EXECUTIVE SUMMARY

NRO-GNC

Prepared by:	NRO-GNC team
Approved by:	Thomas Peters
Authorized by:	Pablo Colmenarejo

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1. INTRODUCTION

1.1. PURPOSE

The purpose of this work is to provide a concise summary of the work performed during the NRO-GNC activity.

- Section 1 provides a general introduction to this document.
- Section 2 provides the list of applicable and reference documents to this document.
- Section 3 provides an overview of the HERACLES LAE mission
- Section 4 gives a brief overview of the NRO-GNC project
- Section 5 provides the overall study conclusions and recommendations

1.2. SCOPE

This document covers work performed in the context of WP0100, WP0200, WP0300 and WP0400 of the NRO-GNC activity.

1.3. DEFINITIONS AND ACRONYMS

1.3.1. DEFINITIONS

Table 1-1 lists the concepts and terms used in this document.

Table 1-1 Definitions

Concept / Term	Definition
Chaser	The chaser is the active vehicle during rendezvous, performing all manoeuvres. In the case of the NRO-GNC project, the LAE takes on the role of chaser.
Target	The target is the passive vehicle during rendezvous. In the case of the NRO-GNC project, the LOP-G or DSG takes on the role of target.
LOP-G	He LOP-G or Lunar Orbital Platform-Gateway (also referred to as DSG or Deep Space Gateway) is a space station located in a so-called near-rectilinear halo orbit with a close approach to the Moon.
Docking	During docking the GNC system of the chaser delivers the chaser vehicle to the docking port of the target with non-zero relative velocity, such that the docking mechanism on the target and the chaser are activated and the chaser attaches itself to the docking port on the target. During the process the GNC system of the chaser controls the position, velocity, attitude and attitude rate of the chaser vehicle and the target remains passive.
Berthing	During berthing the GNC system of the chaser delivers the chaser vehicle at a terminal hold point close to the target with nominally zero relative velocities and angular rates. A robotic manipulator located on either the chaser or the target then grapples the other vehicle, transfers it to the final position and attaches it to the relevant berthing port. To be precise, the berthing phase is defined to be the phase that starts at the moment the spacecraft arrives at the terminal hold point inside the berthing box and ends at the final mating of the chaser to the target and release of the robotic arm. The berthing phase includes extension of the arm, grappling and relocation of the chaser.
Grappling	The grappling phase is a sub-phase of berthing. The start of the grappling phase is defined as the moment the control of the LAE is switched off. The end of the grappling phase is defined as the moment of capture of the LAE by means of the robotic arm.
Capture phase	The capture phase is defined to be the phase that starts at the moment the spacecraft arrives at the terminal hold point inside the berthing box and ends at the moment of capture of the LAE by means of the robotic arm.
Rendezvous	Rendezvous is a process of bringing an active vehicle (the chaser) into the vicinity of another passive vehicle or station (the target) by means of a sequence of orbital manoeuvres.
Near-rectilinear halo orbit	Near-rectilinear halo orbits are members of the family of halo orbits that are located close to the nearest primary (Moon for L1 and L2, Earth for L3). The near-rectilinear halo orbits are thin, almost rectilinear orbits that are nearly perpendicular to the synodic plane. The L1 and L2 near-rectilinear halo orbits approach close to the surface of the Moon.
Halo orbit	Halo orbits are special orbits in the three-body problem that orbit one of the Lagrange points in the synodic frame.

1.3.2. ACRONYMS

Table 1-2 lists the acronyms used in this document and in the NRO-GNC project.

Table 1-2 Acronyms

Acronym	Definition
3DOF	Three degrees of freedom
6DOF	Six degrees of freedom
ACS	Attitude Control System
AG	Attitude guidance
AMF	Actuator Management Function
APE	Absolute performance error
BER	Berthing, effectively the terminal conditions of the mission
C	Control
CAM	Collision Avoidance Manoeuver
CBM	Common Berthing Mechanism
CoM	Centre of Mass
CRC	Circularization
CRP	Close range rendezvous phase
DIS	Dispersion analysis
DOF	Degrees of freedom
DP[i]	Drift phase [i], with [i] = 1, 2, 3
DSG	Deep-Space Gateway
ELM	ELMO free drift to aposelene phase
FDIR	Failure Detection, Identification and Recovery
FES	Functional Engineering Simulator
FOV	Field of View
FRA	Fault Robustness Analysis of the GNC
FRP	Far range rendezvous phase
GNC	Guidance, Navigation and Control
GNCDE	GNC Development Environment v3.0, also known as GNCDE3 (GMV/ESA co-funded)
HW	Hardware
HIL	Hardware-in-the-Loop (simulator)
IBDM	International Berthing and Docking Mechanism
ICRF	International celestial reference frame
IDSS	International Docking System Standard
IMU	Inertial Measurement Unit
IP	Image Processing
LAE	Lunar Ascent Element
LAU	Launch phase
LDE	Lunar Descent Element
LIDAR	Light Detection And Ranging
LLO	Low Lunar Orbit
LOI	Loitering
LOP-G	Lunar Orbital Platform-Gateway
LoS	Line of Sight
LTO	Lunar Transfer Orbit
MC	Monte Carlo
MIB	Minimum impulse bit
MIL	Model-In-the-Loop (simulator)
MRP	Mid range rendezvous phase
MVM	Mission Vehicle Management
N	Navigation

Acronym	Definition
NAC	Narrow-angle camera
NIM	NRO insertion manoeuvre
NRHO	Near-rectilinear halo orbit
NRO	Near-rectilinear halo orbit
OBSW	On-Board Software
OOC	On-orbit checkout
PIL	Processor-In-the-Loop (simulator)
PRE	Pre-launch phase
REF	Reference case test
RPE	Relative performance error
RV	Rendezvous
RV	Rendezvous
RvD	Rendezvous and Docking
SEN	Sensitivity analysis
SIL	Simulator-In-the-Loop (simulator)
SoW	Statement of Work
SW	Software
TAS	Thales Alenia Space
TAS-F	Thales Alenia Space – France
TAS-I	Thales Alenia Space – Italy
TBC	To be confirmed
TBD	To be defined
TBW	To be written
TC[i]	Trajectory correction manoeuvre [i], with [i] = 1, 2, 3
TG	Translation guidance
TIM	Transfer injection manoeuvre
TMF	Thruster Management Function
TRP	Terminal range rendezvous phase
WAC	Wide-angle camera

2. REFERENCES

2.1. APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form part of this document to the extent specified herein. Applicable documents are those referenced in the Contract or approved by the Approval Authority. They are referenced in this document in the form [AD.x]:

Table 2-1 Applicable Documents

Ref.	Title	Code	Version	Date
[AD. 1]	Statement of Work – GNC preliminary design for rendezvous and docking in NRO orbits around the Moon	AO/1-9296/18/NL/CRS	3.0	22/11/2017
[AD. 2]	ESA, "HERACLES Lunar Ascent Element", Human Enabled Robotic Architecture and Capabilities for Lunar Exploration and Science, HERACLES	ESA-HSO-K-TN-0013	2.0	10/11/2017
[AD. 3]	Human-Enhanced Robotic Architecture and Capability for Lunar Exploration and Science (HERACLES) Objectives and Requirements Document (ORD)	ESA-E3P-HERA-RS-004	4.0	21/08/2018
[AD. 4]	ESA, "HERACLES Consolidated Report on Mission Analysis," MAS Working Paper No. 619,	ESA-E3P-HERA-TN-005	1.1	01/04/2019

2.2. REFERENCE DOCUMENTS

The following documents, although not part of this document, amplify or clarify its contents. Reference documents are those not applicable and referenced within this document. They are referenced in this document in the form [RD.x]:

Table 2-2 Reference Documents

Ref.	Title	Code	Version	Date
[RD. 1]	LAE GNC Requirements	NRO-GNC-D1	1.5	15/04/2020
[RD. 2]	SIL and PIL Requirements Specification	NRO-GNC-D2	1.1	18/12/2018
[RD. 3]	Trajectory Analysis Justification File	NRO-GNC-D3	1.5	01/10/2019
[RD. 4]	LAE GNC design technical note	NRO-GNC-D4	1.5	20/11/2019
[RD. 5]	SIL Design Technical Note	NRO-GNC-D5	1.3	30/09/2019
[RD. 6]	Test plans and procedures for the SIL test campaign	NRO-GNC-D6	1.2	05/06/2020
[RD. 7]	MIL Simulation Test Campaign Report	NRO-GNC-D7	1.1	05/06/2020
[RD. 8]	Evaluation and Technology Roadmaps	NRO-GNC-D8	1.0	05/06/2020
[RD. 9]	HIL Simulation Campaigns Test Report	NRO-GNC-D9	1.0	
[RD. 10]	Final Report	NRO-GNC-FR	1.0	
[RD. 11]	Heracles Phase A Mid Term Report	TASI-SD-HCL-TNO-0296	2	8/10/2018
[RD. 12]	Space Engineering: Technology readiness level (TRL) guidelines	ECSS-E-HB-11A	1.0	11/03/2017
[RD. 13]	Prototyping of Bearings-Only Guidance for Rendezvous in NRO Orbits	ESA Contract No. 4000129012/19/NL/CRS		
[RD. 14]	Breadboard of a multi-spectral camera for rendezvous in Lagrangian orbits of the Earth-Moon system	ESA/Contract No. 4000125880/18/NL/CRS		

3. MISSION OVERVIEW

3.1. LUNAR ASCENT ELEMENT

The Lunar Ascent Element (LAE) is the mission element that ascends from the Moon surface, rendezvous with the LOP-G and delivers samples to it. The reference LAE configuration used for this study is presented in the HERACLES Lunar Ascent Element ESA study (RD. 1) and is shown in Figure 3-1. The concept proposed by the ESA CDF team is a structure enclosed by panels that reduce as much as possible thermal dissipation toward the external to keep the propellant and batteries (the most sensitive elements) above 0°C. The panelled structure also helps to protect the internal equipment from dust and radiation. The symmetry and balancing of the system reduces the burden on the AOCS/GNC subsystem to counteract asymmetrical forces. The dry mass of the LAE in ESA CDF configuration ranges from 487 kg to 496 kg depending on the margin policy applied (ECSS or Exploration Studies Margin Management Plan, respectively). It includes 30 kg of GNC equipment and 210 (or 217) kg for the propulsion. The propellant mass is 843 kg for a total wet mass of 1330 kg or 1339 kg respectively.

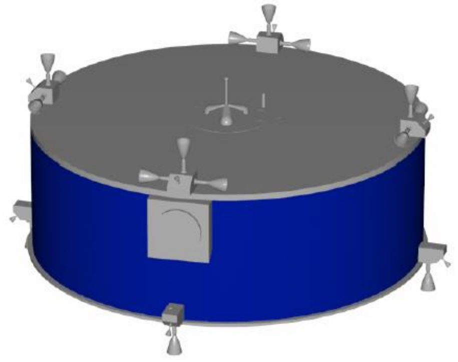

Figure 3-1: LAE configuration proposed by ESA CDF team [AD. 2]

In the frame of the Heracles study ([AD. 2]), the CDF configuration was reviewed, using updated size of avionic equipment, batteries and propulsion tanks. In order to increase the area where the equipment can be installed, an octagonal based box with shear panels was proposed, leading to the configuration shown in Figure 3-2. This configuration will be used as baseline, in order to maximize the commonalities with the Heracles study. The result of the first design loop leads to a LAE dry mass of 547 kg, including 20% system margin. Adding the 22 kg of the Sample Container, the required propellant to perform ascent, attitude control, transfer to NRHO and RDV with LOP-G is 888 kg, including pressurant (4 kg) and 2% margin. The overall wet mass (Sample Container excluded) is 1435 kg.

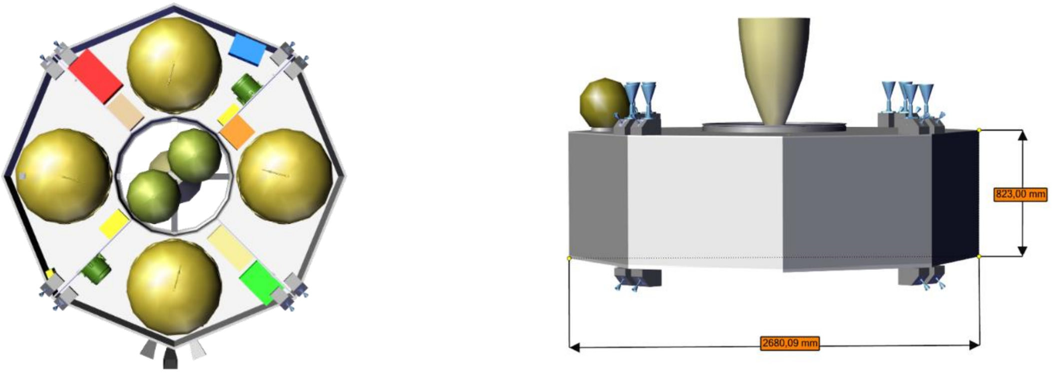

Figure 3-2: Baseline LAE configuration [RD. 11]

Form a physical interfaces perspective, the LAE shall provide an accessible interface where to locate the sample container that needs to have also data and power interface. Same kinds of interfaces are required toward the LDE which is relaying on the LAE for power, communication and data handling.

The major drivers for LAE design are:

- Capability of lift-off and thrust from the Moon surface up to the Cis-lunar orbit until the starting of the rendezvous and berthing phase. This means to enable the ascent element with a Propulsion Subsystem delivering high thrust and Isp while limiting the mass.
- Human rating: it has to do with reliability, risk, failure management (other than sizing). The LAE has to be designed with a human-rating perspective, as the future envisaged missions after the first robotic one will be manned.

The configuration of the actuators is the following:

- The main engine is derived from Aestus and Aestus II RS 72 engines. It is a bipropellant engine providing 6 kN. It is a pump-fed model, in order to maximize the specific impulse (Isp = 340 s). It can be noted that the main engine will be a key element of the design, since an engine with the required performances does not exist and a dedicated development will have to be proposed.
- 4+4 220 N bipropellant thrusters mounted on the lower part of the structure are used for main control manoeuvres and main engine compensation.
- 8+8 10 N bipropellant thusters are used for fine control & RDV.

The sensor trade-off led to the following sensor suite:

- Sun Sensor. Sun sensor is used for sun acquisition following launcher separation or for failure in orbit. Not applicable for the Ascent phase.
- Star Tracker. Star tracker and Inertial Measurement Unit can provide high accuracy attitude measurement and estimation during all phases. During Lunar Ascent, if the duration of the phase is sufficiently short, the IMU could be sufficient, but the use of a Star Tracker could be considered if this brings benefits for LAV attitude initialization before lift-off or for reduction of attitude measurement accuracy requested to the IMU. The baselined model is the DTU µ-ASC Star Tracker (3 Optical Head, 1 Electronic Unit), which operates up to 10 deg/s providing measurements with accuracy of 30 arcsec.
- Inertial Measurement Unit (2 units). IMU can be used for attitude rate measurement and for acceleration measurement (and therefore to reconstruct attitude, velocity and position). The baselined model is the LN200S, characterized by a gyrometer drift of 0.1 deg/h and an accelerometer bias of 0.3 mg.
- Altimeter. An altimeter is also included in the sensor suite of the LAE. It is used only for the descent phase. Not applicable for this study.
- Wide Angle Camera (1+1). WAC is used for the close range phase of the RDV. The baselined model is the VisNAV Airbus Camera. It has a 1024x1024 APS detector, with a field of view of 70 deg.
- Narrow Angle Camera (1+1). NAC is used for the far range phase of the RDV. The baselined model is similar to the WAC, but with a smaller field of view of (2.5 deg).
- LIDAR. The LIDAR can be foreseen for backup of the cameras in case of bad illumination conditions. The baselined model is the MDA/Optec LIDAR: it has a high power consumption (25 W) and high mass (5 kg), therefore its usage can possibly be reconsidered in favour of a less heavy an consuming sensor, e.g. a Multi Spectral Camera. However, trade-off performed in Heracles, led to discarding the LIDAR from the baseline sensor suite, due to cost, mass and TRL considerations. Furthermore, ESA confirmed that RdV will be done on Sun side (outside of eclipse), therefore the presence of the LIDAR does not increase the robustness of the design.

3.2. MISSION SCENARIO

For this study the Lunar Ascent Element (or Heracles Ascender) mission scenario definition is considered. The overall graphical synthesis of the mission scenario is reported in Figure 3-3.

The LAE is assumed landed close to the South Pole, in the Schrödinger region #1 (141.33º E 75.47º S), with the Schrödinger region #2 (141.89º E 75.30º S) as back-up.

The rover will be deployed and it will start its exploration and sampling mission with ground support and then supported by the crew in the meantime arrived to the LOP-G. Once the sample container is handed over to the LAE, the ascent operation can start. In this study the best strategy will be studied allowing the LAE to reach the LOP-G in the NRHO and perform the rendezvous and berthing.

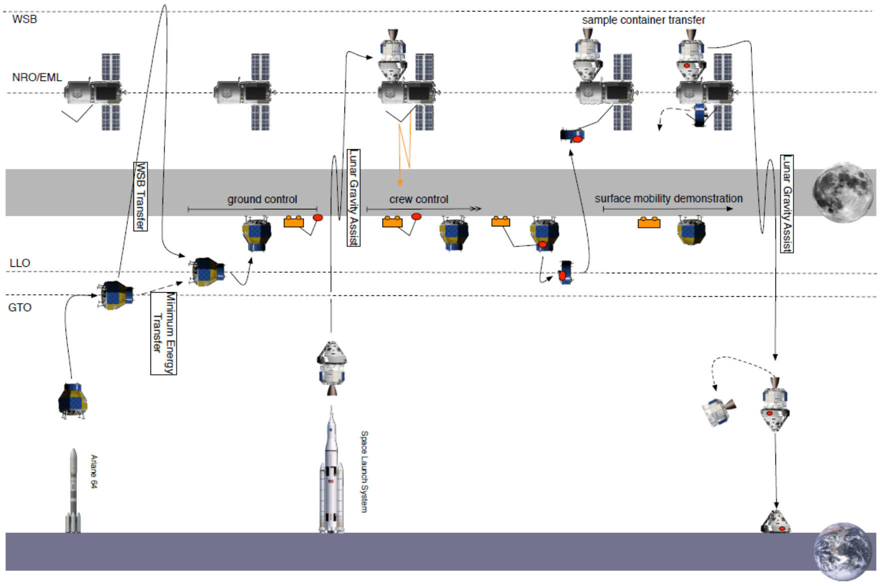

Figure 3-3: LAE Mission scenario

Then the lunar samples will have to be transferred to the Orion S/C for the return to Earth; this means that in some way the container will have to be brought inside the outpost. While berthed to the robotic arm the LAE shall be capable to support the Lunar Sample transfer. Particular attention will have to be made to the dust management, to minimize/avoid contamination of the LOP-G when the Sample container is transferred.

The baseline LAE mission can be summarized in the following phases:

- Pre-Launch. The LAE is prepared for flight on the launch site, checking the correct functioning of the whole system before lift-off
- Launch and Ascent. Starts with launcher lift-off and finishes when the LAE reaches the transfer orbit. The ascent is performed indirectly in 3 consecutive steps or mission arcs:
- Ascent from the Moon landing site into an Elliptical Low Moon Orbit (ELMO)
- Circularisation into a Circular Low Moon Orbit (CLMO)
- Ascent from the Circular Low Moon Orbit into the NRO orbit
- Orbit Transfer and Phasing. The LAE performs the transfer from the launch orbit to the orbit of the LOP-G, carrying out a phasing with the target spacecraft.
- Rendezvous and Forced Translation. The LAE performs a rendezvous with the LOP-G, evaluates its relative attitude dynamics state and performs a forced translation in order to reduce the relative motion to levels adequate to initiate the berthing
- Berthing. The LAE performs a final approach to the target to the distance required to initiate operation of the berthing robotic arm mounted at the LOP-G. This phase is complete when the LAE has been transferred to its final mating location and the robotic arm has been uncoupled from the LAE.

The above baseline assumes that the LAE mission implements Strategy 2 of User Requirement U5. Strategy 1 has been discarded based on insertion accuracy considerations and the small amount of time available for orbit determination from ground.

Furthermore, it is assumed that the berthing scenario has been selected. Main considerations in favour of the berthing technique can be summarized as follows:

- Berthing system requires lower mass (lower shock & vibration at capture)
- Berthing system (grapple fixture) is existing design, to be tailored for lower mass; docking mechanism would be IBDM or custom design
- Berthing is more flexible for capture and attachment location

4. STUDY OVERVIEW

4.1. MISSION ANALYSIS

The principal mission objective of the LAE is to transfer samples obtained from the lunar surface to the LOP-G station. The LOP-G station is located in an NRO orbit, a special orbit in the three-body problem that is influenced by both the Earth and the Moon. Figure 4-1 shows special orbits in the three-body problem in a reference frame that rotates as the Moon rotates around the Earth, and an example of an NRO orbit around L2. Unlike ordinary, Keplerian orbits, the NRO is approximately fixed with respect to the Earth-Moon line, such that the LOP-G is never behind the Moon as seen from the Earth.

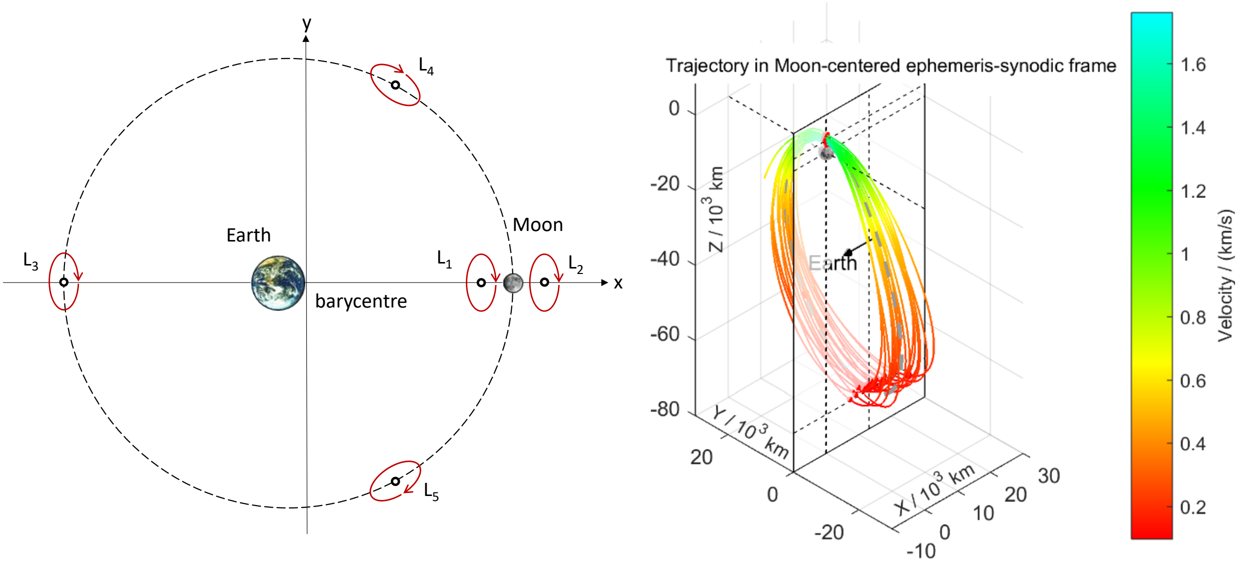

Figure 4-1: Three-body problem (left); uncontrolled, ballistic NRO orbit (right)

Figure 4-2 shows the different manoeuvres indicated on a projection of the LAE trajectories on the yz-plane of the synodic frame. The synodic frame is centred in the Earth-Moon system barycentre with the x-axis pointing in the direction of the position vector of the Moon with respect to the Earth, the z-axis pointing in the direction of the Earth-Moon angular momentum and the y-axis completing the right-handed frame. The basic mission profile of the LAE is as follows:

- Launch (1)
- Orbit circularization (2)
- Loitering in LLO
- Transfer Injection Manoeuvre (3)
- Trajectory Correction Manoeuvre(s) (4,5)
- NRO Insertion Manoeuvre (6)
- Rendezvous (7)

The full mission from launch to berthing lasts approximately one week. Only one Trajectory Correction Manoeuvre has been considered in this activity. Figure 4-2 also shows more detail of the loitering in low-lunar orbit. Loitering in the LLO is required to ensure that the LLO aligns with the NRO. A keplerian orbit maintains a fixed orientation in inertial space. This means that, in the rotating frame of the three-body problem, the orbital plane of a keplerian orbit is rotating with the same angular velocity as the Earth-Moon system. During the loitering phase, the LAE waits until the orbital frame of the LLO aligns with the NRO.

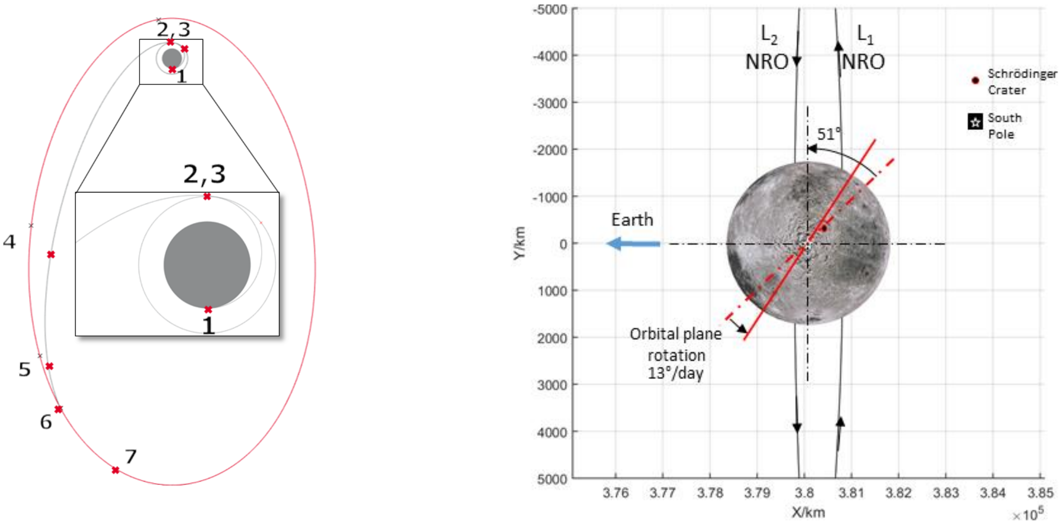

Figure 4-2: NRO mission phases (left); loitering in LLO (right)

Table 4-1 shows the overall ΔV budget, including the margins on each of the principal manoeuvres. The margins on the rendezvous are set higher than the impulsive manoeuvres, and higher for the forced motion rendezvous than for the impulsive rendezvous. For the large impulsive manoeuvres, either the main thruster or the auxiliary thrusters are used, which are oriented in the negative z-direction, optimised to provide ΔV in the positive z-direction. The GNC margins are necessary to compensate for uncertainties in the mass parameters (mass, inertia matrix, location of the centre of mass) and thruster orientations. For the impulsive rendezvous and the forced motion rendezvous the GNC margins are higher because the fine RCS thrusters are used, which suffer from geometric losses (multiple thrusters need to fire to generate force in a specific direction, and some of the force provided by the thrusters that fire cancels out). The margin is higher for the forced motion rendezvous because the trajectory is continuously controlled. Finally, the rendezvous trajectory that is included in this design features a fly-around and a phase in which the chaser follows the attitude of the target. The ΔV for this phase could be reduced by removing the fly-around and by reducing or removing the attitude motion of the target by switching off the attitude control during the final approach.

Table 4-1: ΔV budget

Phase	Thruster	Ideal ΔV / (m/s)	Margin	ΔV plus margin / (m/s)	Comment
Ascent	main	1841	5%	1933.1	
Circularization	aux THR	15.9	5%	16.7	
Transfer Injection Manoeuvre	aux THR	660.9	5%	687.3	
Trajectory Correction Manoeuvre	aux THR	57.0	5%	77.4	Stochastic manoeuvre with (μ = 23.3 σ = 16.8), depending on accuracy of TIM
NRO Insertion Manoeuvre	aux THR	36.1	5%	59.5	Manoeuvre with large stochastic component, dependent with (μ = 35.1 σ = 7.2), depending on accuracy of TIM
Impulsive Rendezvous	fine RCS	25.2	150%	63.0	Value + margin includes geometric losses due to thruster orientation and actuation for attitude control
Forced Motion Rendezvous	fine RCS	7.6	500%	45.6	Value + margin includes geometric losses due to thruster orientation and actuation for attitude control. A larger margin is taken into account because of continuous translation control during forced motion

4.2. GNC DESIGN

Figure 4-3 shows the GNC design and the mode diagram. The GNC consists of guidance, navigation, and control functions. A mode manager MVM is in charge of switching the GNC modes and maintaining the mission plan. An FDIR function checks for equipment failure and performs threshold checks on the GNC (convergence of the navigation, controller errors, state vector bounds etc.).

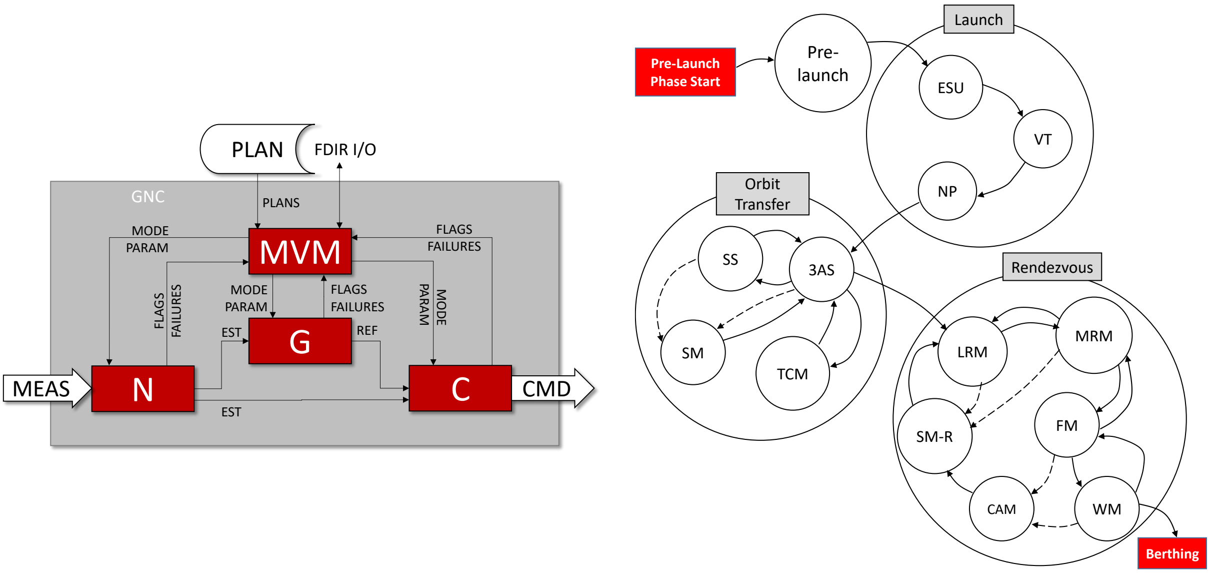

Figure 4-3: GNC design and mode diagram

For the launch phase the following modes are defined:

- ESU: Engine Start-Up: the main engine is ignited and control valves starts opening in the predefined sequence
- VT: Vertical Trajectory: the vehicle perform vertical rising in order to clear the Launchpad and acquire safe altitude
- NP: Nominal Profile: the vehicle is commanded with a Nominal trajectory in order to perform the Ascent phase and reach the determined orbital conditions

The orbit transfer phase makes use of the following modes:

- 3AS: 3-Axis Stabilized Cruise Phase: in this mode the vehicle maintains a predefined attitude. It may be used before Trajectory Correction Manoeuvres, during Nominal Operation of Cruise or During Target searching
- SS: Spin Stabilized Cruise Phase: the vehicle is maintained in spin during cruise phase
- TCM: Trajectory Correction Manoeuvres: the vehicle uses the propulsion system to change orbital parameters or correct accumulated dispersion
- SM: Safe Mode: the vehicle performs minimal operation in order to be maintained alive until a problem has been solved

The rendezvous phase consists of the following modes:

- LRM: Long-range rendezvous mode: the vehicle performs target detection and begins approaching the target once detected. Relative navigation is based on camera measurements and uses line-of-sight measurements. Impulsive guidance is used to compute approach manoeuvres.
- MRM: Mid-range rendezvous mode: the vehicle continues the impulsive approach to the target. Relative navigation is based on camera measurements and uses model-based tracking. Impulsive guidance is used to compute approach manoeuvres.
- FM: Forced motion rendezvous mode: the vehicle performs forced motion in order to reach the berthing box. Relative navigation is based on camera measurements and uses fiducial marker tracking. Forced motion guidance is used to compute approach trajectories and feed-forward forces required to follow the trajectory.
- WM: Waiting Mode: the vehicle waits for berthing or docking in the berthing box or in the docking corridor
- SM-R: Safe Mode: the vehicle performs minimal operation in order to be maintained alive until a problem has been solved
- CAM: Collision Avoidance Manoeuvres: the vehicle commands CAM in order to avoid foreseen collision

4.3. TEST CAMPAIGN

During the NRO-GNC activity the GNC was tested in model-in-the-loop (MIL) tests, processor-in-the-loop (PIL) tests and hardware-in-the-loop (HIL) tests. The objective of the MIL tests is to perform verification and validation and to demonstrate performance of the GNC. The objective of the PIL tests is to verify that the GNC can run on a space-qualified processor. The objective of the HIL tests is to demonstrate that the close-range rendezvous GNC performs well with actual camera hardware in the loop.

4.3.1. MIL TESTS

Model-in-the-loop simulation campaigns are fundamentally targeted to confirm stability and performance analyses already carried out with linear models during the design phase, and to detect potential problems due to non-linear effects not present in the linear synthesis/analysis environment.

In the simulation campaign a large selection of parameters of the real world are randomly varied in a Monte Carlo analysis in order to investigate the performances and robustness of the algorithms. The parameters to be varied include:

- Random number initial seeds
- Implemented bias and noises
- Sensor and actuator errors
- Spacecraft Mass Centring Inertia (MCI)
- Propellant sloshing parameters
- Initial conditions on real states and errors of estimated states

Figure 4-4 show typical MIL test results for the launch, orbit transfer and rendezvous phases of the mission.

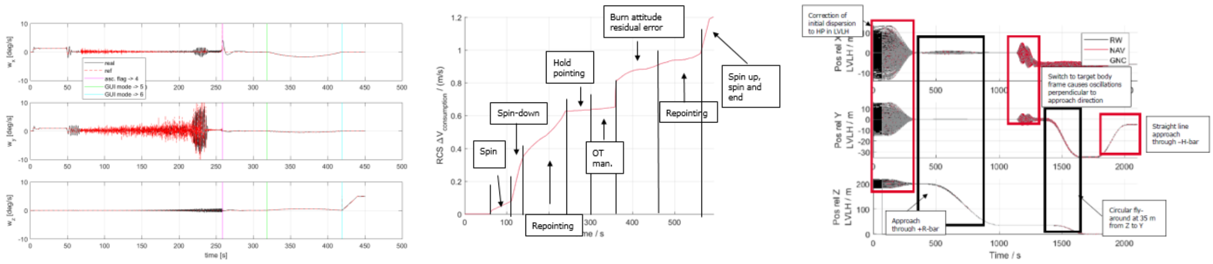

Figure 4-4: Typical MIL test results for launch (l), orbit tranfser (m) and rendezvous (r)

The test results indicate that the HERACLES LAE mission can successfully be performed from the GNC perspective. The current GNC design provides sufficient performance to complete the mission from launch and ascent, orbit transfer and rendezvous.

In particular:

- The launch can be performed with sufficient orbit insertion accuracy using an IMU with performance specifications similar to the LN200S. The dispersions after main engine cut-off are compatible with the overall mission scenario.
- The accuracy with which the transfer injection manoeuvre and the trajectory correction manoeuvre can be performed is well below the 1°, 1% (3σ) performance requirement that is needed for a successful transfer
- The GNC performance at berthing is met apart from the angular velocity accuracy requirement. The angular velocity performance is about 6 times worse than required (0.25 °/s versus a required 0.04 °/s)

4.3.2. PIL TESTS

The main objective of the PIL campaign is to verify the flight software implementations of the GNC running on a space representative processor in closed-loop tests. The PIL test bed allows testing the GNC OBSW in realistic conditions regarding the avionics (using space representative on-board processor) in combination with simulated environmental conditions provided by the real world simulator. The SIL software is generated based on autocoding. The auto coding development strategy consists in generating the GNC SW C-code in a straightforward way, directly from the Simulink model of the GNC algorithms. In order to execute the auto-coded GNC C-code inside the space representative LEON on-board computer, this code shall be coupled with hand-made code in charge of performing operating system tasks and managing the communication links. The process is summarized in figure 4-5.

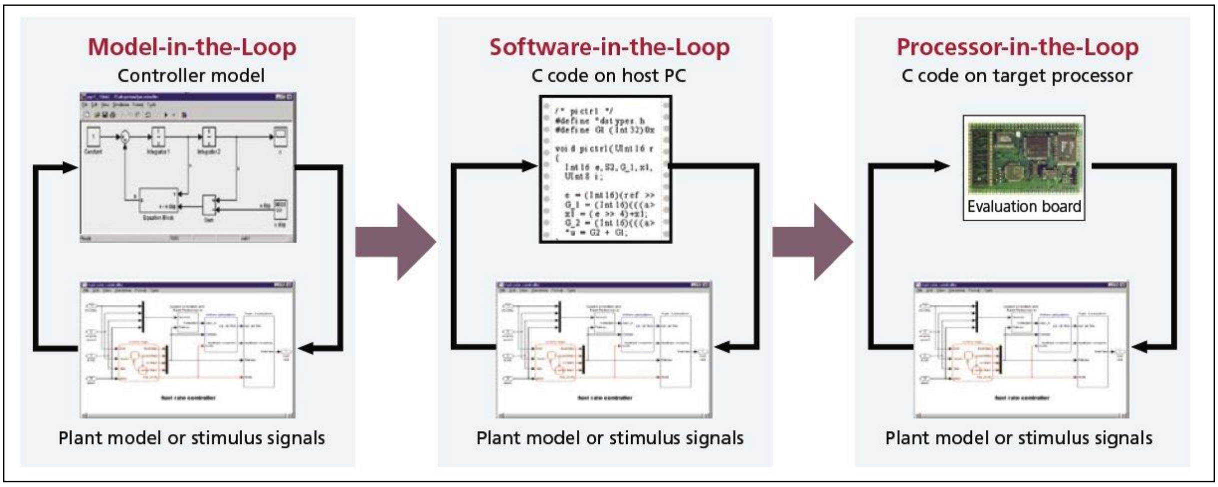

Figure 4-5: Development and validation chain: MIL -> SIL -> PIL

Figure 4-6 shows key results from the PIL test campaign for the launch, orbit transfer and rendezvous phases of the mission.

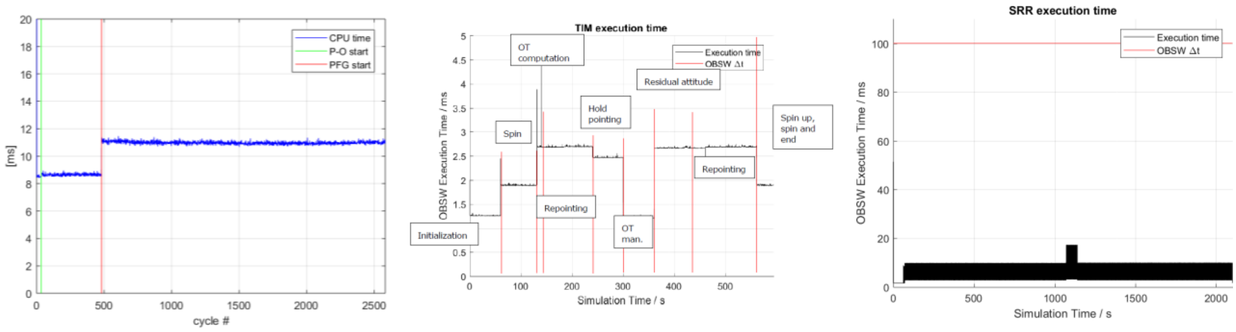

Figure 4-6: Typical PIL test results for launch (l), orbit transfer (m) and rendezvous (r)

The PIL tests have shown that all software can be run on a space-qualified LEON processor board. In some instances, the PIL tests revealed a high processor load, but this high processor load occurs at specific instants (guidance initialization and manoeuvre computation) and for functions that do not require timely output, so it is expected that there will not be any problem to split the computation over multiple cycles.

4.3.3. HIL TESTS

The objective of the HIL tests is to assess the short-range navigation performance with inputs from an image processing function processing real camera images in a low-accuracy set-up. The short-range navigation is based on fiducial marker tracking. The HIL tests are performed in the ***platform-art*** facility. Figure 4-7 shows the marker attachment to the mock-up, and the full test set-up. The chaser (only camera) is mounted on one of the robotic arms and the target (mock-up) on the second robotic arm that can move backwards and forwards on a set of rails. The trajectory of the arms is commanded based on simulator outputs.

Figure 4-7: Marker attachment, and *platform-art* test set-up

Figure 4-8 shows the short-range navigation performance results of the final and most challenging set of tests, namely, the closed loop tests with target attitude motion. The position errors represent the estimation errors of the relative position with respect to the chaser, and the target attitude errors represent the estimation errors of the target attitude with respect to the inertial frame.

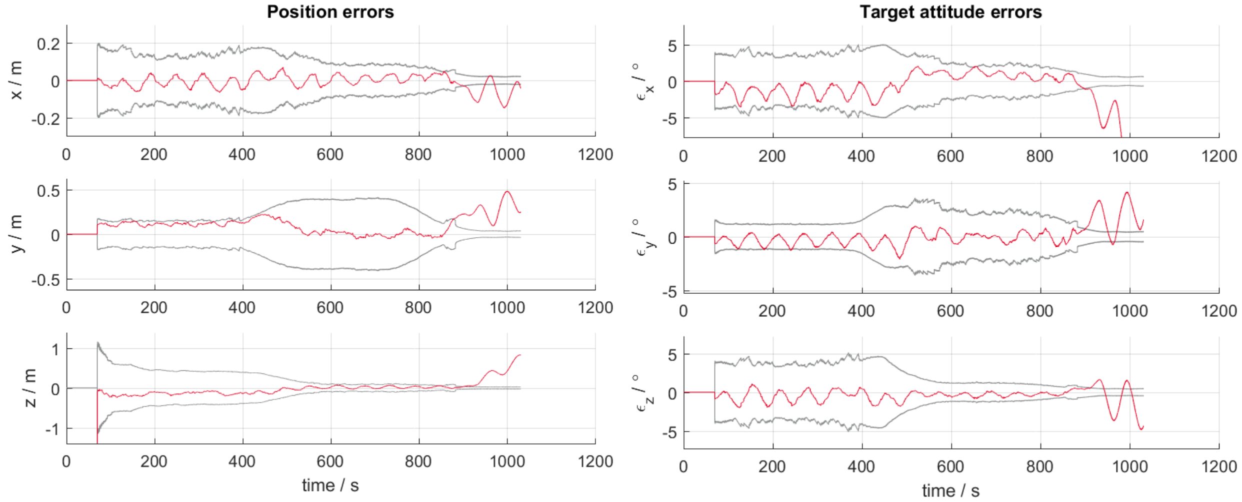

Figure 4-8: Closed-loop HIL test results

The HIL tests have shown that the short-range navigation is capable of operating with real camera measurements and is robust to the additional errors and biases that are introduced by the testing system. The overall GNC system is capable of successfully performing the full terminal rendezvous approach, even as a processing delay of 1 second is introduced, as well as the control function and the thruster models with the associated uncertainties. This demonstrates that the overall GNC system and the SRN navigation function are robust and provide sufficient performance to consider this concept for application in the HERACLES LAE GNC system.

It should be stressed that the testing conditions are a worst case with respect to the real conditions in certain respects. The mock-up is scaled 1:10 with respect to reality, meaning that any manufacturing errors, motion reproduction errors are magnified by a factor of 10. The illumination conditions are poorer in the sense that the intensity is lower and the light beam is conical, which lead to undesirable lighting artefacts (and possibly non-detection of markers). The test set-up was performed in a rather crude way in order to keep cost and development time down. It is expected that better performance can be achieved both in an improved test setting, as well as in the real world.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. STUDY RESULTS

The NRO-GNC project has demonstrated that the HERACLES LAE mission is feasible from the point of view of the GNC. The current GNC design provides sufficient performance to complete the mission from launch and ascent, orbit transfer and rendezvous.

In particular:

- The launch can be performed with sufficient orbit insertion accuracy using an IMU with performance specifications similar to the LN200S. The dispersions after main engine cut-off are compatible with the overall mission scenario as defined in [RD. 3].
- The accuracy with which the transfer injection manoeuvre and the trajectory correction manoeuvre can be performed is well below the 1°, 1% (3σ) performance requirement that is articulated in the CReMA, [AD. 4]
- The GNC performance at berthing is met apart from the angular velocity accuracy requirement. The angular velocity performance is about 6 times worse than required (0.25 °/s versus a required 0.04 °/s)

5.2. TECHNOLOGY ASSESSMENT

Table 5-1contains the results of the technology readiness assessment based on ECSS Technology readiness level guidelines, [RD. 12]. As a general comment, the GNC has been tested in MIL, SIL and a PIL testing environments.

Table 5-1: Assessed Technology Readiness Level

NRO-GNC Element	Description	NRO-GNC TRL	End-of-activity TRL(*)	Remarks
Ascent phase GNC	The ascent phase GNC consist of guidance, navigation and control for the launch and ascent phase.	4-5	4-5	The launch and ascent phase GNC was successfully tested in MIL, SIL and PIL campaigns.
Orbit transfer phase GNC	The orbit transfer phase GNC consist of guidance, navigation and control for the orbit transfer manoeuvres and for the cruise phase in between manoeuvres.	4-5	4-5	The orbit transfer phase GNC was successfully tested in MIL, SIL and PIL campaigns.
Rendezvous phase GNC	The rendezvous phase GNC consist of guidance, navigation and control for impulsive rendezvous and forced motion.	4-5	4-5	The rendezvous phase GNC was successfully tested in MIL, SIL and PIL campaigns. The short-range rendezvous was tested in a low-accuracy HIL test campaign, with an off-the-shelf space-qualified camera. The optical navigation is examined separately.
Optical navigation, long range	The long-range navigation provides the relative state of the chaser with respect to the target. The long-range navigation is based on line-of-sight measurements	2-3	4-5	Long-range optical navigation is assessed in the GUIBEAR activity,[RD. 13]
Optical navigation, medium range	The medium-range navigation provides the relative state of the chaser with respect to the target. The medium-range navigation is based on model-based tracking	2-3	4-5	Medium-range optical navigation is assessed in the MSRN2 activity,[RD. 14]
Optical navigation, short range	The short-range navigation provides the relative state of the chaser with respect to the target. The short-range navigation is based on fiducial marker tracking	4-5	4-5	The rendezvous phase GNC was satisfactorily tested in MIL, SIL and PIL setting. The optical navigation is examined separately.

NRO-GNC Element	Description	NRO-GNC TRL	End-of-activity TRL(*)	Remarks
MVM	The MVM function manages the GNC modes and equipment, and is in charge of maintaining the overall mission plan	4-5	4-5	The MVM was tested for all phases. The full GNC for all phases of the mission was integrated into a single GNC function The GNC plus MVM and FDIR was autocoded into a single PIL that could be configured for each flight phase.
FDIR	The FDIR function is in charge of detecting equipment failure, and monitoring the GNC thresholds(**)	4	4	The performance of the FDIR failure and threshold detection ability was tested in the NRO-GNC activity. Contingency plans for safe modes (attitude safe mode during orbit transfer, attitude and trajectory safe mode during rendezvous), collision avoidance manoeuvres and trajectory retreats were tested for the MVM. The interaction with the MVM and the switching logic was not fully completed.

*: The end-of-activity TRL referred to here is the TRL at the end of the activity referred to in the “remarks” column

**: Thresholds are taken in a broad sense here. This refers to monitoring navigation convergence, control convergence, and trajectory boundaries (i.e., bounds on chaser position, Roadvelocity, attitude and attitude rate) during rendezvous

5.3. TECHNOLOGY ROADMAPS

5.3.1. GNC DEVELOPMENT ACTIVITY

Table 5-2 shows the development schedule milestones for the development of the GNC software up to TRL6. This activity aims to further develop the NRO-GNC software to TRL 6. This activity includes algorithms functional breadboarding including system tests and aims to achieve TRL5-6 by Q4/2021 if the activity KO takes place in Q3/2020. ***Currently, no KO is foreseen for this activity.***

Table 5-2: GNC development schedule milestones

Review	Code	Scheduled date	Main activity to be reviewed
Kick-Off	KO	T0	
Preliminary Design Review	PDR	T0 + 3 months	Preliminary Design
Critical Design Review	CDR	T0 + 9 months	Detailed Design
Intermediate Review	IR	T0 + 14 months	Test progress
Test Review	TR	T0 + 17 months	Hardware in the loop tests
Final Review	FR	T0 + 18 months	

Figure 5-1 shows the development schedule for the GNC.

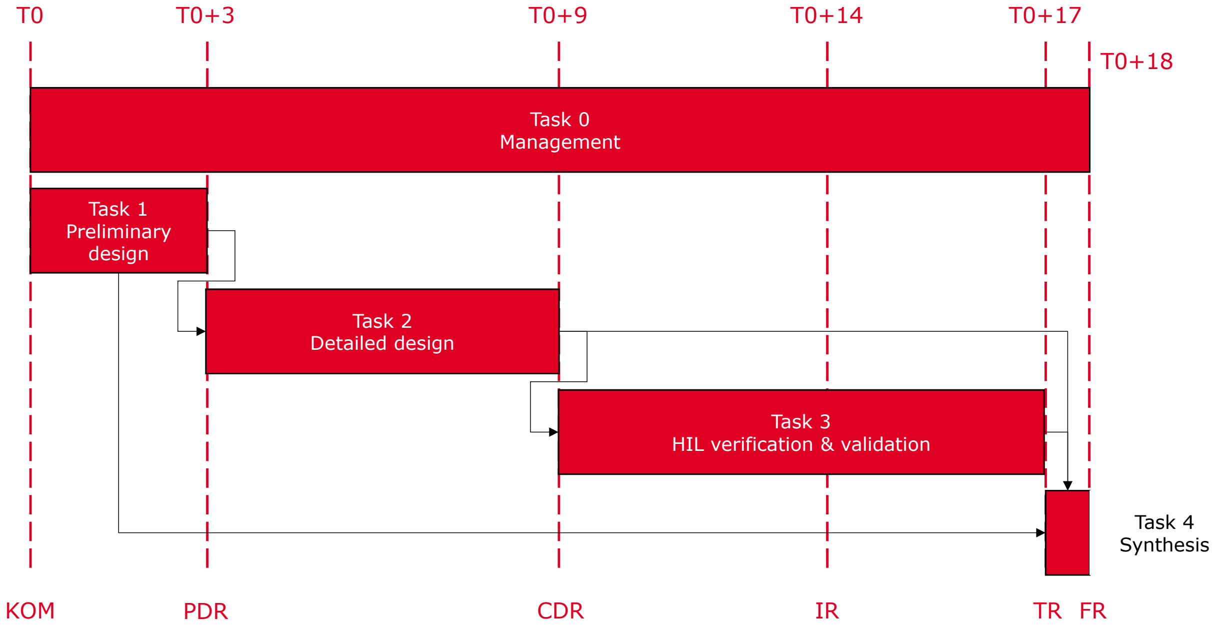

Figure 5-1: GNC development schedule

5.3.2. CAMERA + IMAGE PROCESSING DEVELOPMENT ACTIVITY

Table 5-3 shows the development schedule milestones for the development of the Camera sensor and Image Processing up to TRL6. This activity includes the development of breadboards & test bench, EM functional breadboarding including system tests; HW-in-The-Loop with integrated system. The VNU is composed of camera hardware plus image processing board. While the camera hardware has a high TRL (8), the IPB + SW has a much lower TRL (3-4). The activity aims to achieve TRL6 by Q4/2021 if the activity KO takes place in Q3/2020. ***Currently, no KO is foreseen for this activity.***

Table 5-3: GNC development schedule milestones

Review	Code	Scheduled date	Main activity to be reviewed
Kick-Off	KO	T0	
Requirements Review	RR	T0 + 2.5 months	Requirements
Preliminary Design Review	PDR	T0 + 7 months	Preliminary Design
Design Review	CDR	T0 + 12 months	Procurement/Manufacturing
Intermediate Review	IR	T0 + 15 months	Assembly
Test Review	TR	T0 + 17 months	Technology and I/F demonstration/ Environmental test in controlled lab
Final Review	FR	T0 + 18 months	

Figure 5-2 shows the development schedule for the camera sensor including image processing.

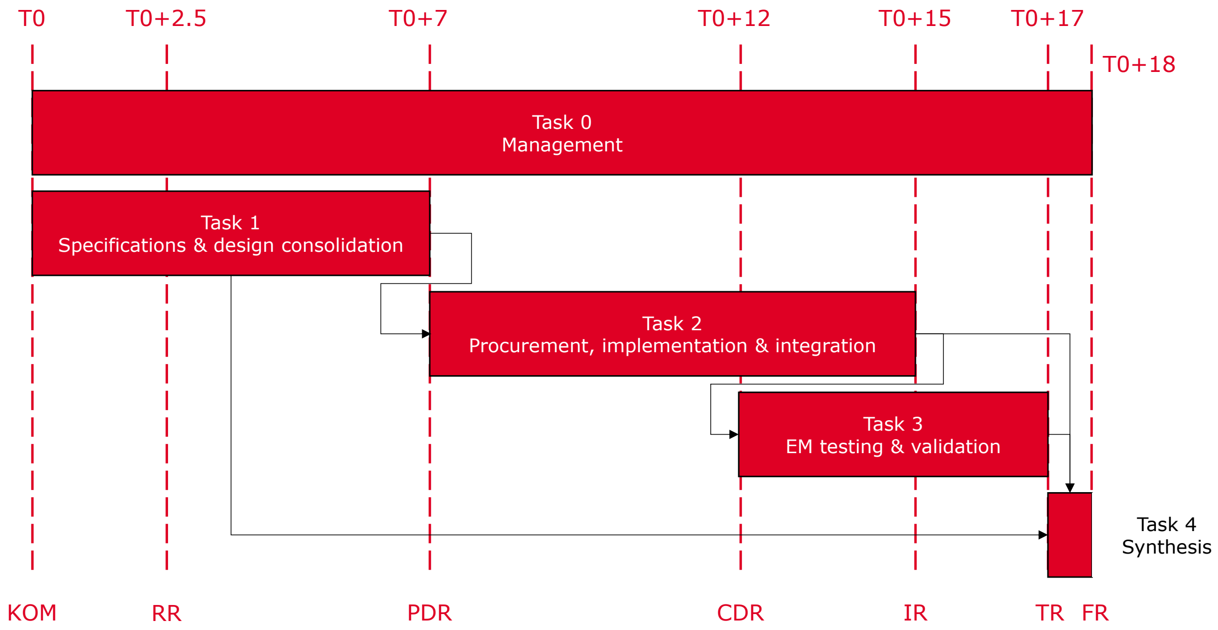

Figure 5-2: Development schedule for Camera + IP

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