main engine consists first in evaluating the pressure inside the LH2 tank (ie the source of energy) and then takes into account an experimental abacus (pressure / thrust) to evaluate thrust. (More details on the methods and the propulsion model description are described in [7]).

The appropriate margin policy of this model has been identified and consolidated via experimental flights and standard flights with the support of diphasic CFD computations.

The prediction model of the manoeuvre and the amount of thrust/deltaV we could get from it has proved its efficiency through numbers of flights that have occurred prior to JWST one and could therefore be used for JWST launch.

Figures below show that the flight data on JWST launch have been near nominal of the previsions.

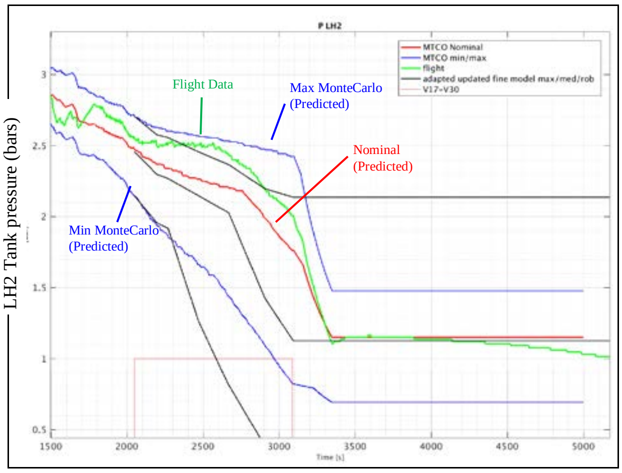

Figure 10. Hydrogen pressure versus previsions

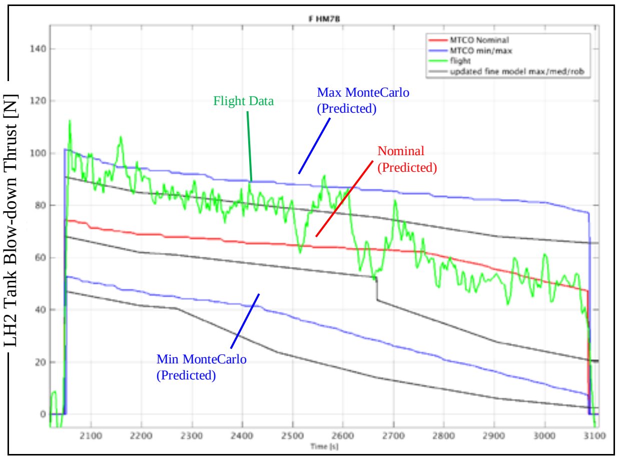

Figure 11. HM7B thrust versus previsions

Minimal DeltaV Determination

The minimal blowdown Delta V has been determined and demonstrated by the application of dual approach:

- An empirical model derived mathematically has been developed based on GNC observations during short manoeuvers.
- A physical model of Hydrogen thermodynamics and diphasic flow in the tank, lines and engine described before and in [7]. This model has been used to justify robustness of minimal push to degraded cases of propellant budget beyond usual flight experience

Prior to JWST launch on L5114, these two models have been successfully confronted to ten orbital EOLM implemented on GTO mission for the purpose of perigee reduction. This return of experience has confirmed the validity of the models and the robustness of the forward push manoeuver.

7. POSTFLIGHT ANALYSIS OF UPPER STAGE MANOEUVRE

DeltaV performed by upper stage has been nominal within Nominal +1sigma and has ensured proper dissociation of paths with JWST.

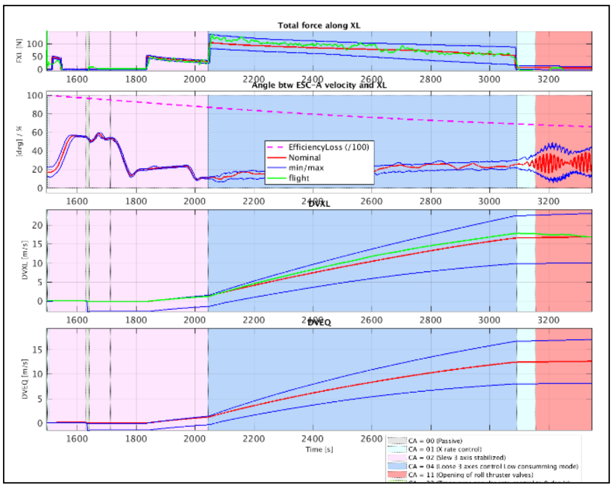

Figure 12: Flight / ESCA DeltaV

Apogee reached by upper stage after its push has been nominal within Nominal +1sigma approx. 1.6 Millions km which ensured Upper stage to be on an Earth-Escape trajectory.

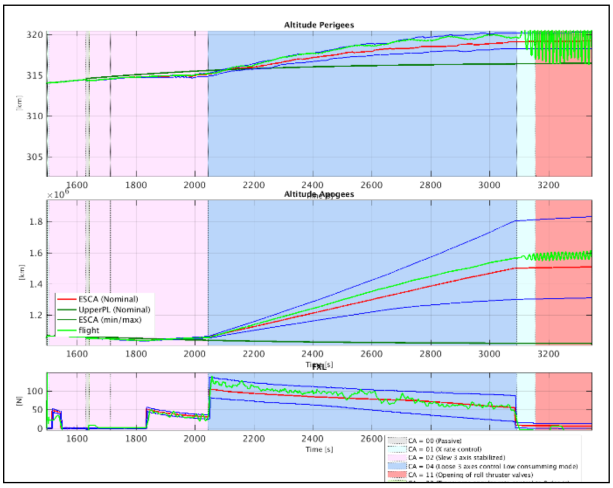

Figure 13: Flight / ESCA Orbital Parameters

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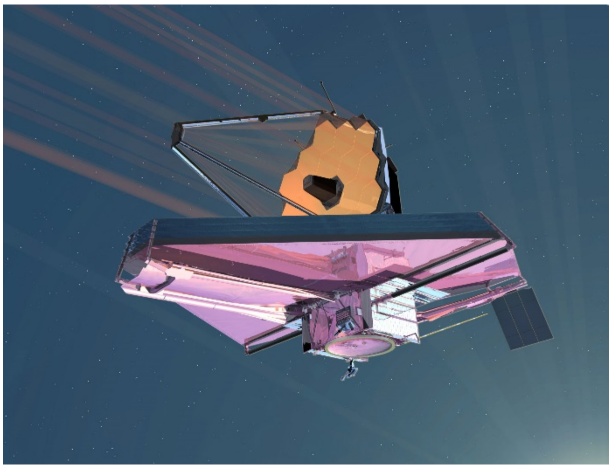
8. CONCLUSION

The successful launch of JWST on an Ariane 5 rocket and the successful deployment of JWST that followed are the result of many across USA, Canada, and Europe.

JWST has benefited from the high standards Ariane can provide in terms of pre-launch operations, launch operations and launcher reliability & accuracy. Ariane has also put in place some specificities for this launch: the mission (as presented in this document), gradual depressurization under the fairing to avoid any shock at separation, extra care for ground operations etc …

At this day, JWST has reached its L2 orbit, and has successfully performed its deployment sequence. Also the ability of the Ariane5 launcher to provide the perfect trajectory at injection has led to minimum extra manoeuvre to be performed by JWST. The saved propellant may then be allocated to station keeping manoeuvres which extends the life duration of JWST on its halo orbit (expected to now be 10-20 years waiting for confirmation).

Ariane engineers wish the very best to JWST with its journey through space, and in its mission to unravel the mysteries of our universe.



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