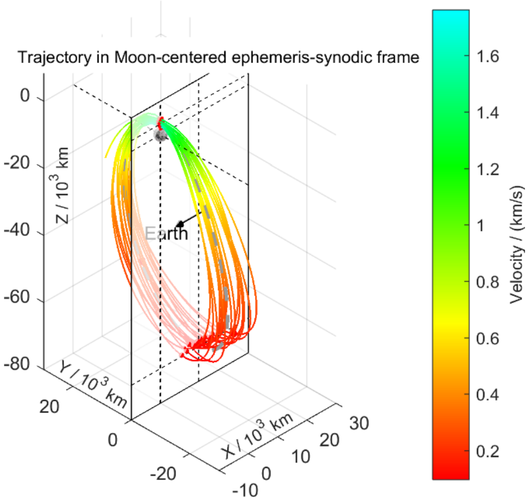
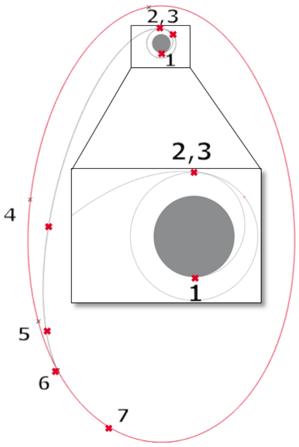
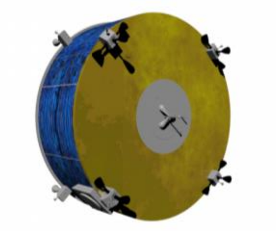
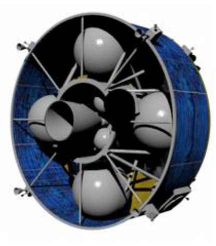
NRO-GNC

Final Presentation









Contents

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MIL & PIL Testing	11:15 – 12:00
HIL testing	12:00 – 12:15
Conclusions, Evaluation and Roadmaps	12:15 – 12:30
Q & A	12:30 – 13:00

Introduction to NRO-GNC Project

09:30 – 09:45

NRO-GNC project

ESA Contract No. 4000125271/18/NL/CRS

Objective

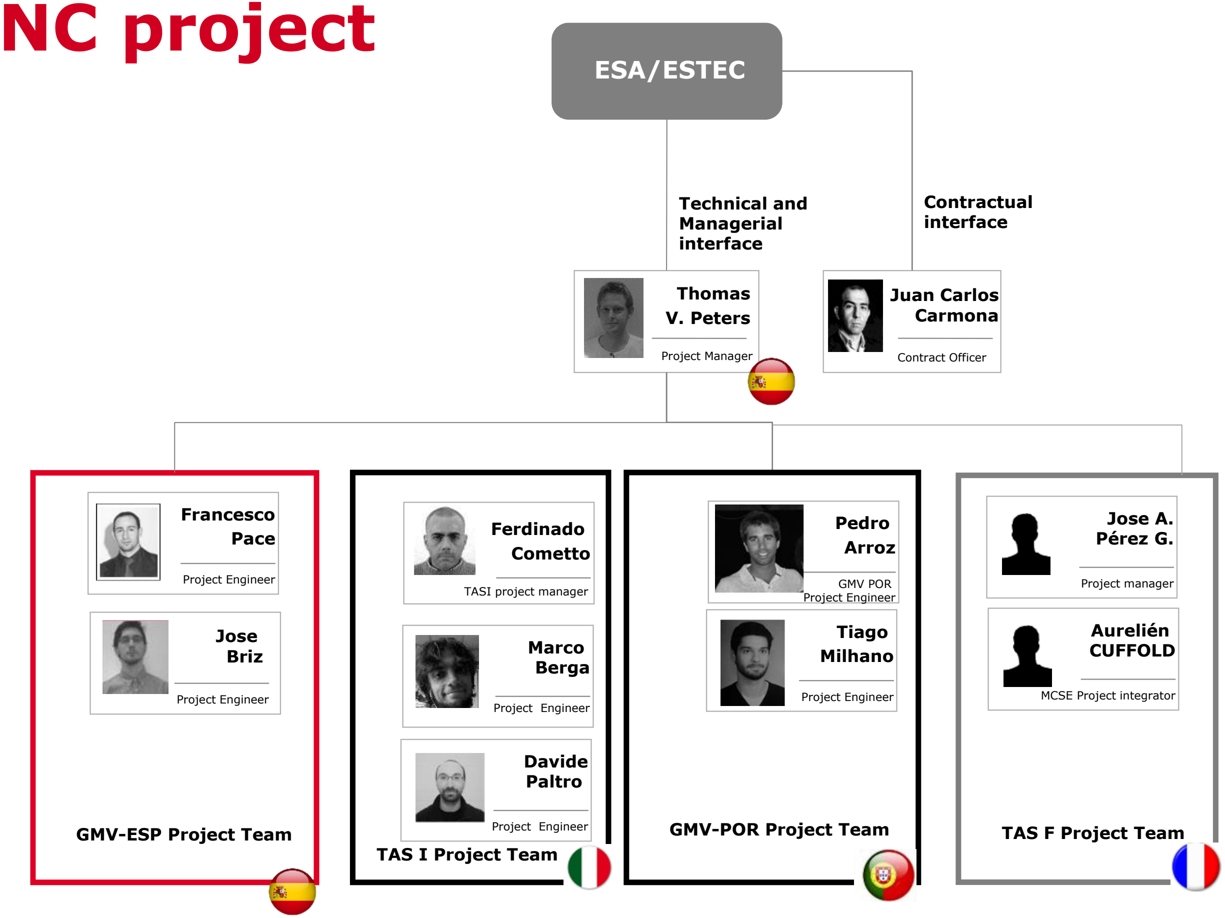
- To perform the pre-development and prototyping of the GNC system of the Lunar Ascent Element for both the ascent to, and rendezvous & docking/berthing in NRHO orbits around the Moon
  - GNC system includes MVM and FDIR
  - Development to be carried out to TRL 3
  - GNC is required to be Safety Critical, i.e. Fail-Operational and Fail-Safe (FOFS)

- KO of the activity on September 11th 2018

- Study duration 1 year
- Extended by CCN
- PIL & HIL tests delayed (COVID19)

NRO-GNC project

TEAM



ESA/ESTEC

Technical and Managerial interface

Contractual interface

Thomas V. Peters
Project Manager

Juan Carlos Carmona
Contract Officer

Francesco Pace
Project Engineer

Jose Briz
Project Engineer

GMV-ESP Project Team

Ferdinado Cometto
TASI project manager

Marco Berga
Project Engineer

Davide Paltro
Project Engineer

TAS I Project Team

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GMV POR
Project Engineer

Tiago Milhano
Project Engineer

GMV-POR Project Team

Jose A. Pérez G.
Project manager

Aurelién CUFFOLD
MCSE Project integrator

TAS F Project Team

NRO-GNC

Tasks

TASK 1: To compile and analyze GNC requirements, and to perform trajectory analysis

- Analyze mission scenarios and extract requirements
  - System level requirements, including assessment of the problematics of LAE manned missions
  - Reference rendezvous scenario requirements
  - GNC / MVM / FDIR requirements
  - SIL / PIL requirements
- Trajectory analysis
  - Define and develop trajectory simulation tools
  - Define rendezvous strategies, including (but not limited to) collision avoidance manoeuvres, hold points, safety spheres and retreat areas

TASK 2: To design the GNC system

- GNC design (GNC, MVM & FDIR, including trade-offs)
  - Launch and ascent
  - Orbit transfer and rendezvous
- SIL framework design and implementation

TASK 3: To develop and implement the GNC software

- GNC development and integration (GNC, MVM & FDIR)
  - Launch and ascent
  - Orbit transfer and rendezvous
- PIL framework design, implementation and cross-validation

TASK 4: To demonstrate the prototype GNC to TRL 3

- SIL Validation and Verification
  - Launch and ascent
  - Orbit transfer and rendezvous
- PIL Validation and Verification
  - Launch and ascent
  - Orbit transfer and rendezvous

TASK 5: To summarize the study results and synthesize recommendations for future activities

- Study synthesis
- Roadmap

NRO-GNC

Tasks (CCN)

TASK 6: Extended detailed design
- Launch and ascent detailed design
- Orbit transfer and rendezvous detailed design

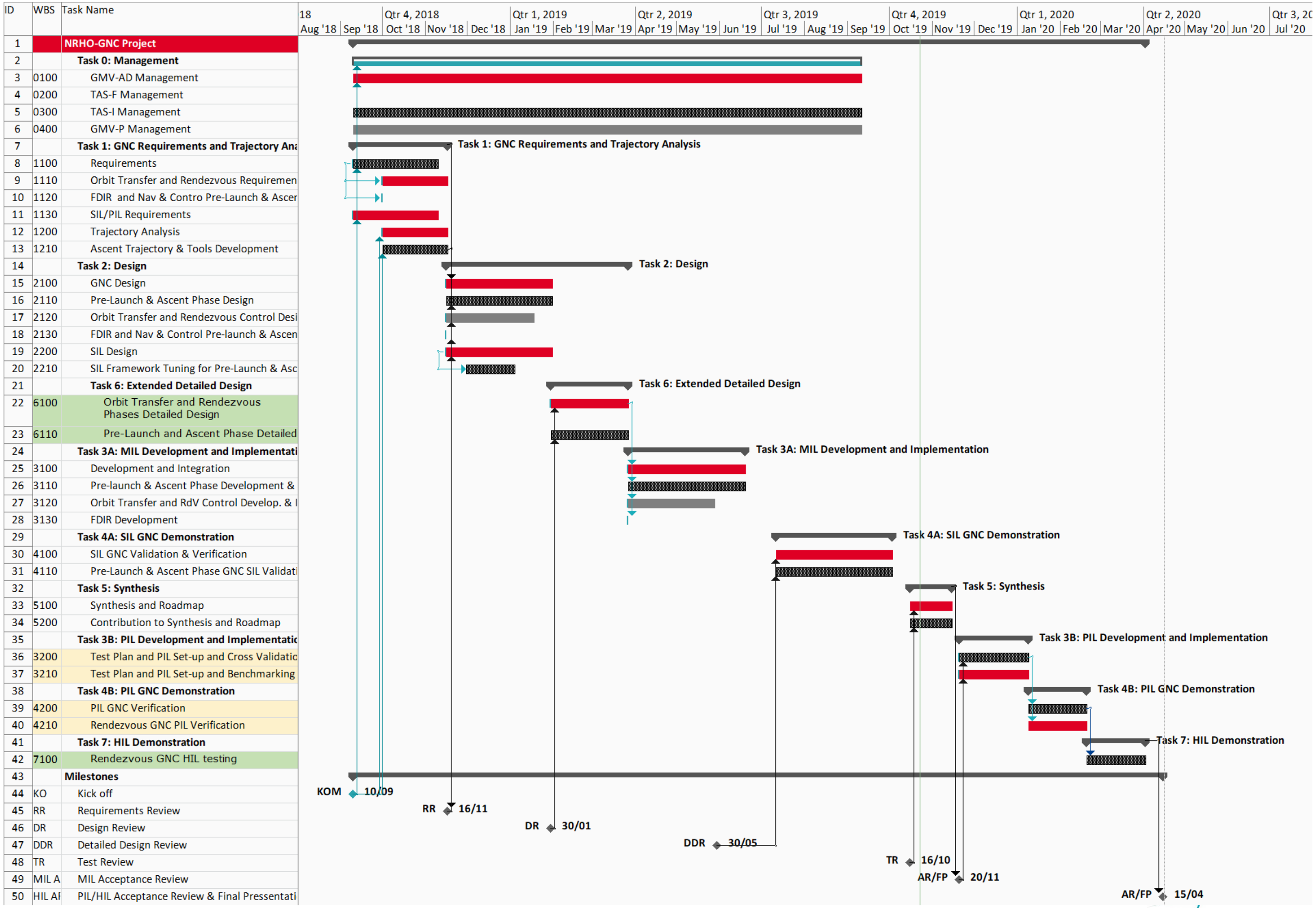
TASK 7: HIL demonstration
- HIL set-up, cross-validation and benchmarking
- Testing of the rendezvous GNC in the HIL

Key dates

ITT issued:	12/02/2018
NM:	22/08/2018
KoM:	11/09/2018
RR:	16/11/2018
DR:	07/02/2019
DDR:	16/07/2019
TR:	16/10/2019
ΔTR:	13/12/2019
AR:	18/06/2020

NRO-GNC

Schedule



ID	WBS	Task Name
1		**NRHO-GNC Project**
2		**Task 0: Management**
3	0100	GMV-AD Management
4	0200	TAS-F Management
5	0300	TAS-I Management
6	0400	GMV-P Management
7		**Task 1: GNC Requirements and Trajectory Ana**
8	1100	Requirements
9	1110	Orbit Transfer and Rendezvous Requiremen
10	1120	FDIR and Nav & Contro Pre-Launch & Ascer
11	1130	SIL/PIL Requirements
12	1200	Trajectory Analysis
13	1210	Ascent Trajectory & Tools Development
14		**Task 2: Design**
15	2100	GNC Design
16	2110	Pre-Launch & Ascent Phase Design
17	2120	Orbit Transfer and Rendezvous Control Desi
18	2130	FDIR and Nav & Control Pre-launch & Ascen
19	2200	SIL Design
20	2210	SIL Framework Tuning for Pre-Launch & Asc
21		**Task 6: Extended Detailed Design**
22	6100	Orbit Transfer and Rendezvous Phases Detailed Design
23	6110	Pre-Launch and Ascent Phase Detailed
24		**Task 3A: MIL Development and Implementati**
25	3100	Development and Integration
26	3110	Pre-launch & Ascent Phase Development &
27	3120	Orbit Transfer and RdV Control Develop. & I
28	3130	FDIR Development
29		**Task 4A: SIL GNC Demonstration**
30	4100	SIL GNC Validation & Verification
31	4110	Pre-Launch & Ascent Phase GNC SIL Validati
32		**Task 5: Synthesis**
33	5100	Synthesis and Roadmap
34	5200	Contribution to Synthesis and Roadmap
35		**Task 3B: PIL Development and Implementatic**
36	3200	Test Plan and PIL Set-up and Cross Validatic
37	3210	Test Plan and PIL Set-up and Benchmarking
38		**Task 4B: PIL GNC Demonstration**
39	4200	PIL GNC Verification
40	4210	Rendezvous GNC PIL Verification
41		**Task 7: HIL Demonstration**
42	7100	Rendezvous GNC HIL testing
43		**Milestones**
44	KO	Kick off
45	RR	Requirements Review
46	DR	Design Review
47	DDR	Detailed Design Review
48	TR	Test Review
49	MIL A	MIL Acceptance Review
50	HIL AI	PIL/HIL Acceptance Review & Final Pressentati

Mission Analysis

09:45 – 10:15

- Ascent	09:45 – 09:55
- Orbit transfer	09:55 – 10:05
- Rendezvous	10:05 – 10:15

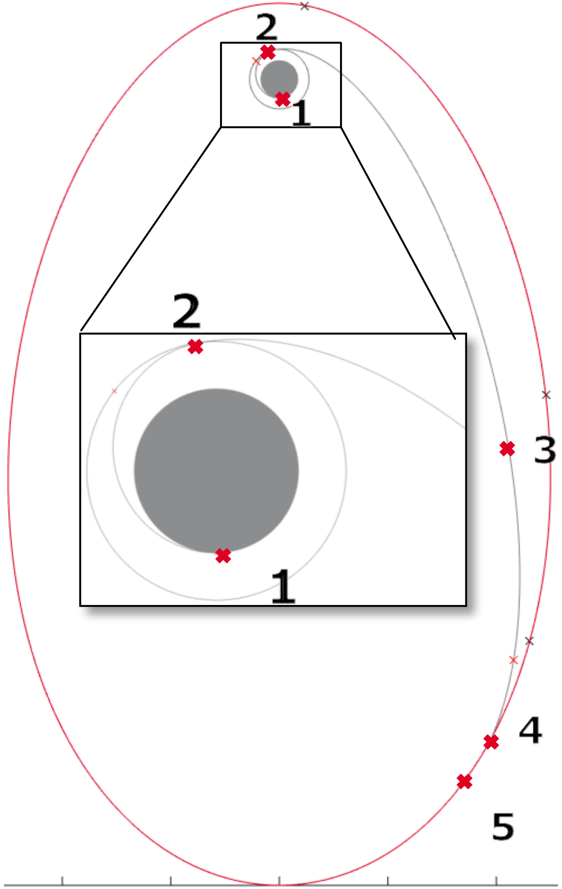
Mission Analysis

Mission Phases Overview

1. **Ascent**

- Loitering and Phasing in LLO

2. **Orbit Transfer Manoeuvre**
3. **Trajectory Correction Manoeuvre**
4. **NRO Insertion Manoeuvre**
5. **Rendezvous**



Mission Analysis

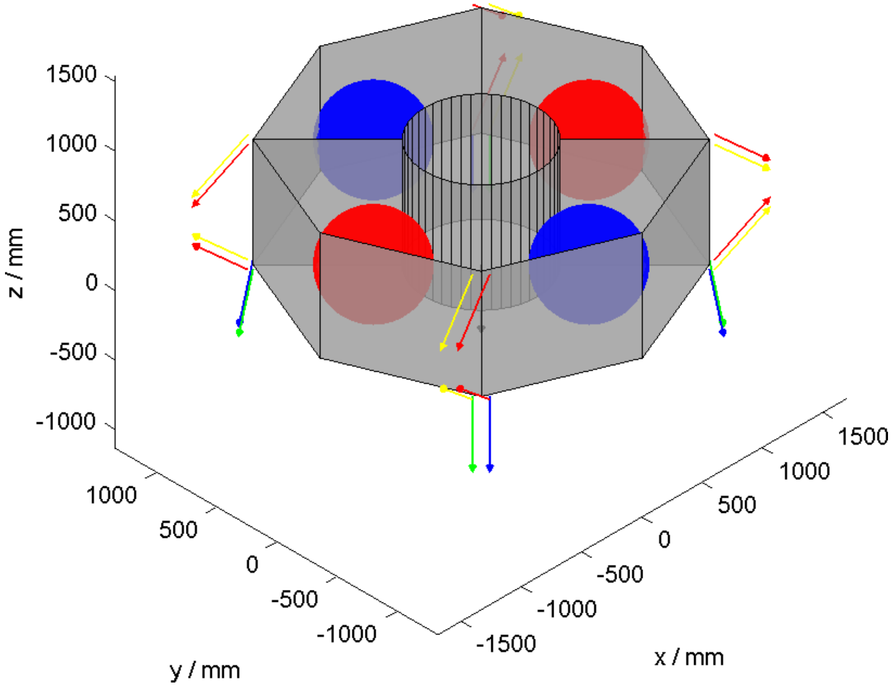
LAE configuration

Actuators

- 1 6 kN bipropellant main thruster
- 4+4 220 N bipropellant auxiliary (AUX) thrusters
- 8+8 10 N bipropellant reaction control system (RCS) thrusters

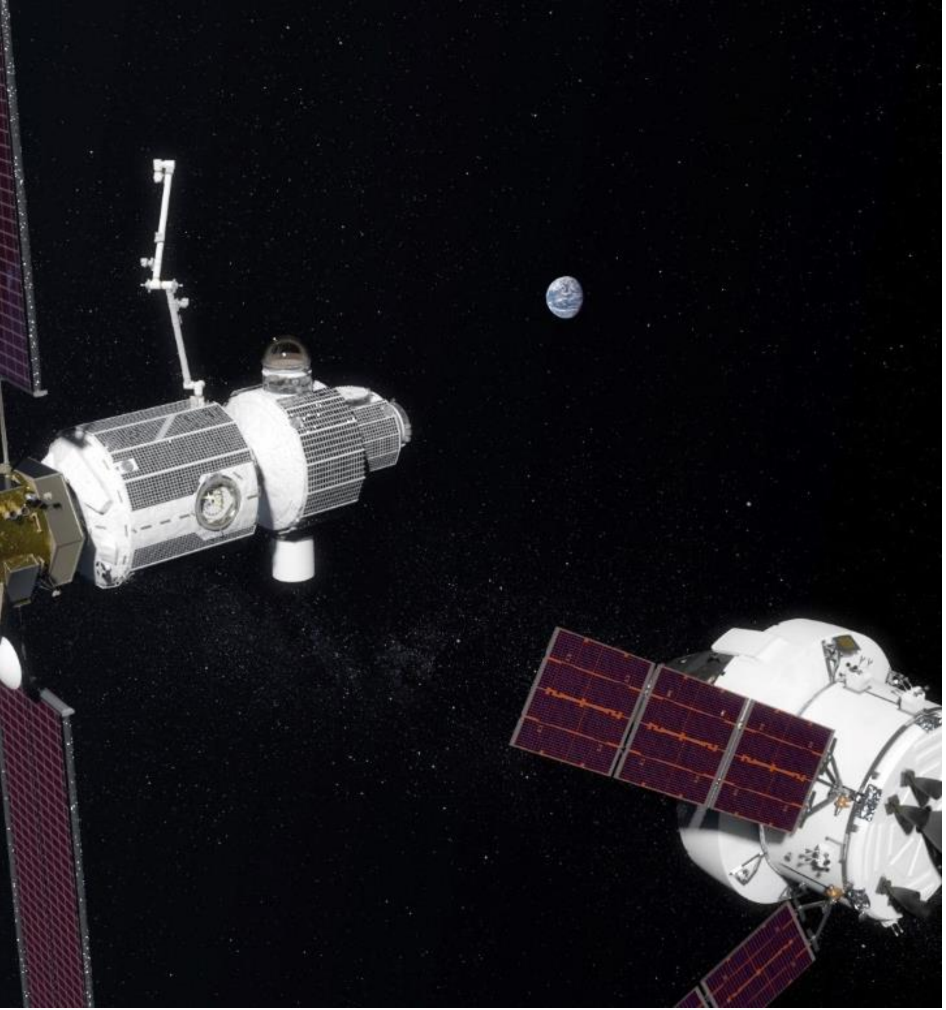
Sensors

- IMU
- Star trackers
- Sun sensors
- Camera (NAC + WAC) pointing upwards



ΔV Budget

Phase	Thruster	Ideal ΔV / (m/s)	Margin	ΔV plus margin / (m/s)	Comment
Ascent	main	1841	7.5%	1979.1	
Circularization	AUX	15.9	5%	16.7	
Transfer Injection Manoeuvre	main	660.9	5%	693.9	
Trajectory Correction Manoeuvre	AUX	57.0	10%	62.7	Stochastic manoeuvre with (μ = 18.0 σ = 12.8), depending on accuracy of TIM, as obtained from mission analysis.
NRO Insertion Manoeuvre	AUX	36.1	10%	39.7	Manoeuvre with large stochastic component, dependent with (μ = 20.8 σ = 6.2), depending on accuracy of TIM, as obtained from mission analysis
Impulsive Rendezvous	RCS	25.4	170%	68.5	Value + margin includes geometric losses due to thruster orientation and actuation for attitude control
Forced Motion Rendezvous	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



Ascent

Mission Analysis. Ascent

Nominal ascent profile

Ascent trajectory starts from the Schroedinger crater (-75° N, 132.4° E)

Ascent is composed of three phases:

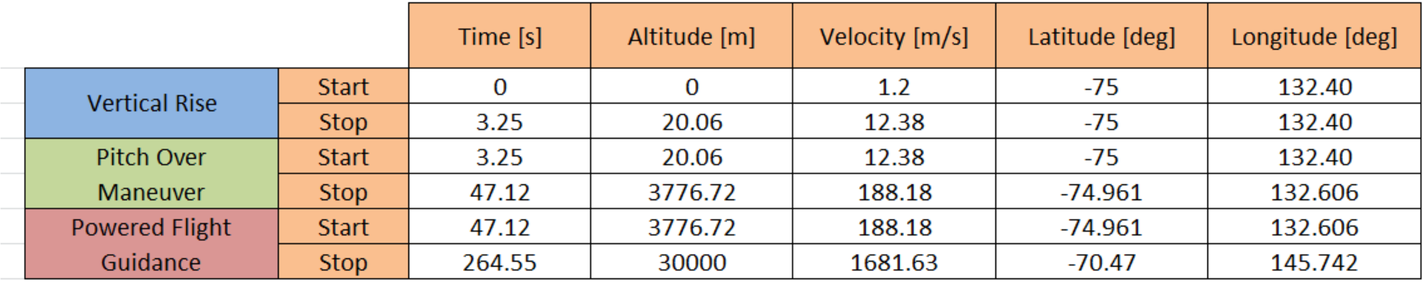
- Vertical Rise, to prevent collision risks during the very first leg of the ascent
- Pitch Over phase, to avoid the abrupt manoeuvres to get the correct thrust direction
- Powered Flight, in which the thrust direction is rotated by pitch and yaw angles to target the desired intermediate elliptical transfer orbit

Ascent parameters:

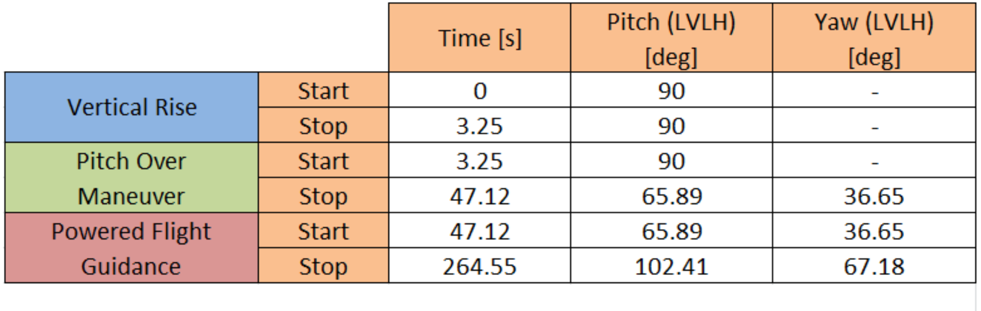
- Target orbit: apoapsis 100 km, periapsis 30 km, inclination 80 deg
- Engine thrust: 6 kN. Specific impulse 340 s
- Dry mass 451.83 kg. Propellant mass 659 kg
- Vertical Rise altitude: 20 m
- Pitch rate during the Pitch Over phase: 1.5 deg/s

Mission Analysis. Ascent

Nominal ascent profile



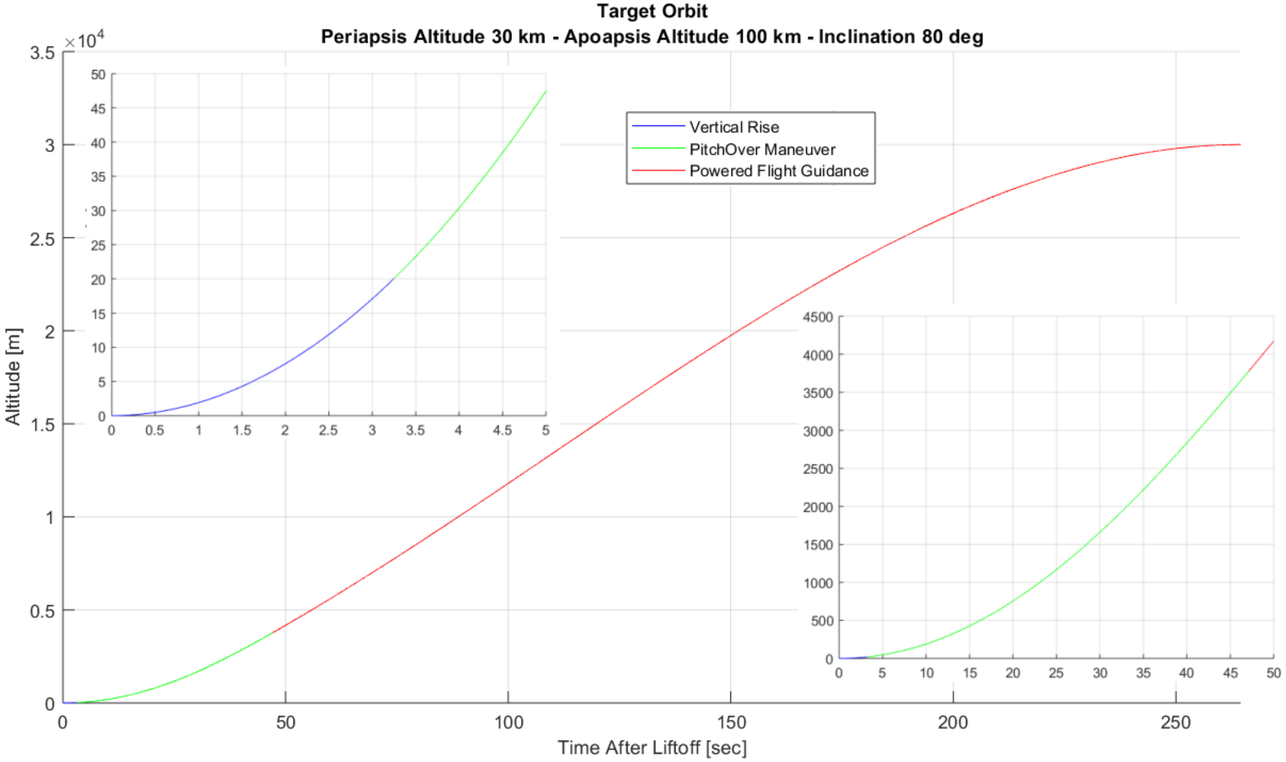
		Time [s]	Altitude [m]	Velocity [m/s]	Latitude [deg]	Longitude [deg]
Vertical Rise	Start	0	0	1.2	-75	132.40
	Stop	3.25	20.06	12.38	-75	132.40
Pitch Over Maneuver	Start	3.25	20.06	12.38	-75	132.40
	Stop	47.12	3776.72	188.18	-74.961	132.606
Powered Flight Guidance	Start	47.12	3776.72	188.18	-74.961	132.606
	Stop	264.55	30000	1681.63	-70.47	145.742



		Time [s]	Pitch (LVLH) [deg]	Yaw (LVLH) [deg]
Vertical Rise	Start	0	90	-
	Stop	3.25	90	-
Pitch Over Maneuver	Start	3.25	90	-
	Stop	47.12	65.89	36.65
Powered Flight Guidance	Start	47.12	65.89	36.65
	Stop	264.55	102.41	67.18

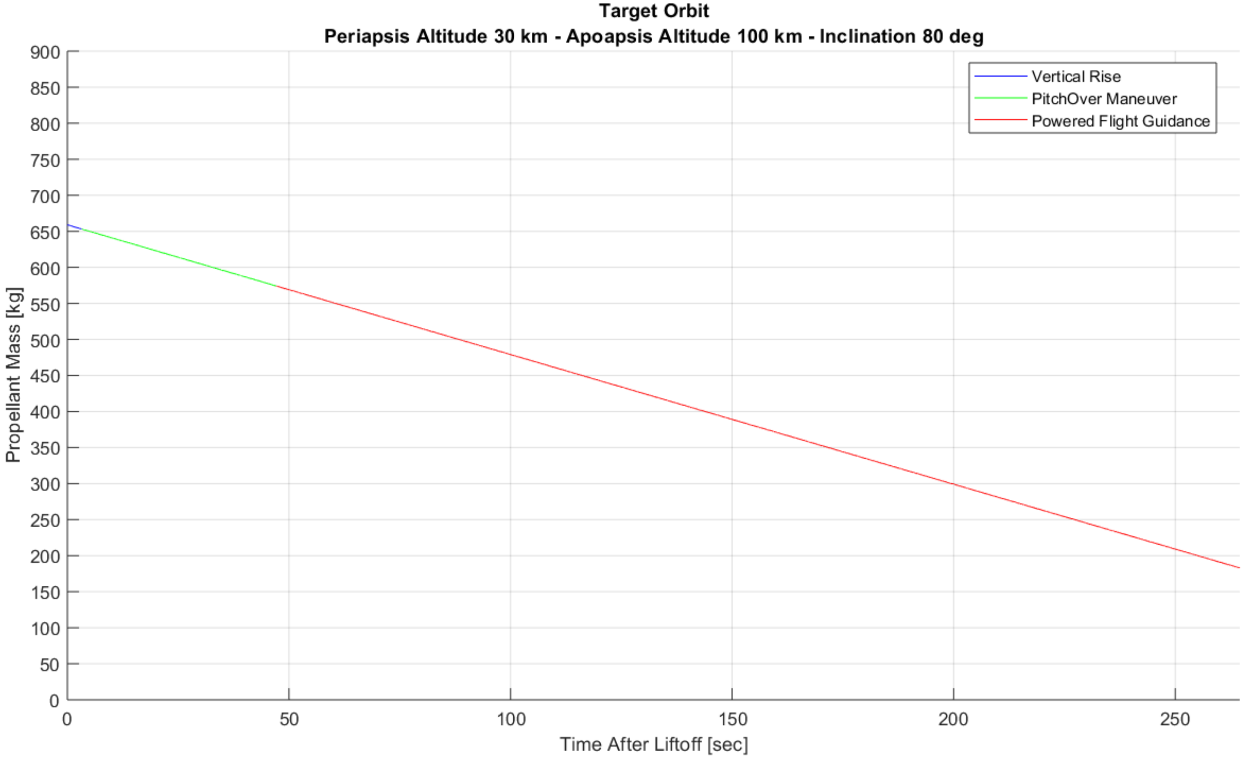
Mission Analysis. Ascent

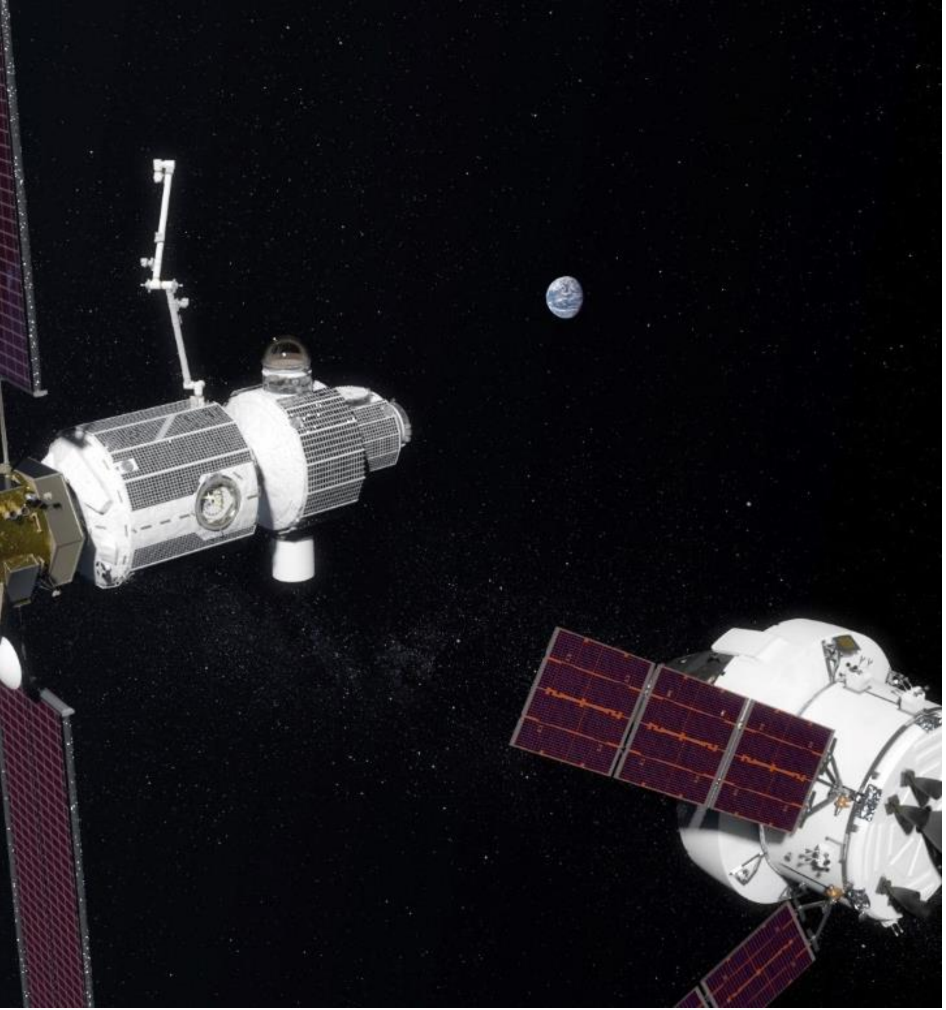
Nominal ascent Profile. Altitude



Mission Analysis. Ascent

Nominal ascent Profile. Propellant





Orbit transfer

Mission Analysis

Ephemeris NRHO

Ephemeris NRHO

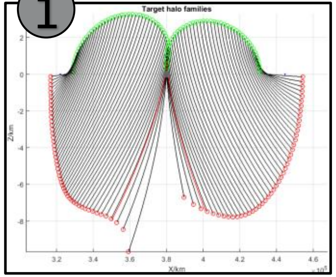
CRTBP NRHO

Transfer trajectory

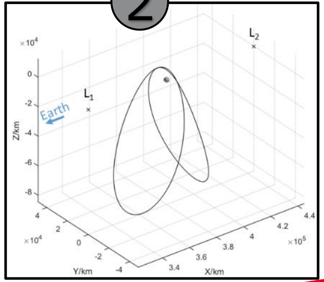
Nominal transfer trajectory

Dispersion and handover

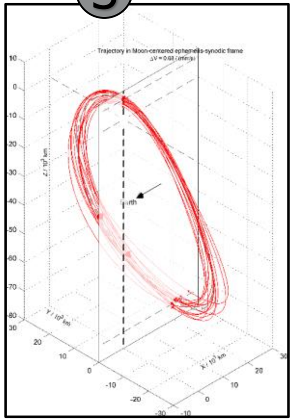
CRTBP family

①


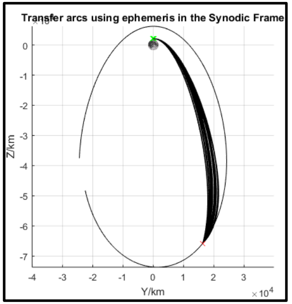
CRTBP target NRO

②


Eph. target NRO

③


Transfer parametric study

④


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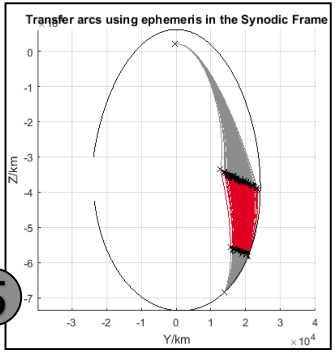
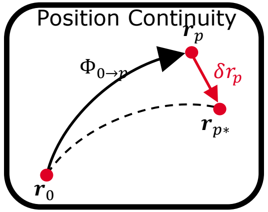
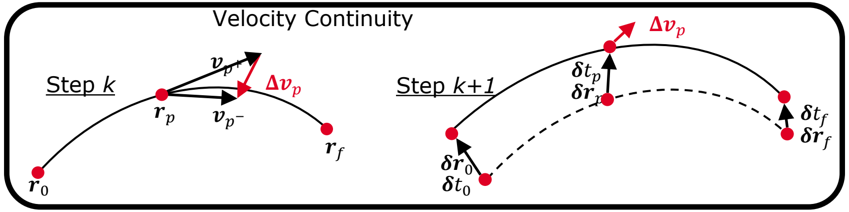


Dispersion

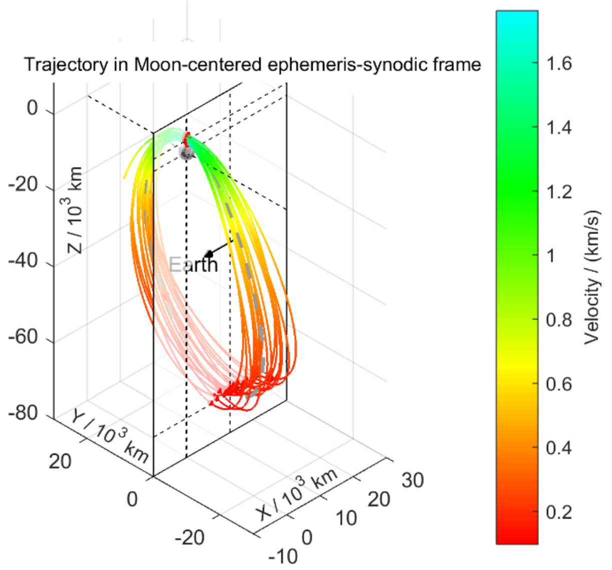
Mission Analysis





NRO generation

1. **NRO generation in CRTBP**
2. **Rotation of seed points to ephemeris**
3. **Correction of seed points**
   1. Two-level corrector: Position continuity
   2. Two-level corrector: Velocity continuity
   3. Update: Minimize correction and velocity with optimization algorithm



LOP-G trajectory

- Continuous in position and velocity
- Consistent with Earth-Moon ephemeris
- Stable without manoeuvres for 15 orbits (~98 days)

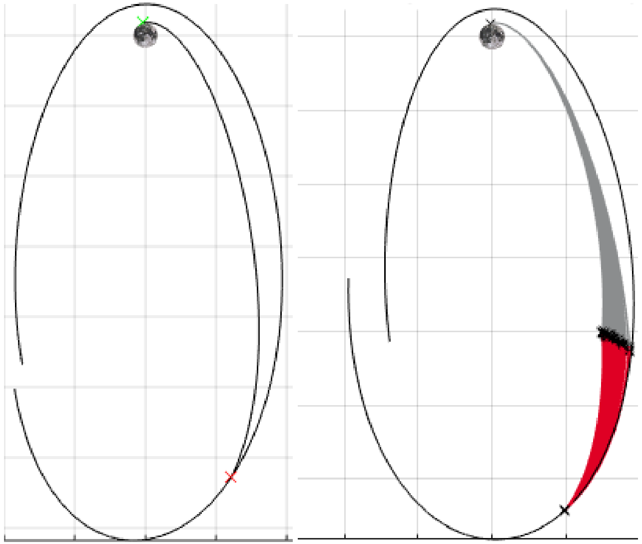
Mission Analysis

Orbit Transfer Computation

Lambert Differential Corrector

1. Transform boundary conditions to Moon centred frame
2. Lambert solver to obtain initial guess
3. Correct manoeuvre using state transition matrix

Same algorithm contained in OBSW

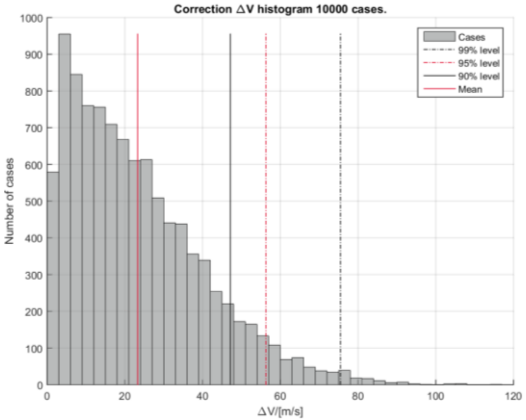


Dispersion Analysis

Addition of navigation errors to computation and manoeuvre execution errors

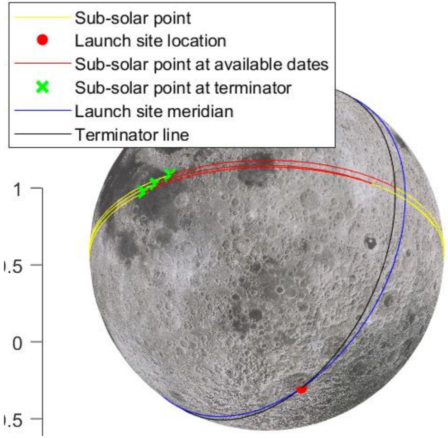
1 TCM strategy

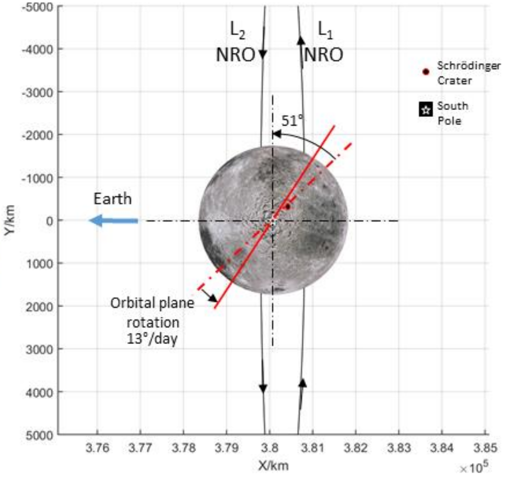
Monte Carlo estimate trajectory dispersion and correction ΔV



Mission Analysis

Date Selection

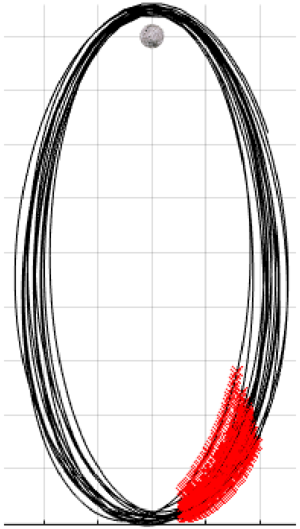




Initial and Final Conditions

Constraints in ascent with constraints in insertion

1. Maximize surface operations but launching before sunset (7 days before sunset)
2. Loitering in LLO to synchronize manoeuvre plane and orbital plane (1 to 5 days)
3. Variable transfer arc duration (2.3-2.7 days)
4. Arrival conditions close to aposelene and tangent to transfer arc
5. Multiple target revolutions considered



Parametric study to obtain reduced manoeuvre cost

Mission analysis

End-to-end mission profile

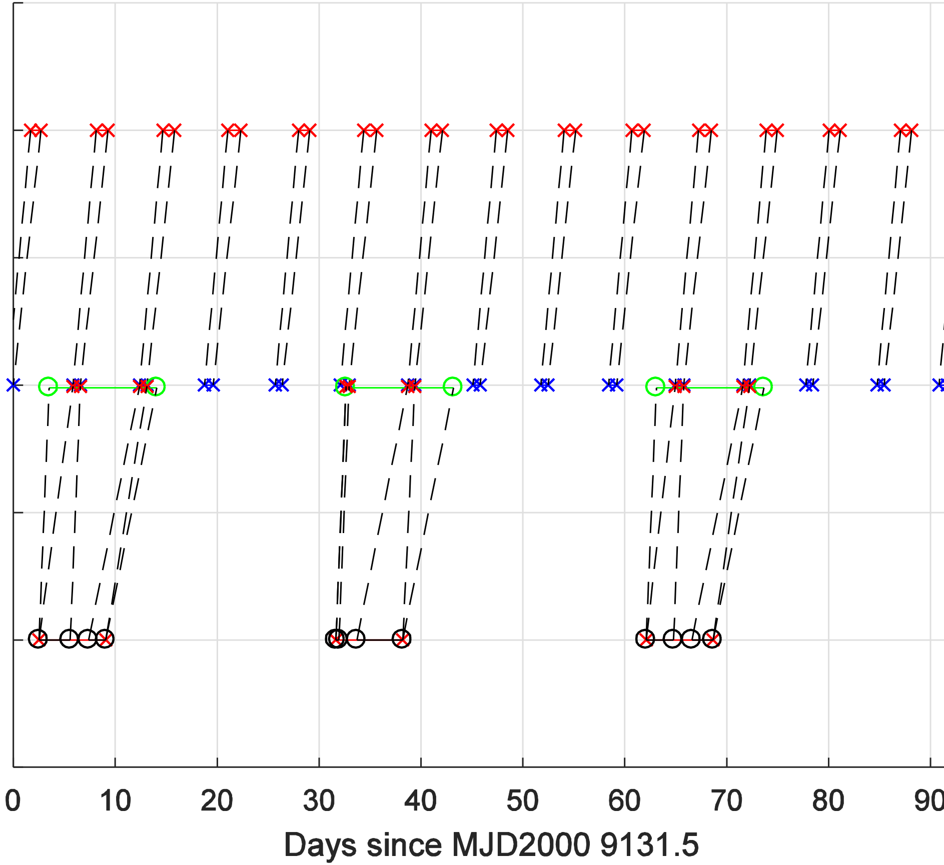
Stepwise analysis of the end-to-end mission profile:

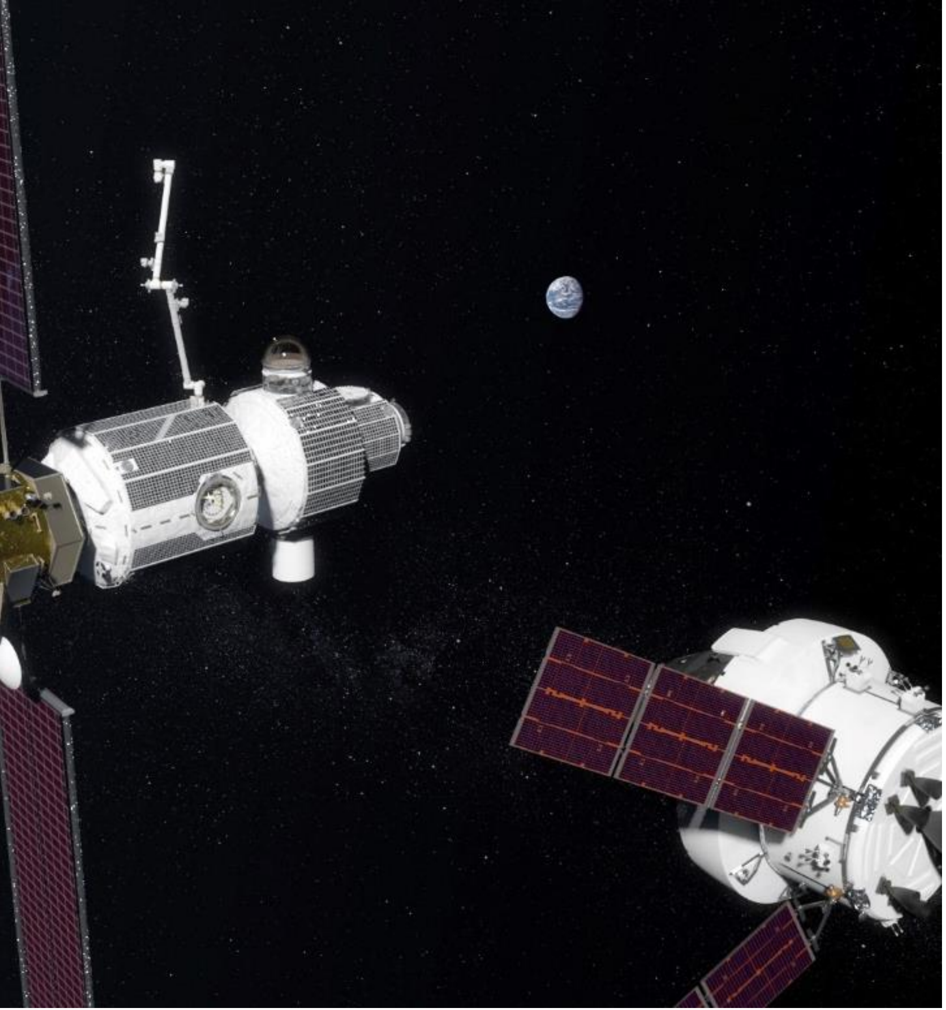
- 1: Analyse arrival to NRO conditions
- 2: Propagate backwards to obtain TIM ranges
- 3: Analyse ascent conditions
- 4: Propagate ascent and loitering forwards to obtain TIM ranges
- 5: Analyse intersection of TIM ranges from steps 2 and 4, with the following guidelines:

_ Dates closer to dusk are preferred to maximize lunar ground operations

_ Shorter loitering times are preferred to reduce lunar disturbances and overall mission duration, with a minimum of 1 day to perform orbit determination

- 6: Obtain a transfer below a ΔV threshold given the available dates

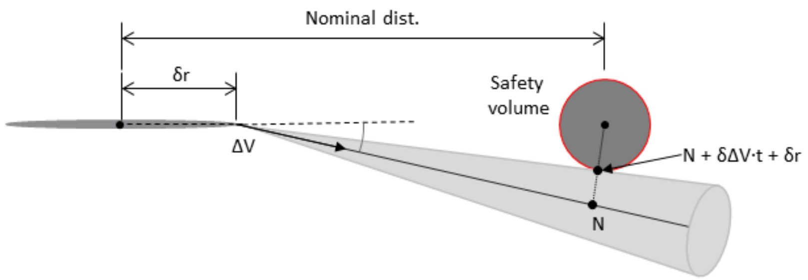




Rendezvous

Mission Analysis

Impulsive Rendezvous

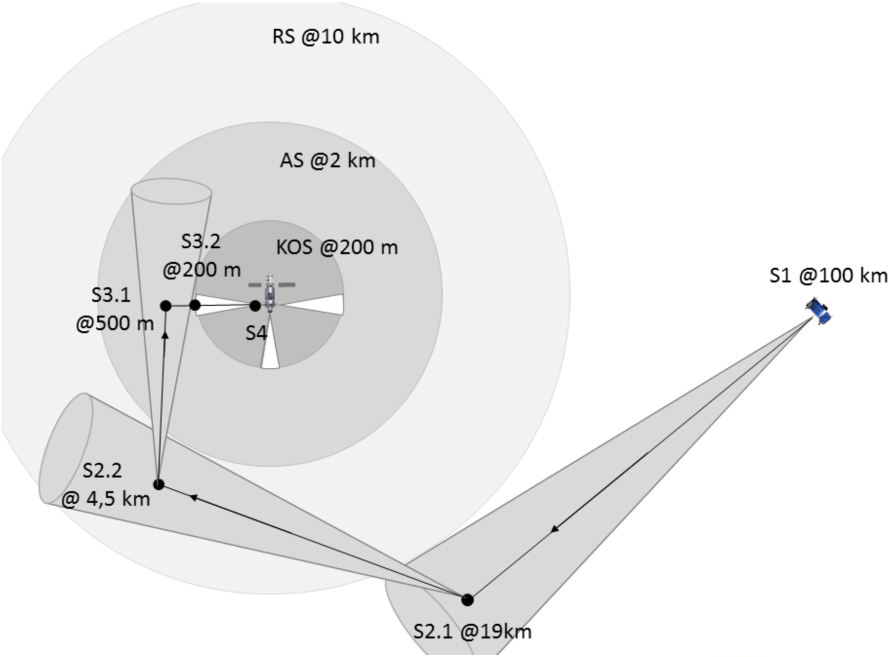


Defined safety volumes

- Rendezvous Sphere (RS) – The RS is a 10 km radius sphere around the LOP-G centre of mass.
- Approach Sphere (AS) – The AS is a 2 km radius sphere centred at the LOP-G centre of mass.
- Keep-out Sphere (KOS) – The KOS is 200 m radius sphere centred at the LOP-G centre of mass.

Transfer errors

- Guidance errors of 5% of the transfer distance, or a cone of 2.9°
- Control error of 2° in application, cone of 2°.
- Navigation errors depending on phase:
    - At handover, errors coming from ground tracking
    - After manoeuvres, errors as 10% of relative distance



Mission Analysis

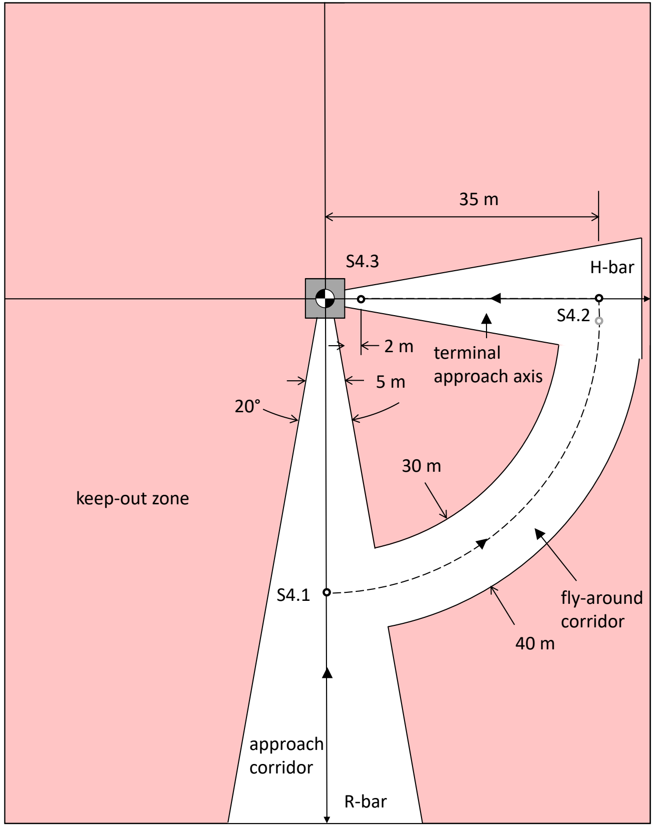
Forced Motion Rendezvous

Approaching corridors

- Approach/Departure Corridors – ±10° centred to the docking port axis within the KOS
- Circular Fly-around corridors at 35 metres

Conditions analysed

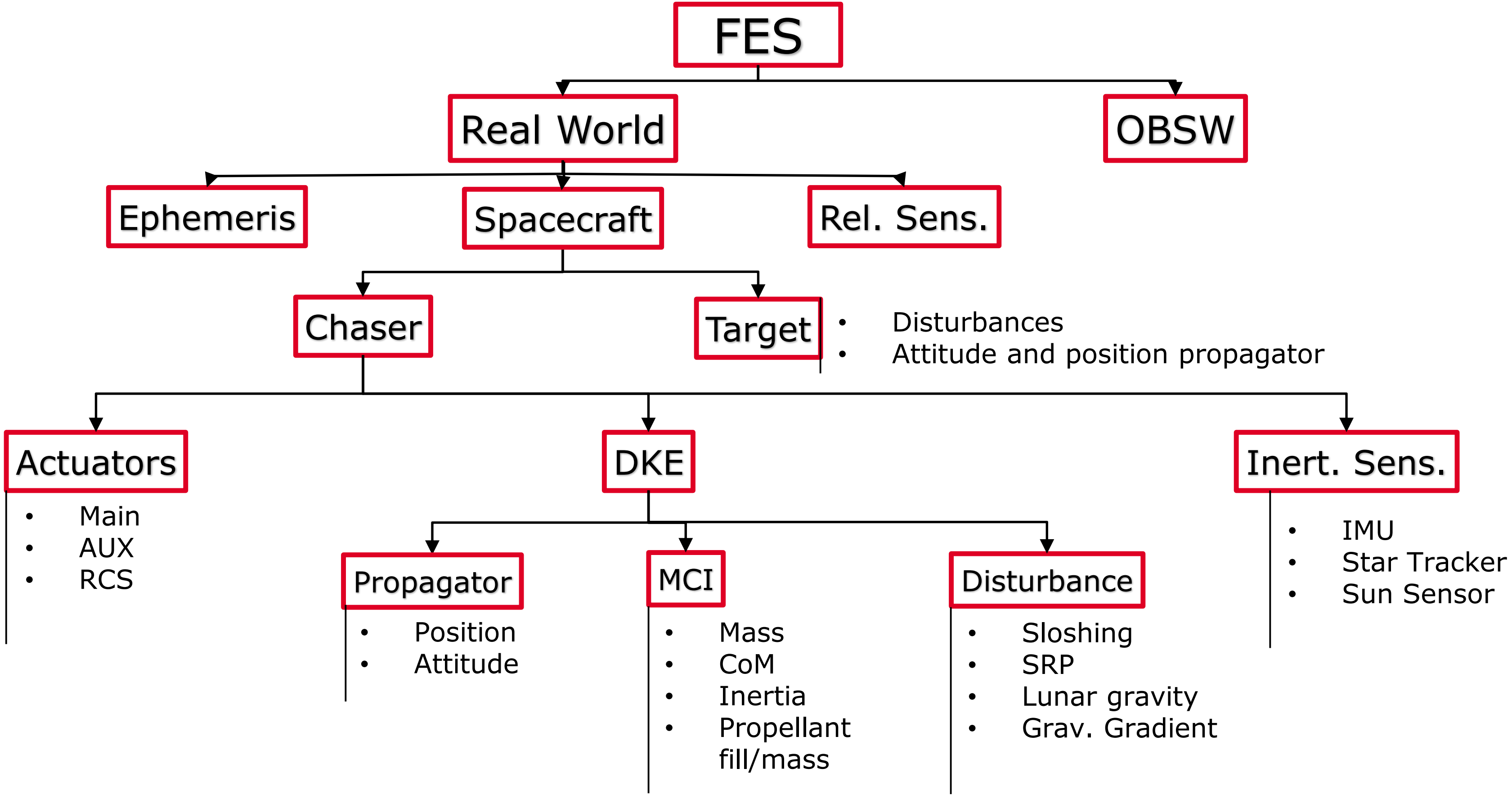
- Motion in target body frame matching target rotation from S4.1
- Circular fly-around
- CAM and Safe Mode analysed



Simulator Overview

10:15 – 10:30

Simulator Overview



FES

Real World

OBSW

Ephemeris

Spacecraft

Rel. Sens.

Chaser

Target

- Disturbances
- Attitude and position propagator

Actuators

- Main
- AUX
- RCS

DKE

Propagator

- Position
- Attitude

MCI

- Mass
- CoM
- Inertia
- Propellant fill/mass

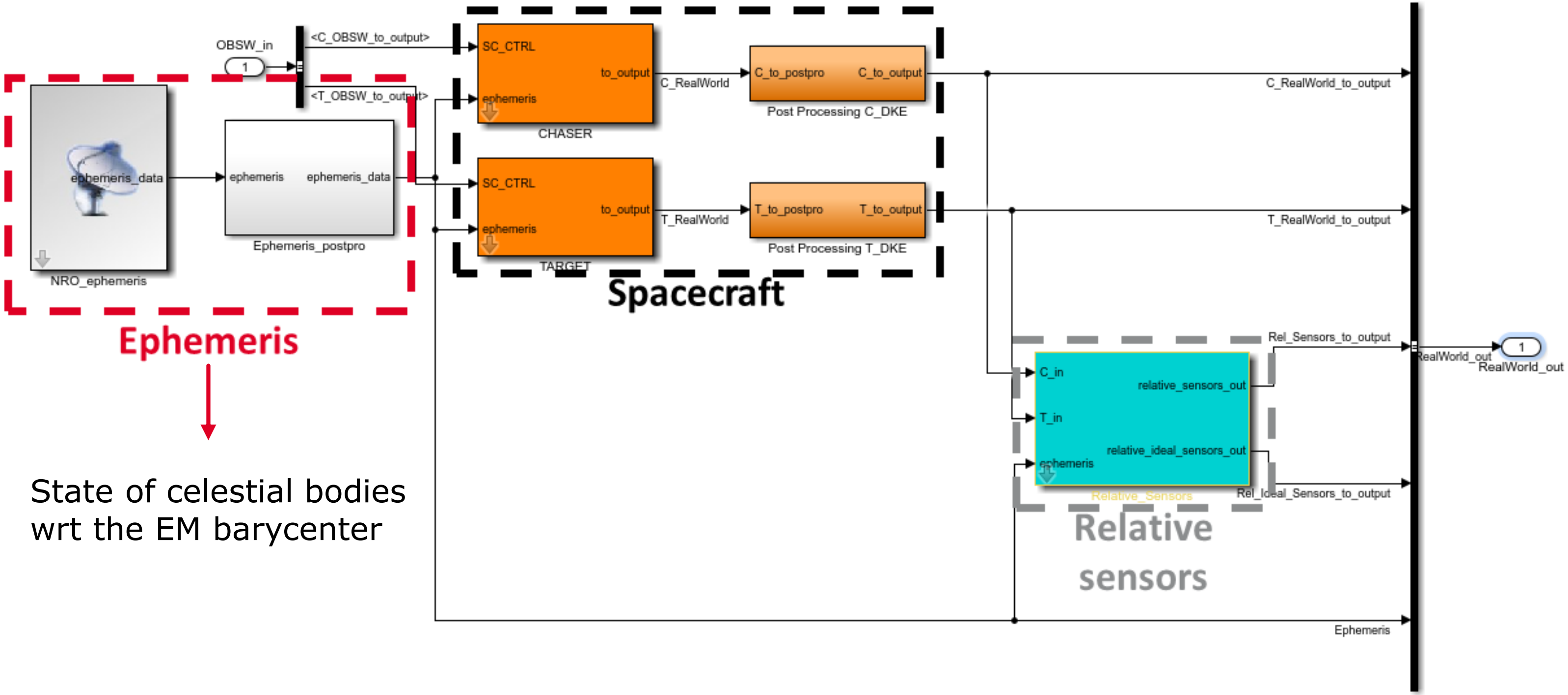
Disturbance

- Sloshing
- SRP
- Lunar gravity
- Grav. Gradient

Inert. Sens.

- IMU
- Star Tracker
- Sun Sensor

Real World



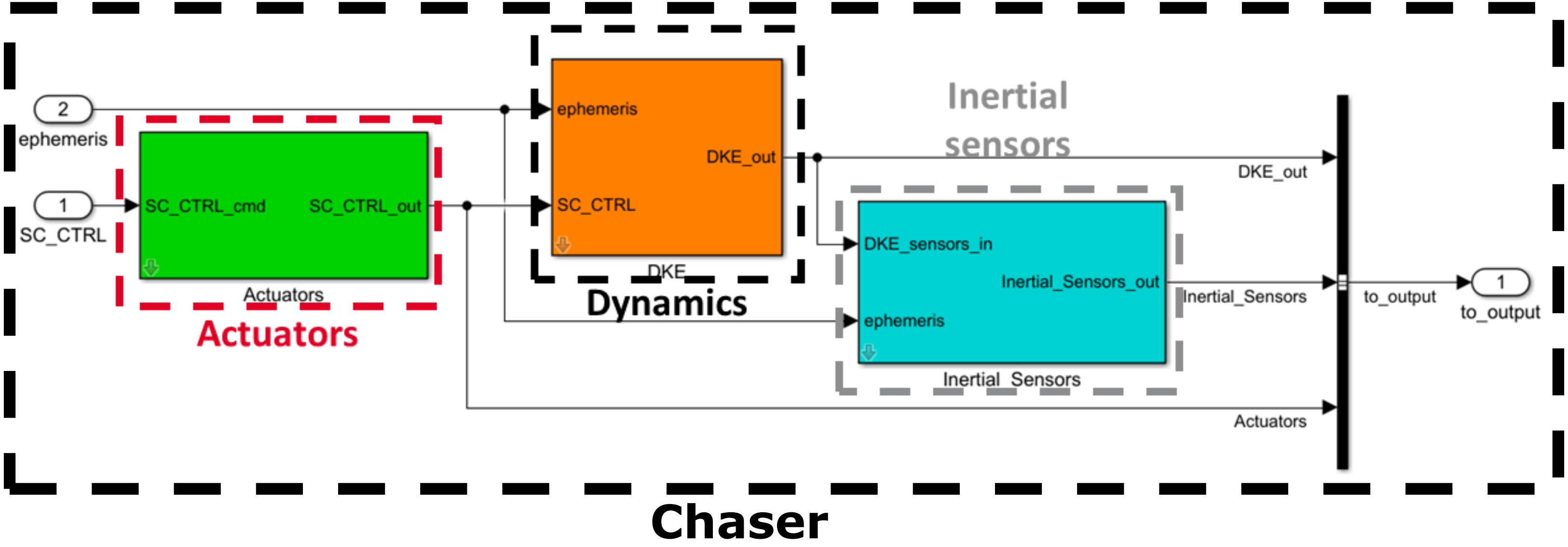
Spacecraft

Ephemeris

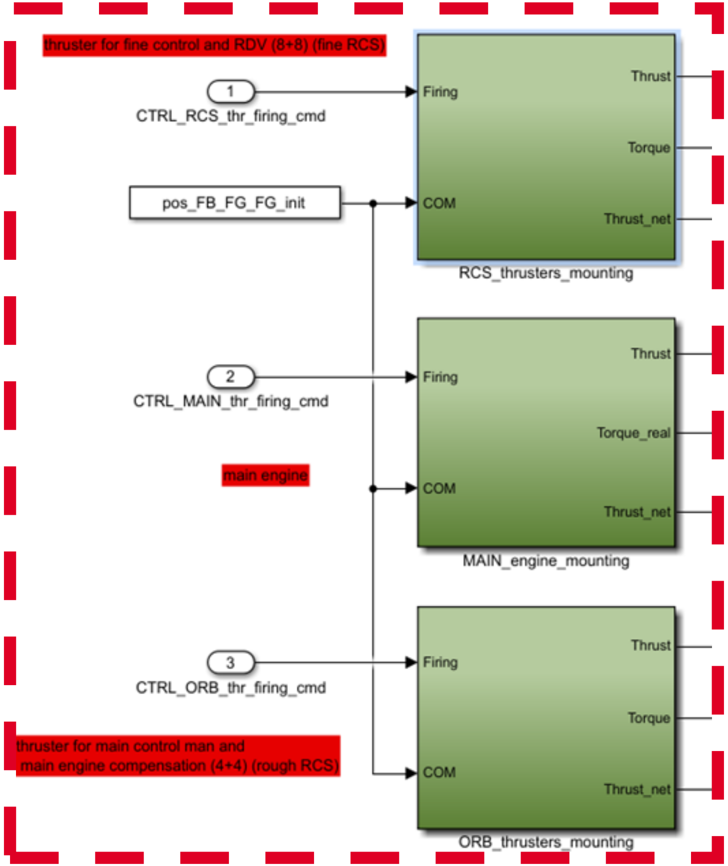
State of celestial bodies wrt the EM barycenter

Relative sensors

Simulator Overview



Actuators



Three sets of thrusters

- Main
- AUX
- RCS

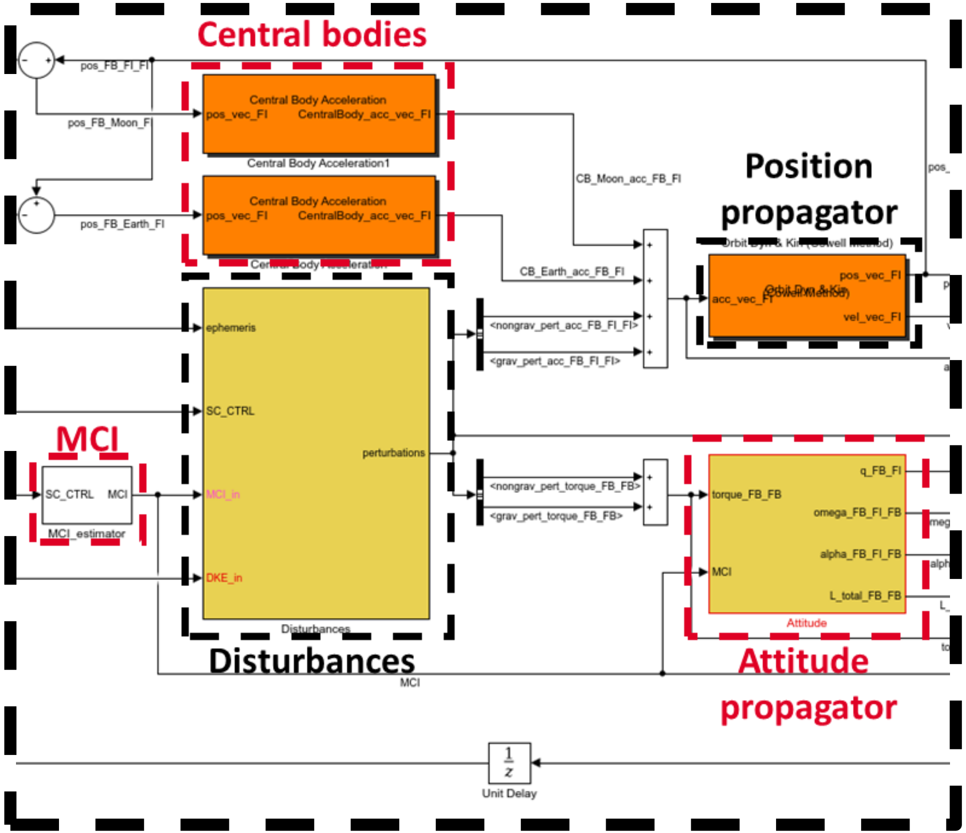
Thruster models

- Individual thruster force and torque
- Sum of all thruster vector for resultant
- Sum of all thruster forces for propellant consumption

Thruster error models

- Misalignment
- Magnitude bias
- Magnitude noise
- MIB
- Rise time and delay

DKE



MCI

- Update of mass, CoM and inertia based on dry values and propellant mass in tanks

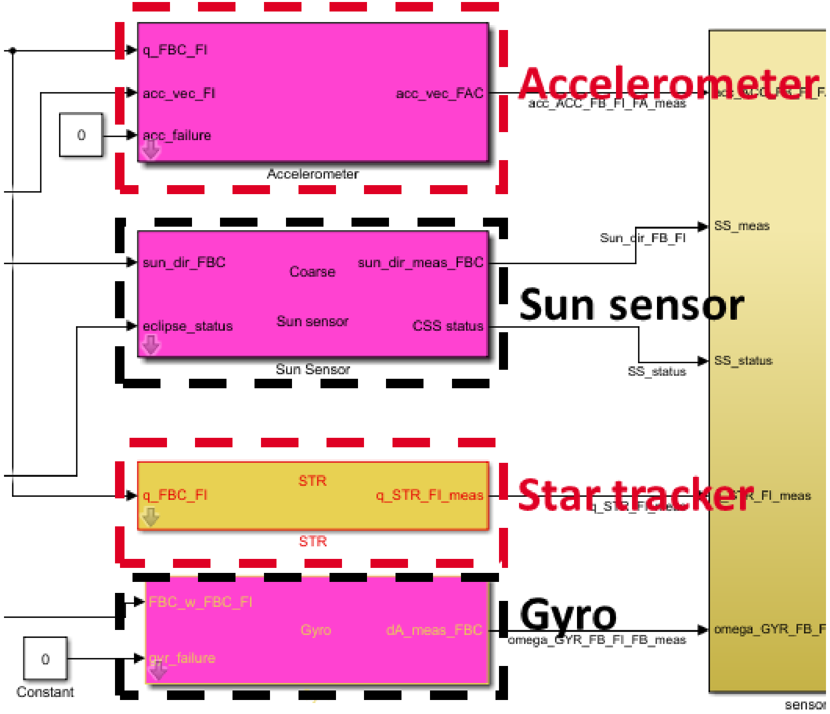
Earth and Moon central forces

Disturbances

- Propellant sloshing
  - Spring-mass-damper for zero/low-g
  - Parameter-evolving sloshing for ascent
- Third body gravity
- SRP
- Lunar gravity model

Attitude and trajectory propagators

Sensors



IMU signal modelling

- Noise
- Random walk
- Misalignment

Sun sensor/Star tracker modelling

- Noise
- Misalignment

Sensor redundancy

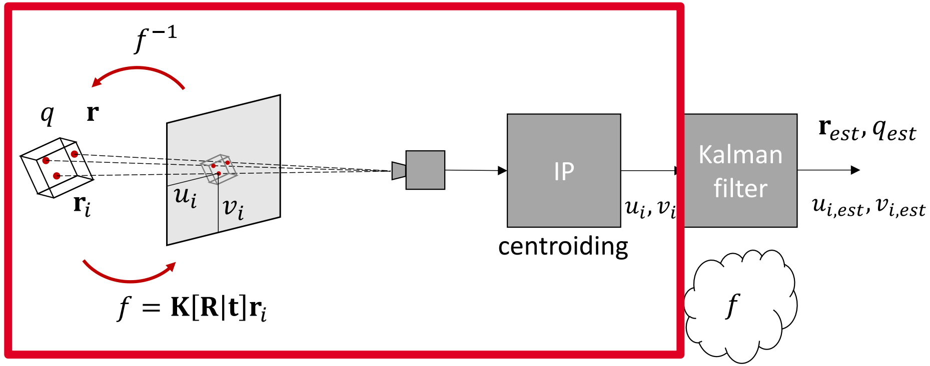
Failure introduction

- Increased noise
- Sensor Dead
- Sensor Locked in Place

Relative Sensors

NAC/WAC + IP models

- Projection of 3D marker positions in camera frame
- Addition of noises and mounting errors
- Pixel position sent to navigation

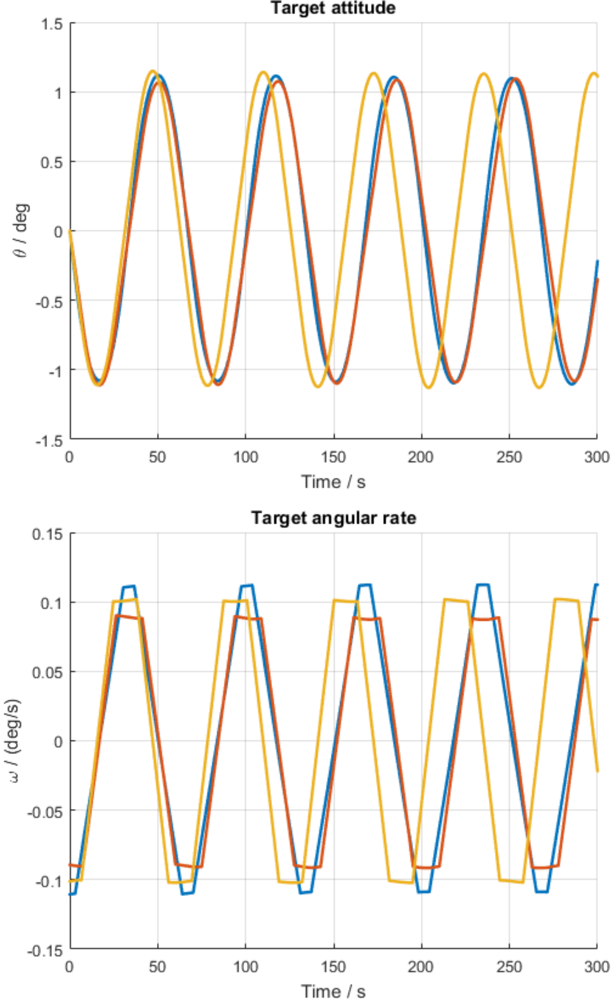


Simulator Overview

Target Attitude Profile

Target Motion for Short Range Rendezvous

- Three independent, small periodic rotations ~1°
- Combination of accelerated and constant angular velocity segments
- Oscillation period of ~60 s
- Amplitude, period and duration of acceleration as tuneable parameters



GNC Design

10:30 – 11:15

- Ascent	10:30 – 10:45
- Orbit transfer	10:45 – 11:00
- Rendezvous	11:00 – 11:15

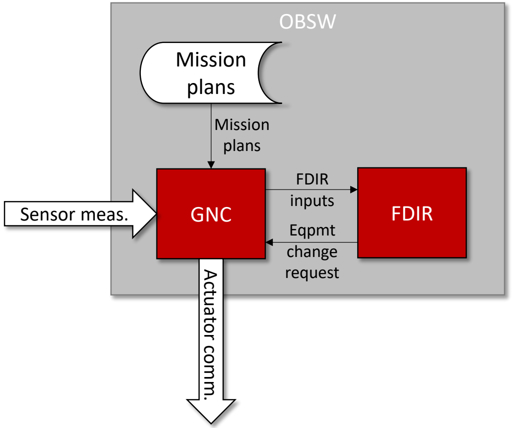
GNC Design

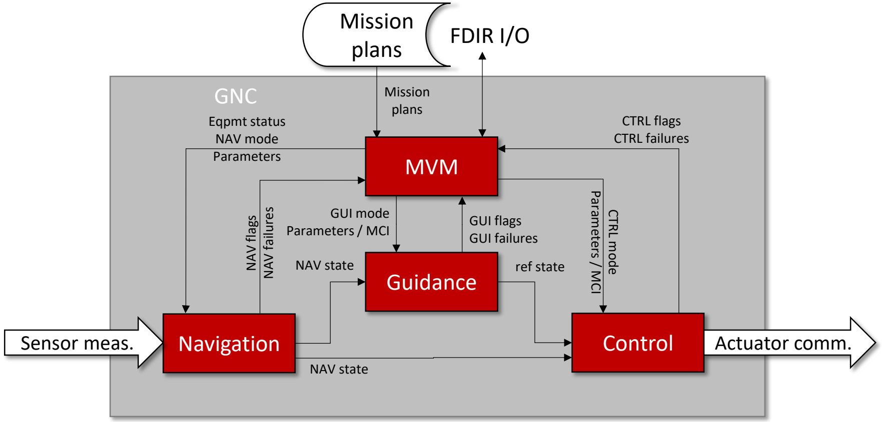
Architecture

GNC consists of:

- MVM
- Navigation
- Guidance
- Control

- FDIR


OBSW
Mission plans
Mission plans
Sensor meas.
GNC
FDIR inputs
Eqpmt change request
FDIR
Actuator comm.


Mission plans
FDIR I/O
GNC
Mission plans
Eqpmt status
NAV mode
Parameters
CTRL flags
CTRL failures
MVM
NAV flags
NAV failures
GUI mode
Parameters / MCI
GUI flags
GUI failures
Parameters / MCI
CTRL mode
NAV state
Guidance
ref state
Sensor meas.
Navigation
Control
Actuator comm.
NAV state

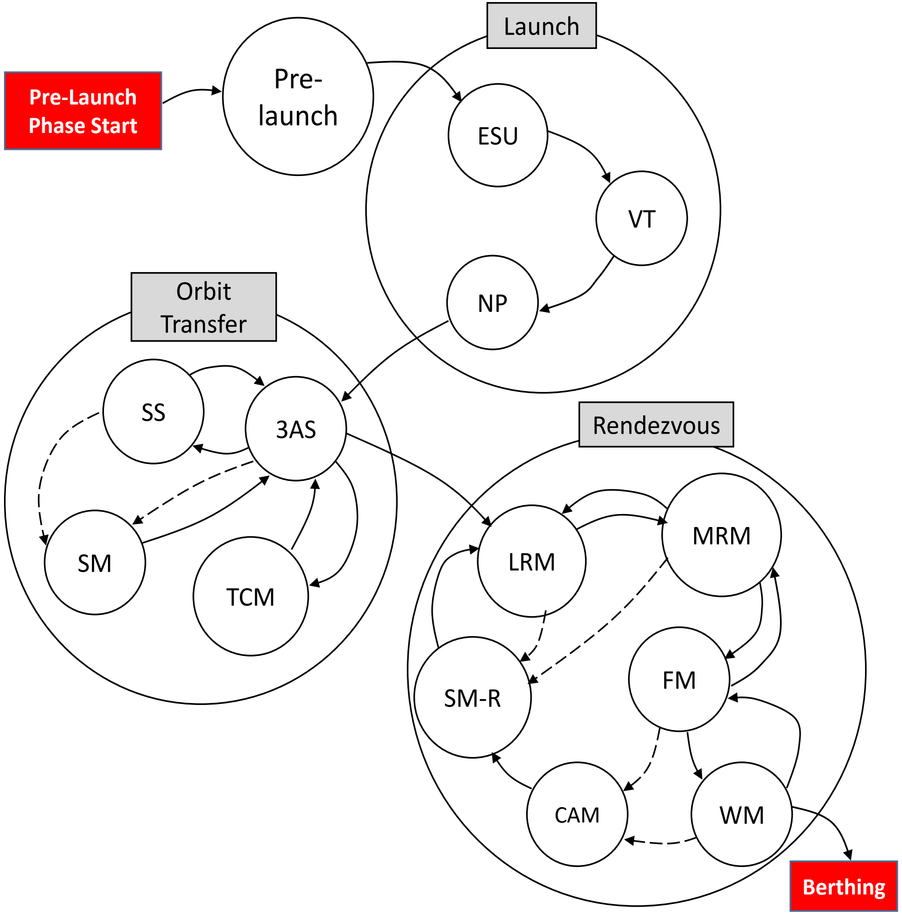
GNC Design

GNC Modes

Launch
- **ESU: engine start-up**
- **VT: vertical trajectory**
- **NP: nominal profile**

Orbit transfer
- **3AS: three-axis stabilized**
- **SS: spin stabilized**
- **TCM: trajectory correction manoeuvre**
- **SM: safe mode**

Rendezvous
- **LRM: long-range mode**
- **MRM: medium-range mode**
- **FM: forced motion mode**
- **WM: waiting mode**
- **CAM: collision avoidance mode**
- **SM: safe mode**



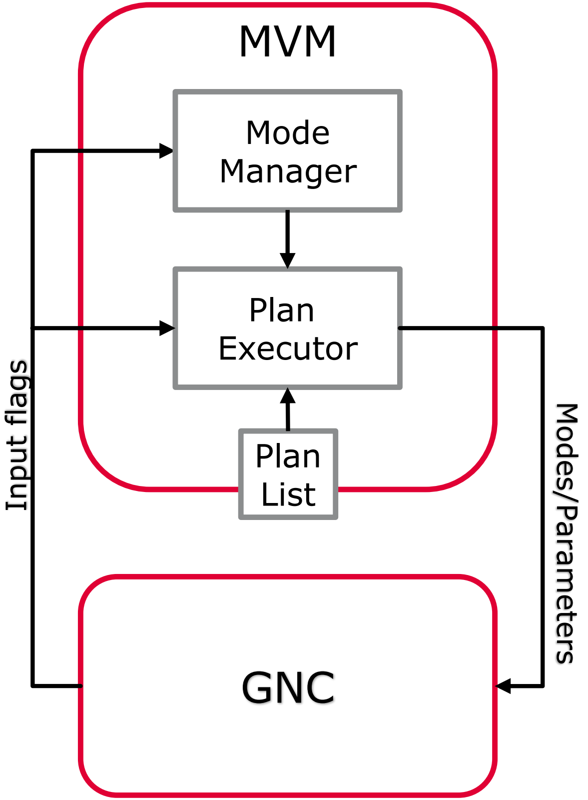
GNC Design

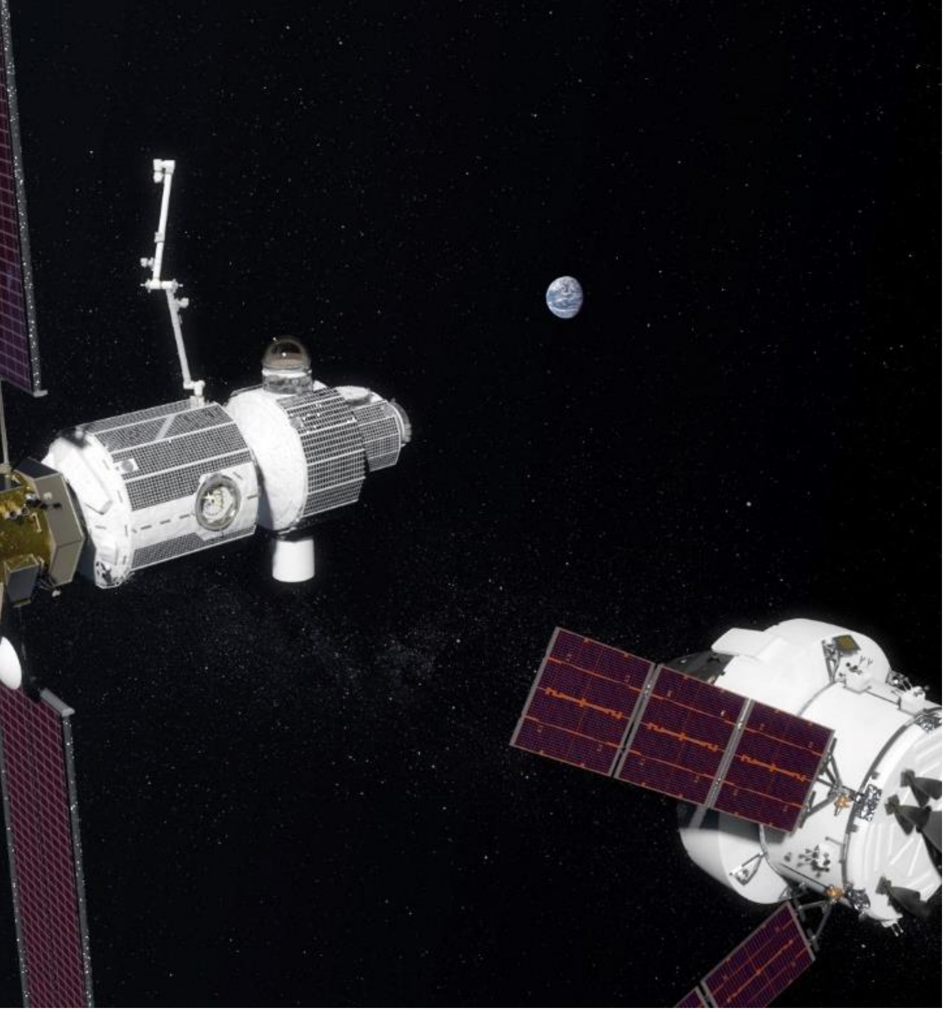
MVM

- ***Plan*** **is a** ***fixed*** **set of instructions (checks and commands) performed** ***sequentially***
- **Each and every** ***mode*** **is characterized by a single** ***plan***
- **In this context,** ***mode*** **≃** ***plan***
- **The** ***plan*** **instructions are executed from start to finish until the plan is completed (or a higher priority command forces a change in mode)**

- **The MVM contains:**
  - Mode Manager: Selects the current GNC mode/plan.
  - Plan executor: Executes the instructions of the current plan. Every plan is contained in the **Plan List**.

- **The MVM also performs signal safety checks:**
  - I/O range checks
  - Timeout check





Ascent

GNC Design
Ascent

Guidance (1/4). Overview

- **Three consecutive phases**

- **Vertical trajectory**
  - Starting leg to avoid obstacles due to specific launch site orography
  - Pre-loaded profile (no corrections from navigation)

- **Pitch Over Maneuver**
  - Rotation of thrust direction at a constant pitch rate with respect to the local horizontal to achieve optimal thrust direction
  - Pre-loaded profile (no corrections from navigation)

- **Powered Flight**
  - Thrust direction rotated by pitch and yaw angles to target the desired transfer orbit
  - Corrections based on navigation data

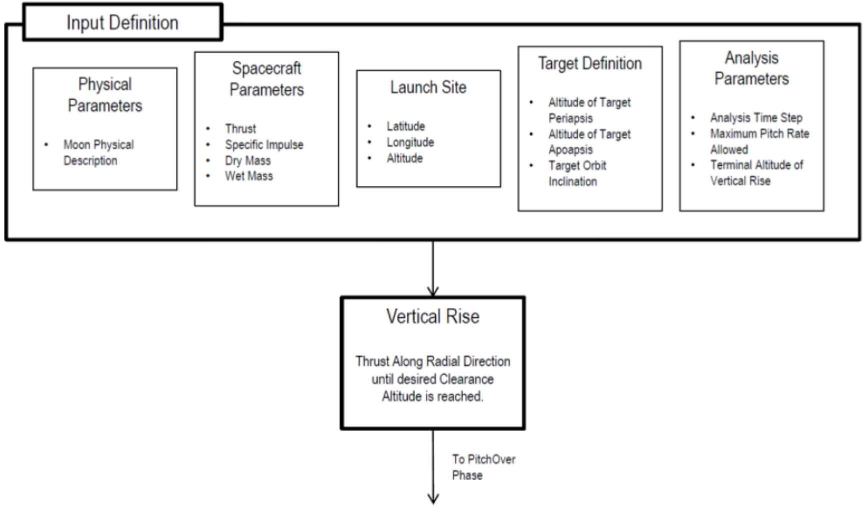
GNC Design
Ascent

Guidance (2/4). Vertical trajectory

Guidance parameters: moon physical description, LAV parameters, launch site, target orbit definition

Guidance takes into account the Moon gravitational field effect (point mass), gravity losses, thrust acceleration, propellant consumption

Vertical Rise duration fixed and completely defined by the input parameters set and altitude limit



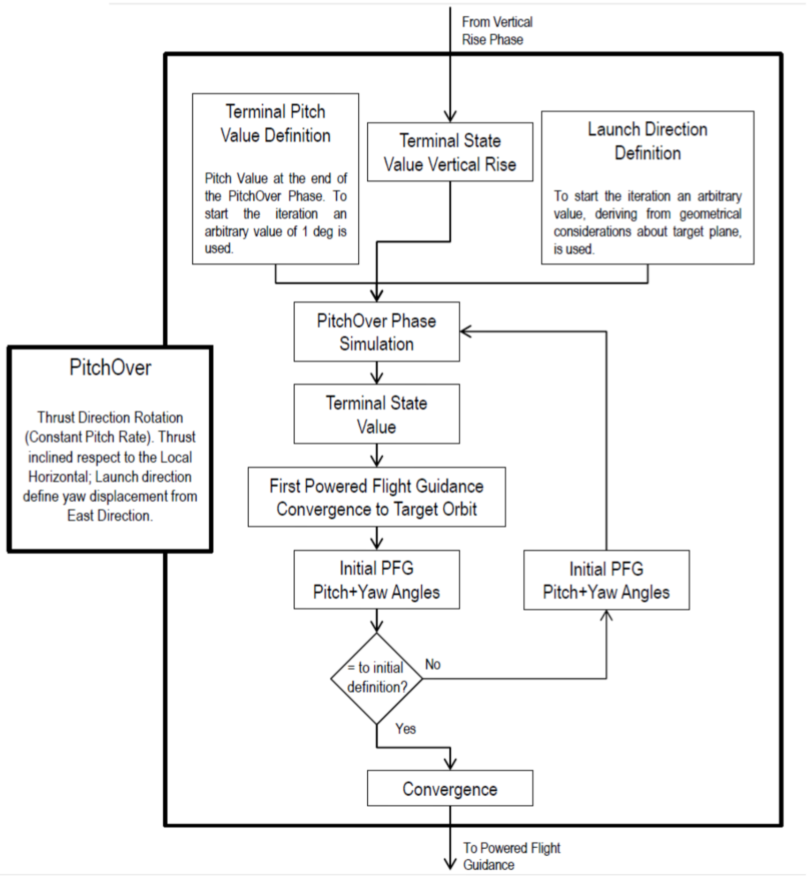
GNC Design Ascent

Guidance (3/4). Pitch Over Phase

Pitch Over Phase duration computed such that terminal attitude is consistent with the initial state of the powered flight guidance phase

Pitch Over Phase constrained by selected pitch rate

Pitch Over Phase duration iteratively corrected until: final pitch angle = optimal pitch angle of Powered Flight Phase



From Vertical Rise Phase

Terminal Pitch Value Definition

Pitch Value at the end of the PitchOver Phase. To start the iteration an arbitrary value of 1 deg is used.

Terminal State Value Vertical Rise

Launch Direction Definition

To start the iteration an arbitrary value, deriving from geometrical considerations about target plane, is used.

PitchOver

Thrust Direction Rotation (Constant Pitch Rate). Thrust inclined respect to the Local Horizontal; Launch direction define yaw displacement from East Direction.

PitchOver Phase Simulation

Terminal State Value

First Powered Flight Guidance Convergence to Target Orbit

Initial PFG Pitch+Yaw Angles

= to initial definition?

No

Yes

Initial PFG Pitch+Yaw Angles

Convergence

To Powered Flight Guidance

GNC Design
Ascent

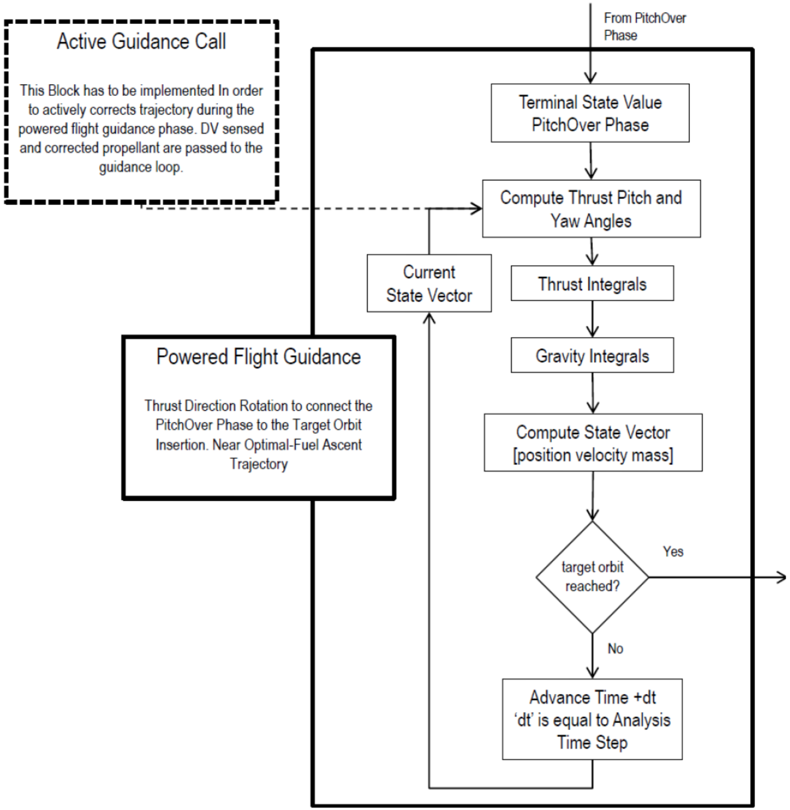
Guidance (4/4)

The algorithm iteratively takes as input the previous state vector (position, velocity and mass) to compute next values of pitch and yaw angles

Once successive Yaw and Pitch angle values are obtained, next state vector is computed

Nominal previous state vector values can be overridden by navigation data

Limitations in angular rate an acceleration can be applied if Yaw/Pitch variations are too large

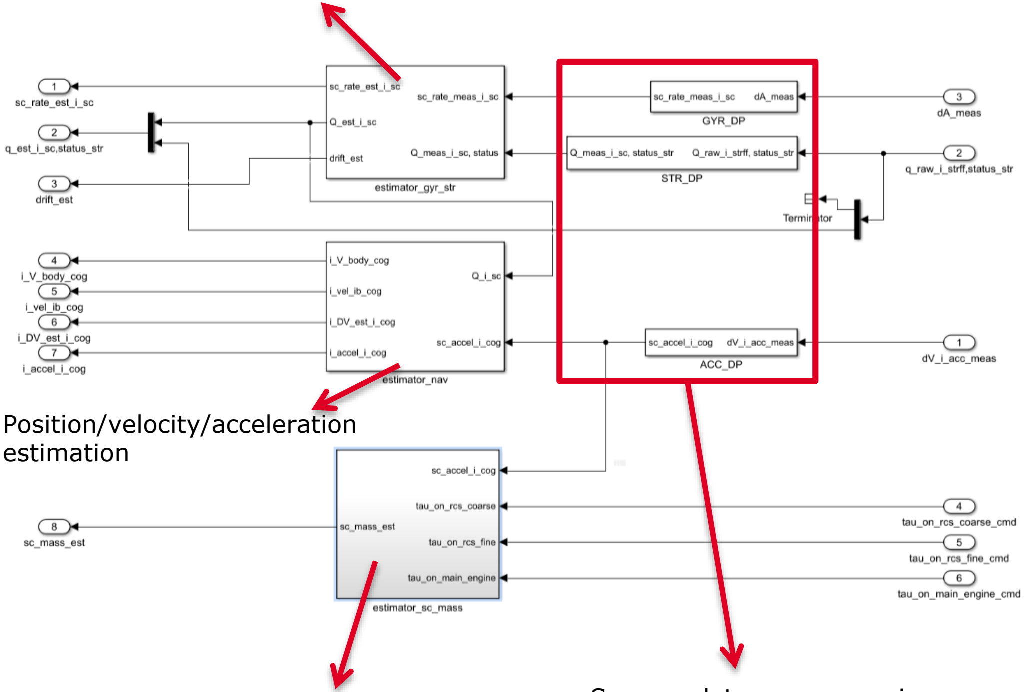


GNC Design Ascent

Navigation (1/2) : Overview

The **ascent navigation function** is composed of :

- **Sensor Data Pre-processing** (accelerometer, gyroscope, STR)
- **Navigation algorithms** (position / velocity / acceleration and attitude navigations)
- **LAE mass estimation** using spacecraft acceleration and thrust applied by the main engine, the RCS coarse and fine thrusters



Attitude estimation

Position/velocity/acceleration estimation

LAE mass estimation

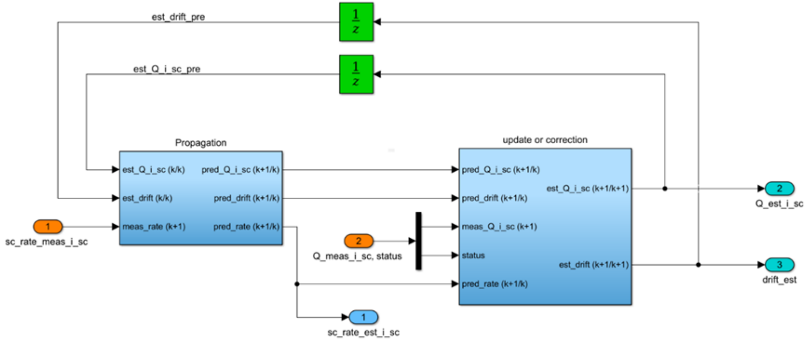
Sensors data pre-processing

GNC Design Ascent

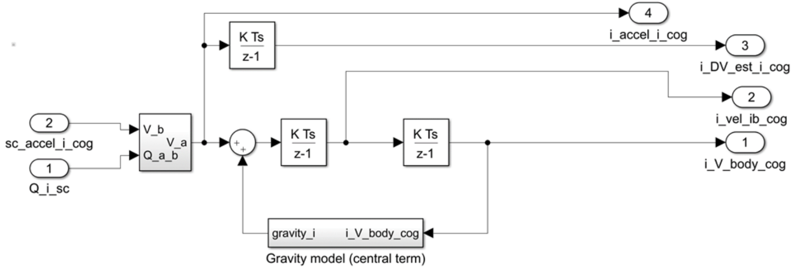
Navigation (2/2) : Navigation algorithms

- **Attitude navigation** is based on a conventional Kalman Filter (KF) with constant gain to estimate the LAE quaternion, inertial angular rates in spacecraft frame and the gyrometer bias.

- **Position/velocity/acceleration navigation** uses a deterministic algorithm, which integrates the acceleration to determine position and velocity. The measured accelerations in LAE body frame are passed to the inertial frame in order to integrate and estimate LAE states using a simplified gravity model of the Moon.



Attitude navigation



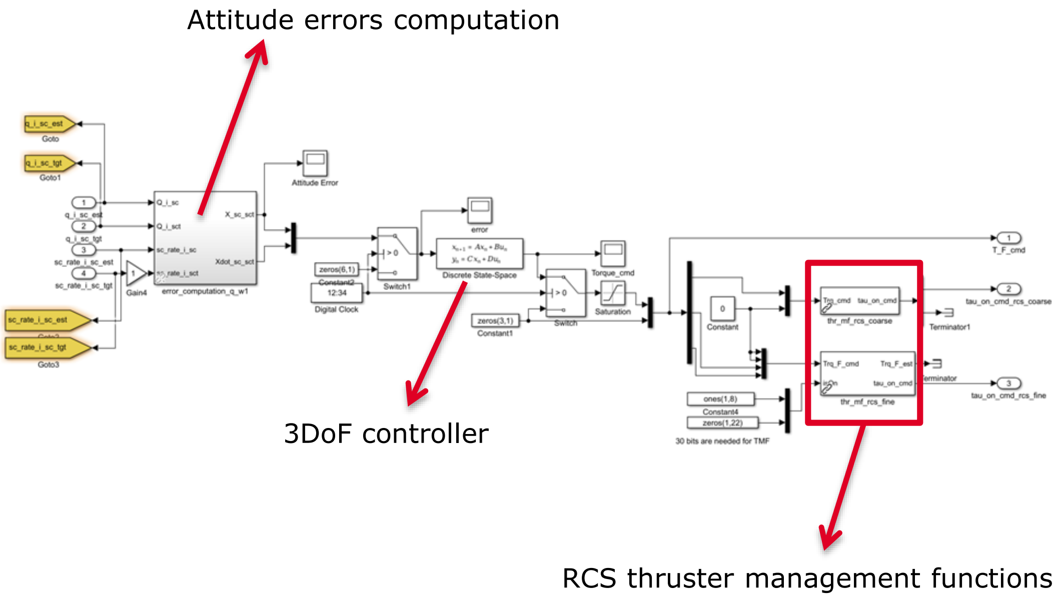
Position/velocity/acceleration navigation

GNC Design Ascent

Control (1/4) : Overview

The **ascent control function** is composed of three sequentially connected functions :

- **Attitude errors computation** (attitude and angular rates)
- **3DoF attitude controller** that computes RCS commanded torques in LAE body reference frame
- **Thruster management functions** (one for coarse and one for fine RCS thrusters) based on Simplex algorithm, which converts the commanded torques in LAE frame to actuation ratio (τ_{ON}) to be realized by the RCS thrusters


Attitude errors computation

3DoF controller

RCS thruster management functions

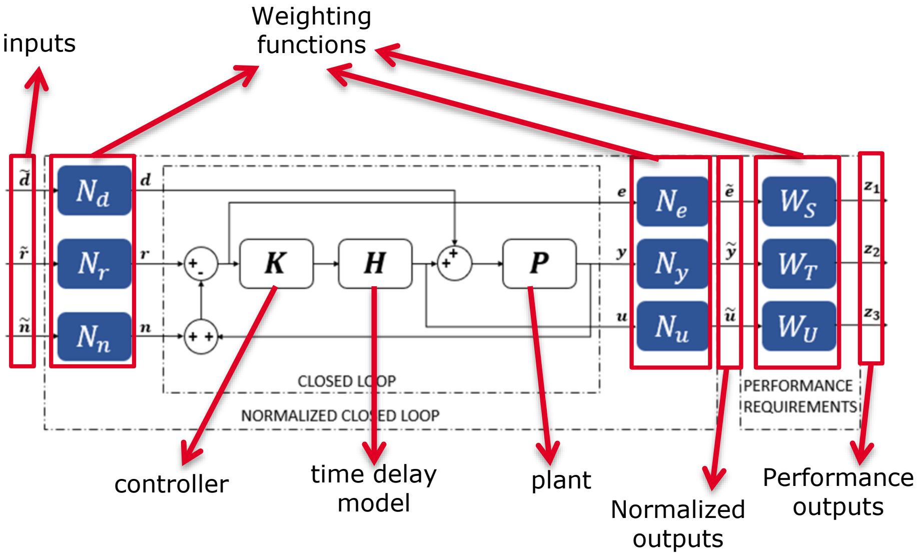
GNC Design Ascent

Control (2/4) : Controller design & synthesis

Ascent controller is composed of 6 inputs (attitude and rate) and three outputs (torques) :

- Controller design is based on **structured $\boldsymbol{H\infty}$** control approach based on **loop-shaping** technic

- Controller synthesis performed :
  - With model uncertainties : actuation time delay within [0 – 0.2] sec, fuel mass of the system within [42 – 98] % of total fuel mass (636 kg)
  - Using an LFT model of the LAE 6DoF mass-variable dynamic model (including transversal sloshing)

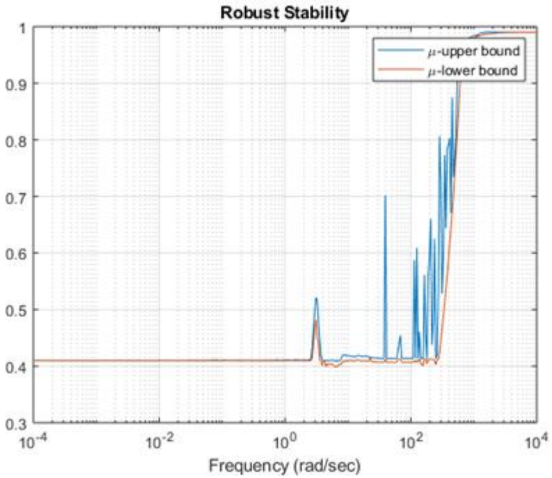


GNC Design
Ascent

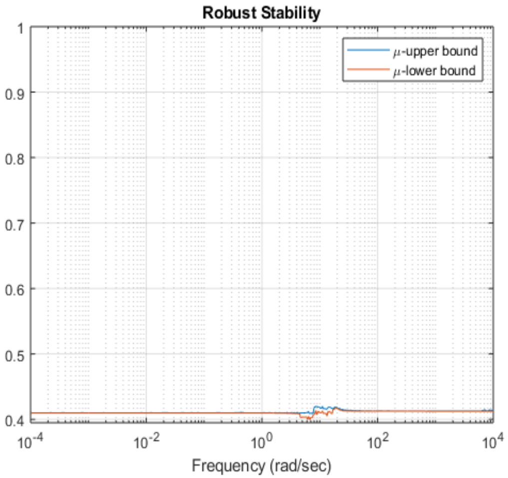
Control (3/4) : Robust stability

Robust stability based on μ-analysis :

- **With time delay model** : the peak value is **0.99** (current uncertainties could be increased in norm by 1%)



- **Without time delay model** : the peak value is **0.42** (current uncertainties could be increased in norm by 132%)

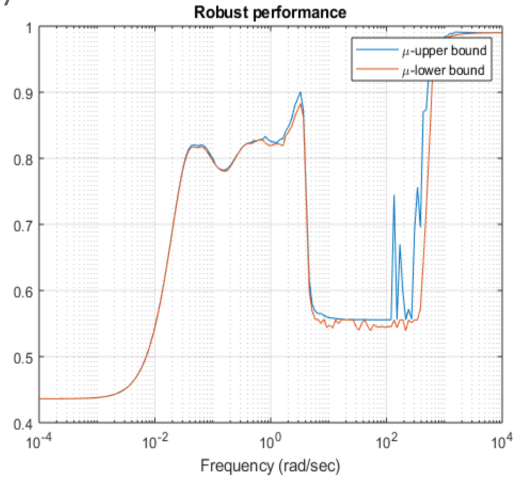


GNC Design
Ascent

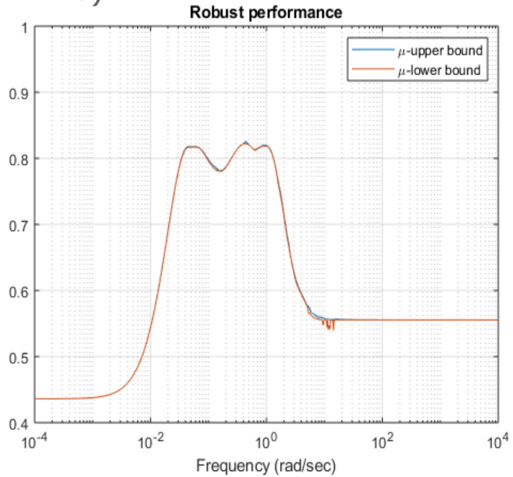
Control (4/4) : Robust performances

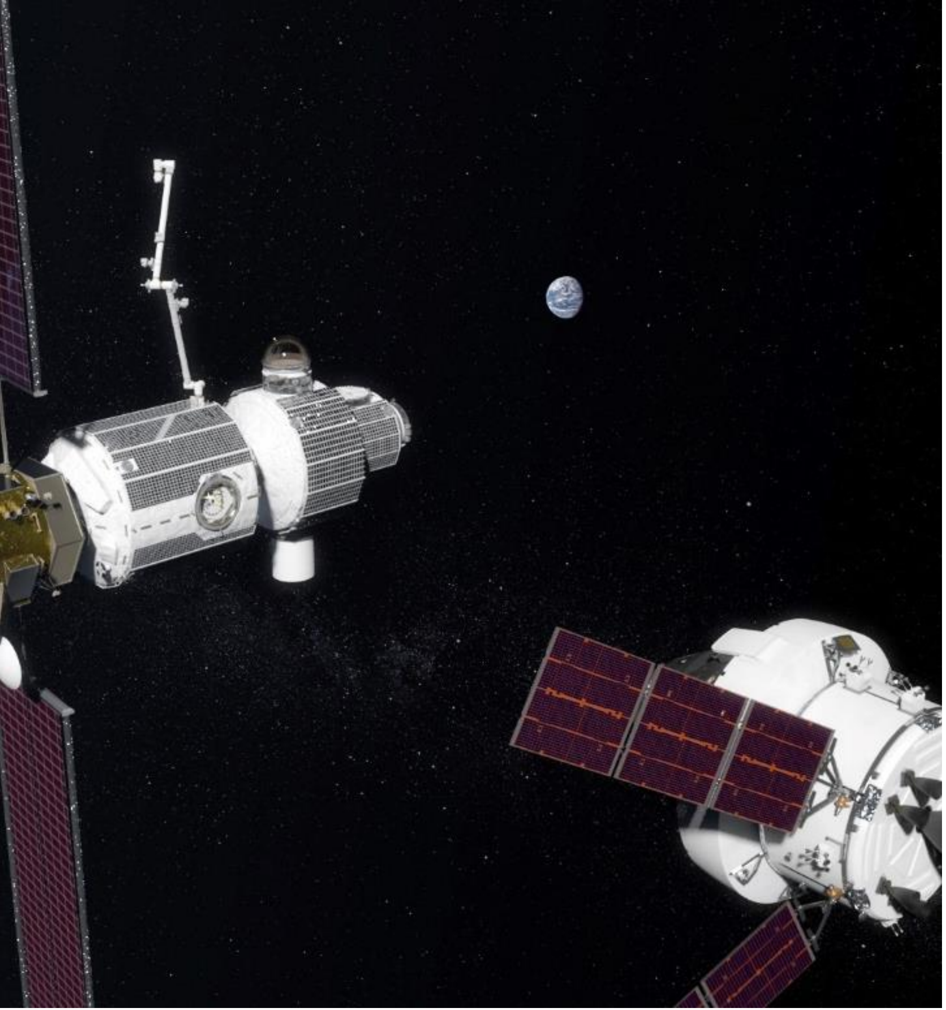
Robust performances based on μ-analysis :

- **With time delay model** : the peak value is **0.99** (current uncertainties could be increased in norm by 1%)



- **Without time delay model** : the peak value is **0.82** (current uncertainties could be increased in norm by 21%)





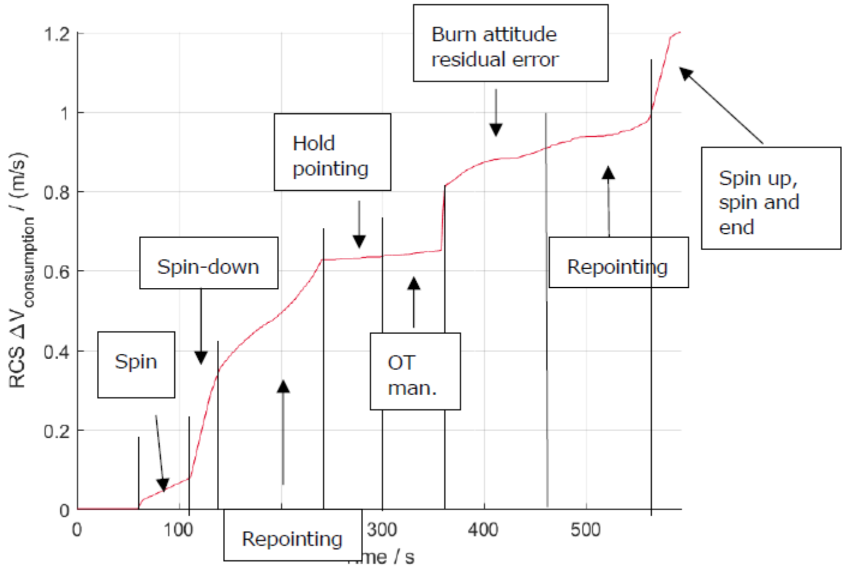
Orbit transfer

GNC Design

Orbit transfer manoeuvres

General sequence of operations for manoeuvres:

- Despin
- Re-orient (align thrusters with desired ΔV)
- Perform burn
- Tranquilize
- Re-orient (point to spin direction)
- Spin-up



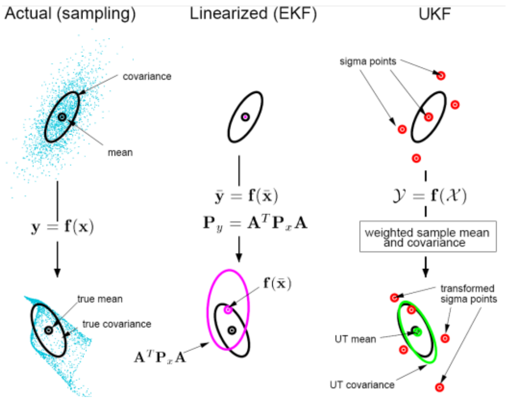
GNC Design

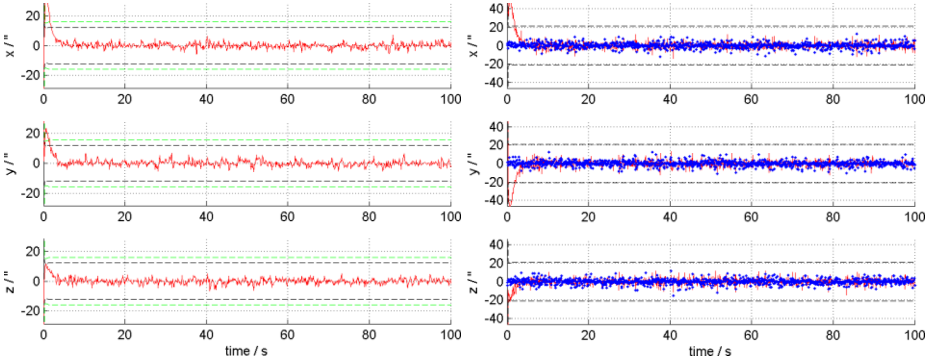
navigation

USQUE attitude navigation based on

- Star tracker measurements
- IMU measurements

USQUE is an unscented filter, sampling covariance matrix for propagation and observation





GNC Design

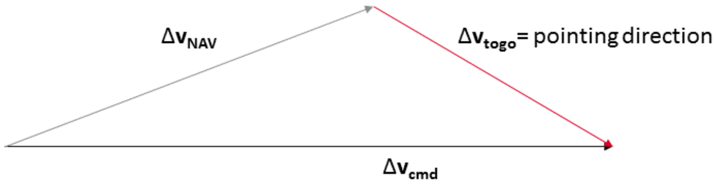
orbit transfer guidance

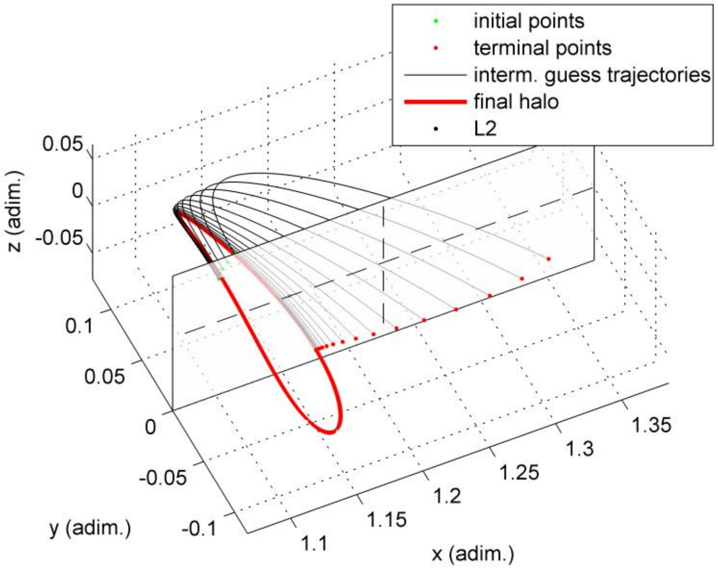
First guess based on (two-body) Lambert algorithm

Differential correction to generate final transfer

- Requires integration of variational equations
- Requires about 8 iterations to converge

Burn performed as inertially oriented manoeuvre





GNC Design

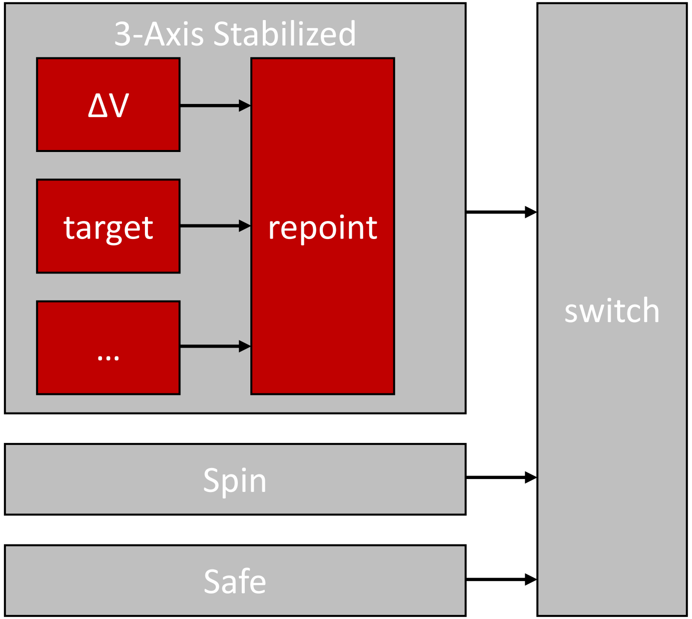
orbit transfer guidance

Attitude guidance algorithms

- Steady state spin axis guidance
- Spin axis repointing
- Spin-up guidance
- Spin down guidance
- Two axis pointing guidance
- Re-orientation guidance
- De-tumbling guidance
- Burn guidance

Attitude guidance consists of:

- Pointing functions (pointing to a specific direction)
- Attitude manoeuvring functions (manoeuvre between specific pointing directions)



Control Design: Orbit Transfer & Rendezvous

Modes

Orbit transfer phase

- **3 Axis Stabilized**
  - 3 DoF control for tracking a reference attitude profile (achieve desired pointing after burn).
  - Actuators: RCS thrusters (Torque)
- **Spin Stabilized**
  - For orbital manoeuvres where the spacecraft is spinning about its Z-axis
  - Control the attitude: orientation of the spin axis
  - Actuators: RCS thrusters (Torque)
- **TCMC (Burn)**
  - 3 DoF control to tackle the transfer from LLO to NRO and orbit circularization.
  - Actuators: auxiliary and RCS thrusters (Torque)

Rendezvous phase

- **3 Axis Stabilized**
  - 3 DoF control for tracking a reference attitude profile
  - Long and Medium range control
  - Actuators: RCS thrusters (Torque)
- **FMC**
  - 6 DoF control for tracking a reference profile specially designed for proximity manoeuvres during rendezvous.
  - Focus on correction of disturbances and uncertain Dynamics.
  - Actuators: RCS thrusters (Force and Torque)

Control Design: Orbit Transfer & Rendezvous

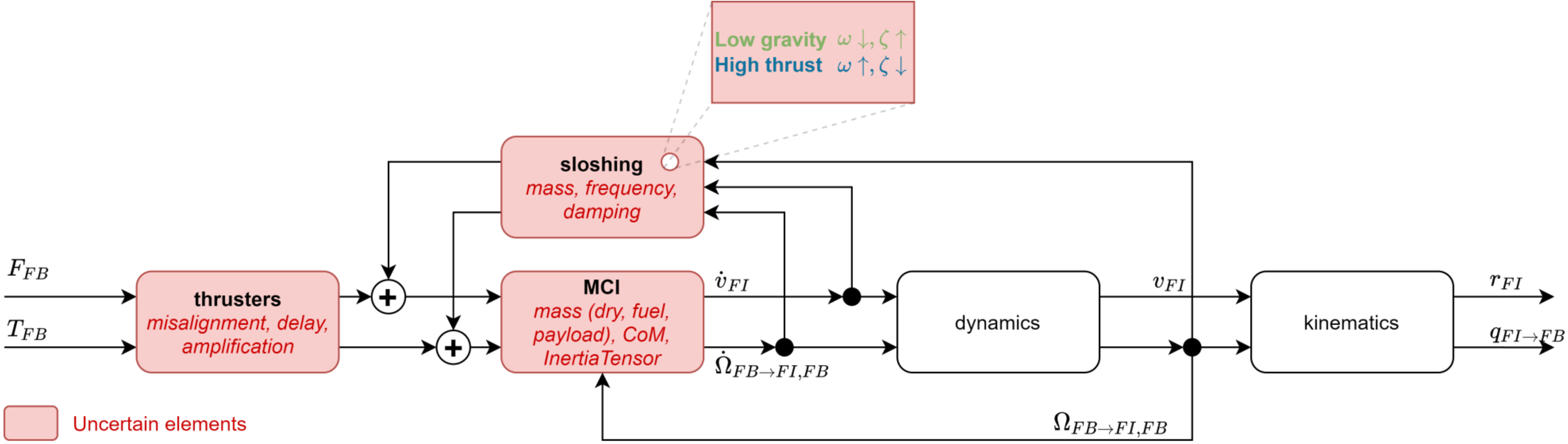
Plants & Uncertainty

Orbit transfer phase

- 3 Axis Stabilized
- Spin Stabilized
- TCMC (Burn)

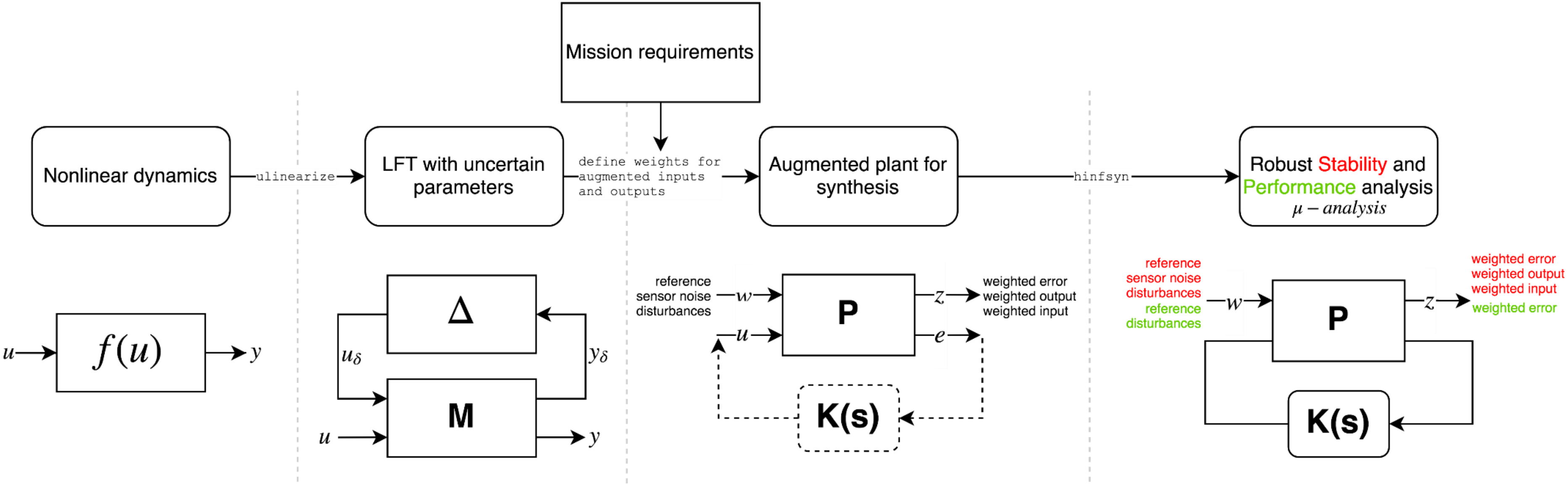
Rendezvous phase

- 3 Axis Stabilized
- FMC



Control Design: Orbit Transfer & Rendezvous

Synthesis & Analysis



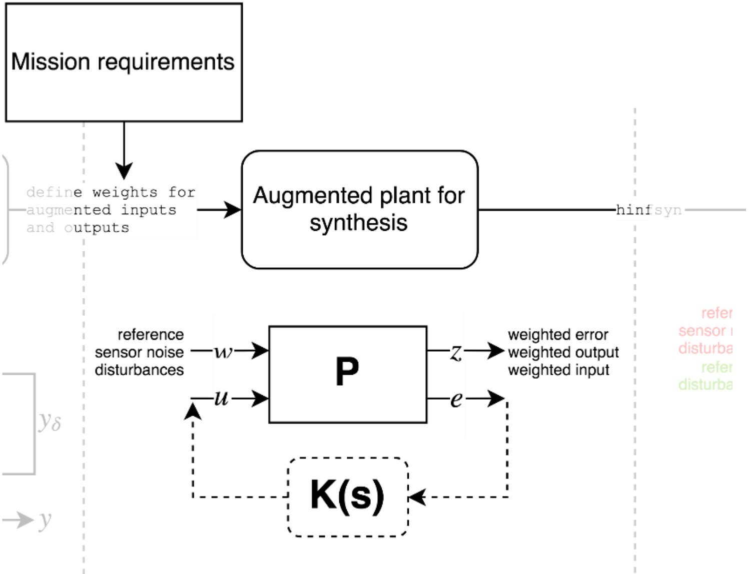
Mission requirements

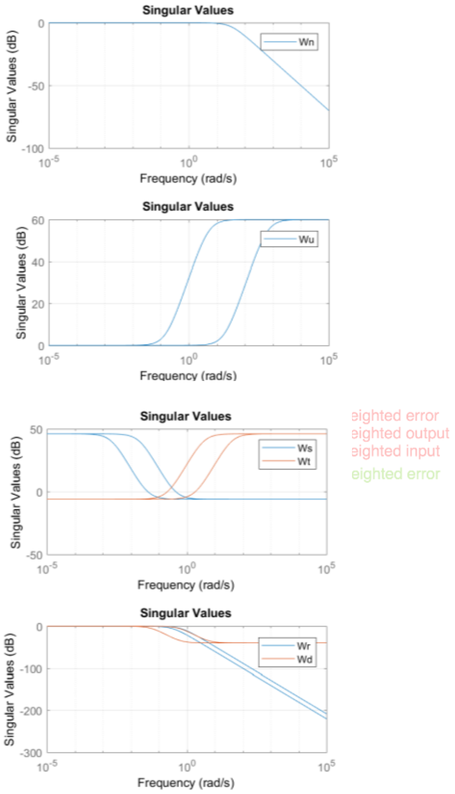
Nonlinear dynamics → ulinearize → LFT with uncertain parameters → define weights for augmented inputs and outputs → Augmented plant for synthesis → hinfsyn → Robust Stability and Performance analysis $\mu - analysis$

Control Design: Orbit Transfer & Rendezvous

Synthesis & Analysis

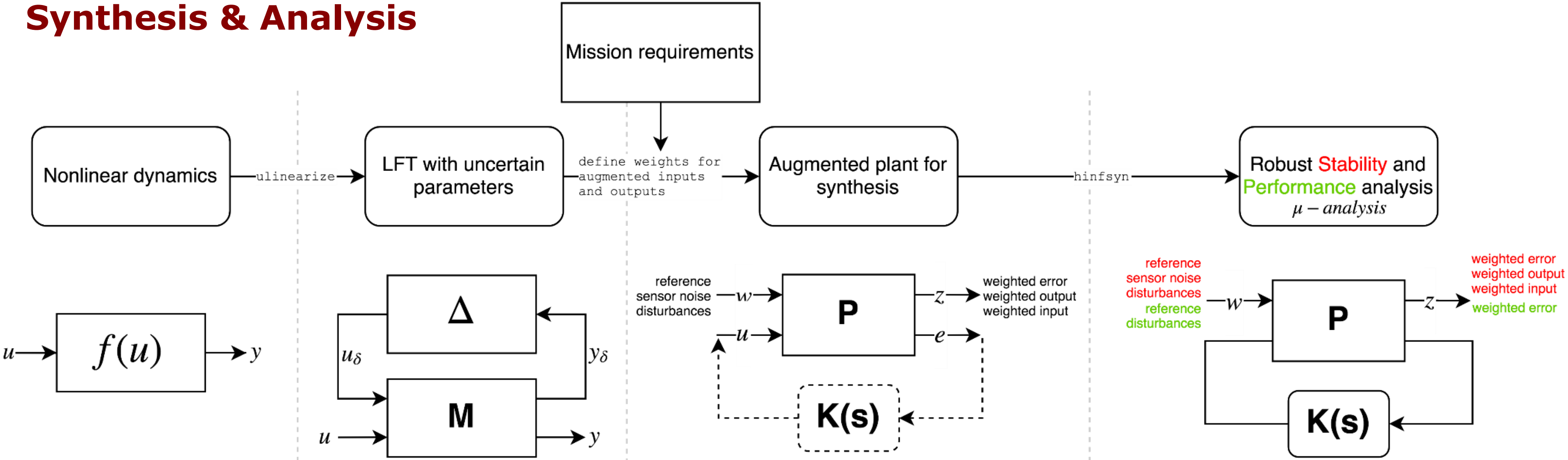
	LF gain	HF gain	Nat. Freq.	Type
$W_S(s)$	Desired tracking	Limit overshoot	Close loop time constant	LP filter
$W_T(s)$	$S+T=1$	Sensor noise rejection	$S+T=1$	HP filter
$W_u(s)$	1	HF control rejection	Control bandwidth / noise frequencies	HP filter
$W_d(s)$	1	$\ll 1$	Model known disturbances	LP filter
$W_r(s)$	1 (tracking)	High attenuation	$>w_S$	LP filter
$W_n(s)$	Power spectral density of measurement noise			LP filter





Control Design: Orbit Transfer & Rendezvous

Synthesis & Analysis



Mission requirements

Nonlinear dynamics

`ulinearize`

LFT with uncertain parameters

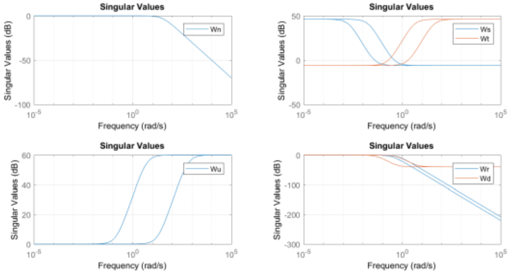
`define weights for augmented inputs and outputs`

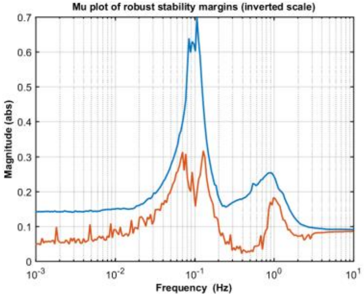
Augmented plant for synthesis

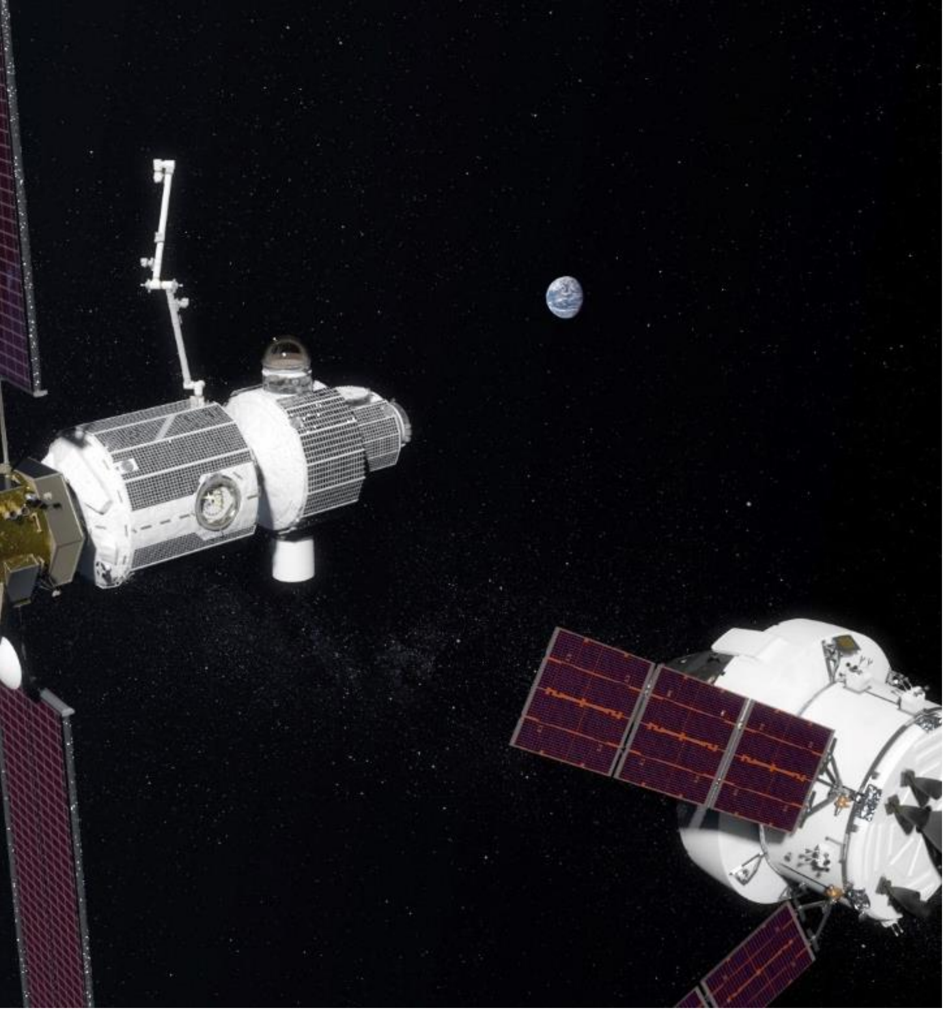
`hinfsyn`

Robust Stability and Performance analysis

$\mu - analysis$







Rendezvous

GNC Design

Rendezvous overview

Hold points

S1.1: 150 km, in LVLH

S1.2: 19 km, in LVLH

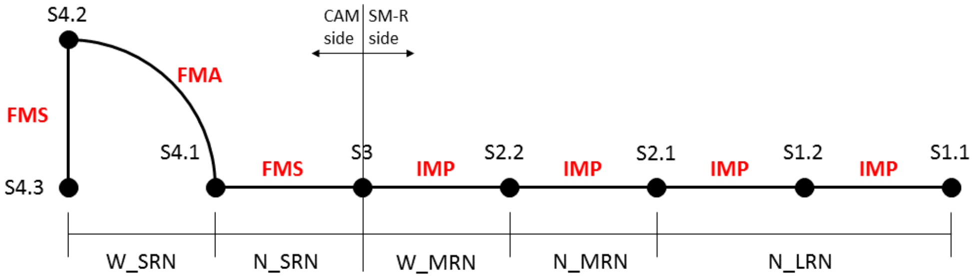
S2.1: 4.5 km, in LVLH – switch to MBT

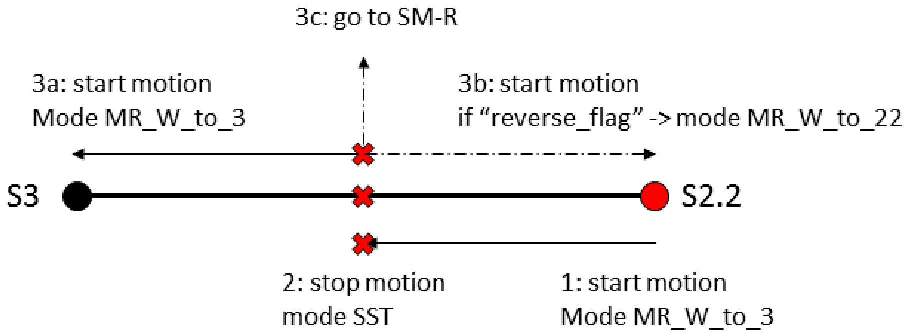
S3: 200 m, in LVLH – switch to SRN

S4.1: 35 m – switch to body frame

S4.2: 35 m

S4.3: 5 m (berthing)





NRO-GNC

long- and medium range navigation

Behavioural models used for long- and medium-range navigation

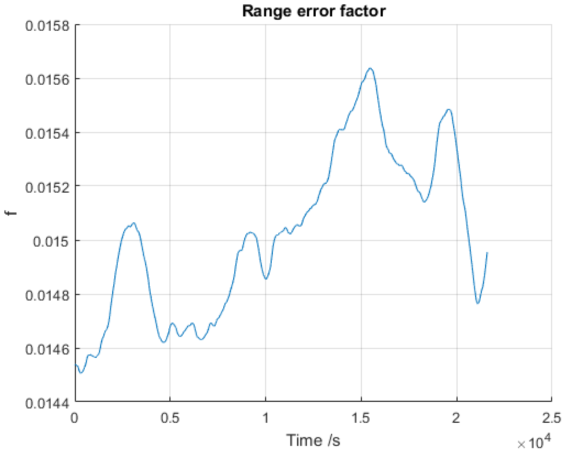
Long-range model:

- **Separate error models for range and direction**

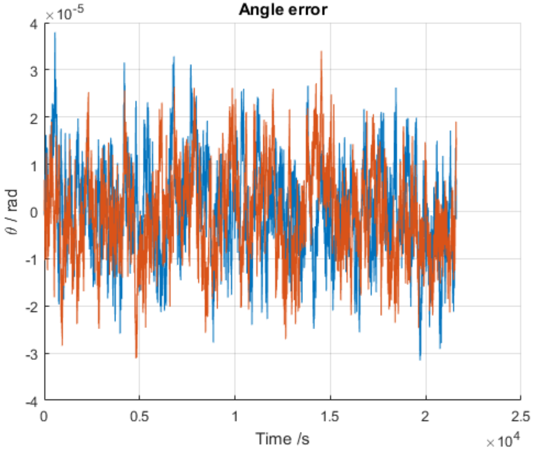
Medium-range model:

- **Short-range navigation used as stand-in**

Both long- and medium-range navigation are subjects of other studies currently being performed



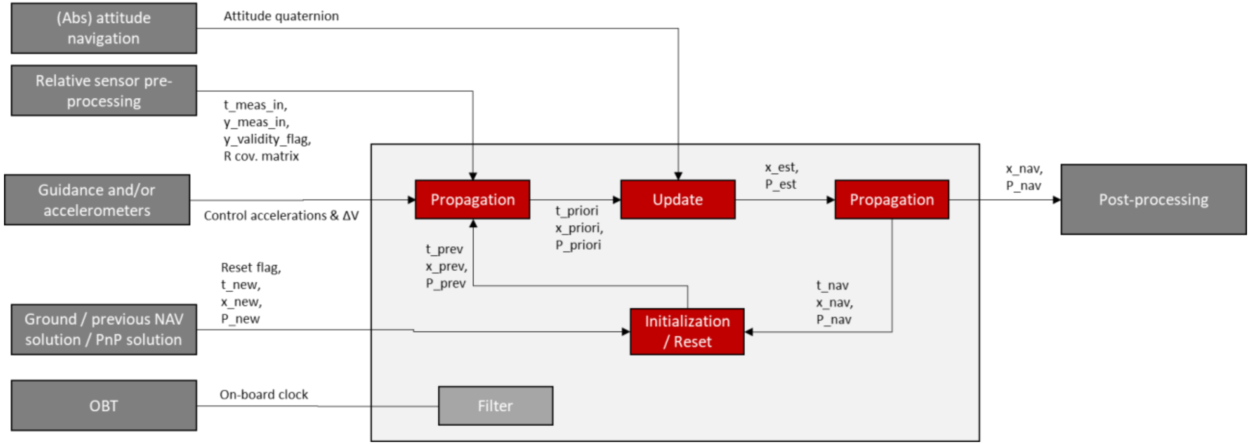
Range error factor



Angle error

GNC Design

Short-range navigation



Initialization/Reset function: containing initial condition for filter algorithm starting

- initial state estimate;
- initial state estimate covariance;
- time of initial estimate

Propagation function: performing Time Update, which means:

- propagating previous state estimate to next time step, thus computing a-priori state estimate;
- propagating previous state estimate covariance to next time step, thus computing a-priori covariance matrix;

Update function: performing Measurement Update, which, in terms of standard filtering algorithms, which means:

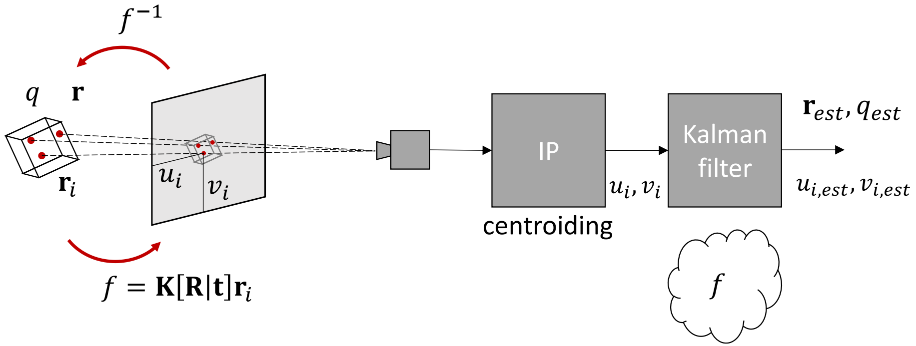
- generating a-priori measurements, through usage of internal sensors model of the filter;
- computing residuals, as difference from real-world measurements and a-priori measurements;
- computing Kalman gain;
- updating state estimate, mixing residuals update information (coming from the measurements) and a-priori state estimate (coming from the propagation) by a Kalman gain weighted sum;
- updating state estimate covariance matrix

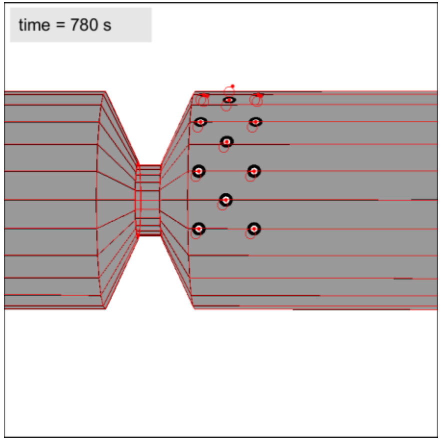
GNC Design

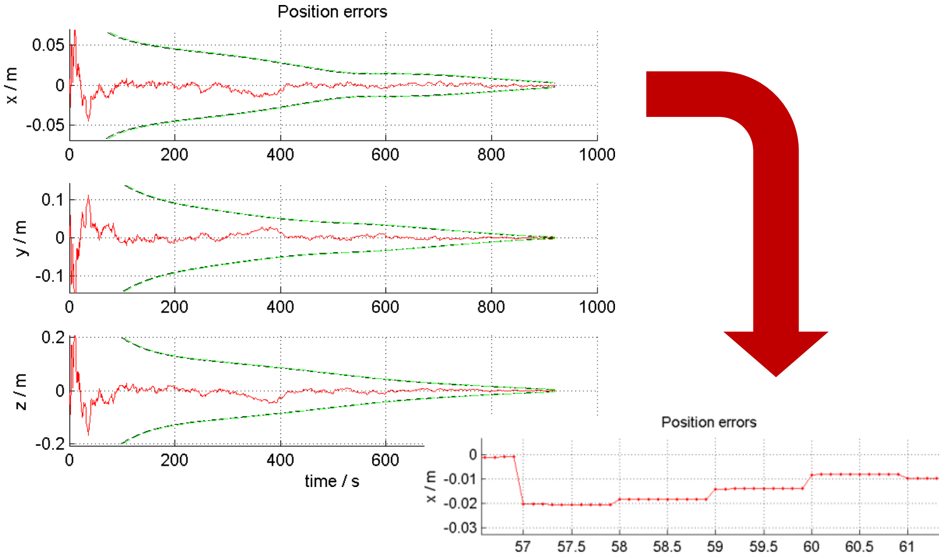
Short-range navigation

Short-range marker tracking navigation
Camera measurements:

- IP performs centroiding & navigation tracks markers individually
- Delay of 1 s for image processing incorporated
- Camera + IP assumed to work at 1Hz







GNC Design

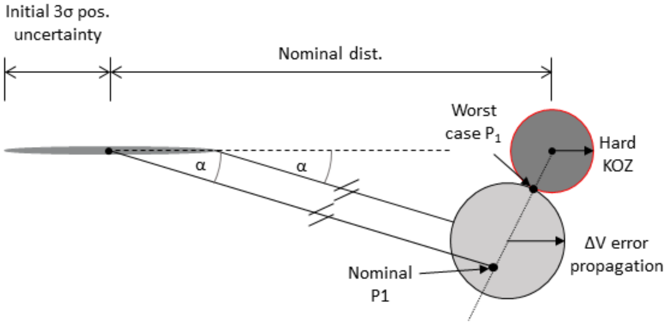
Impulsive rendezvous guidance

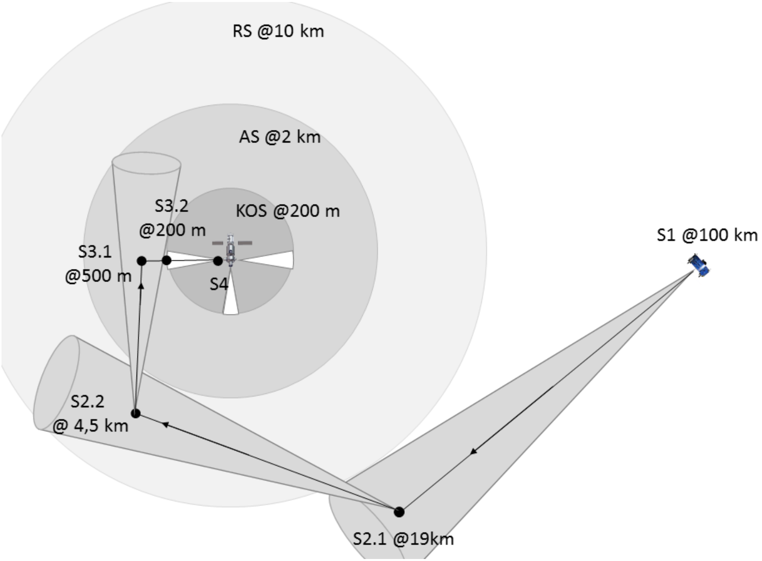
“Tacking” strategy: straight-line manoeuvres intentionally miss target

- Increased safety
- Improved navigation (observability)
- Reduced plume impingement

Fast manoeuvres compared to orbital period

- Effect of dynamics negligible: straight-line
- Unmodelled dynamics, navigation errors and manoeuvre execution errors absorbed in safety cone

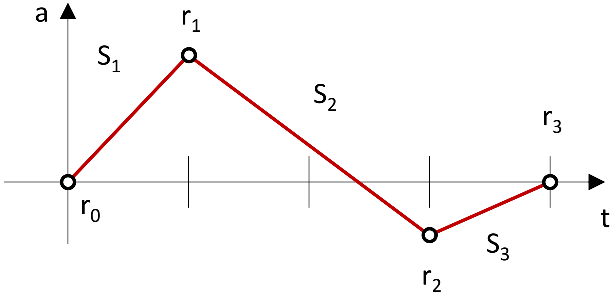


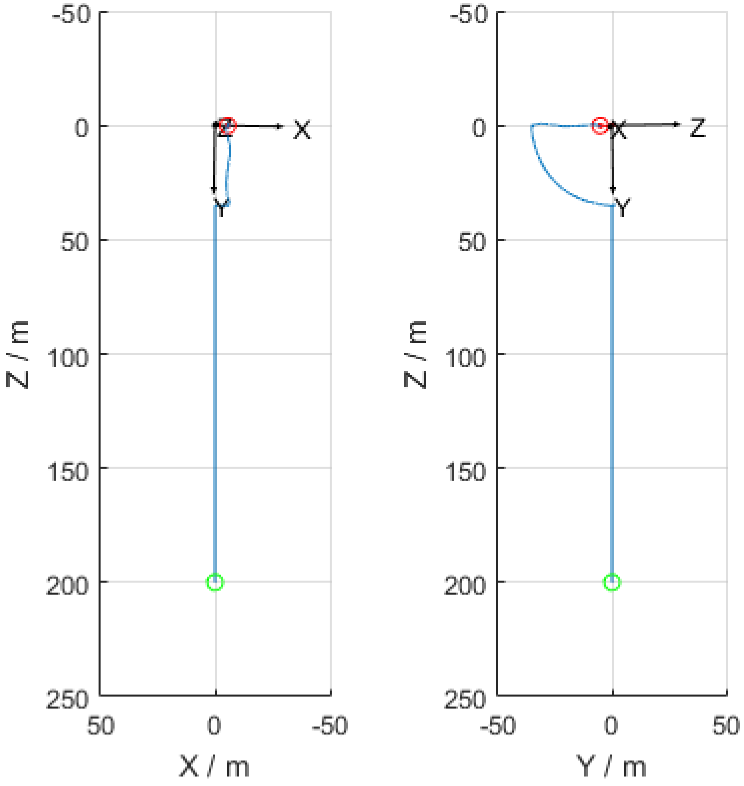


GNC Design

Forced motion guidance

- Smooth profiles without discontinuities in acceleration
- Fly-around guidance to perform fly-around in circular arc
- Manoeuvres in LOP-G body frame: Conversion of position, velocity and acceleration by differentiation of frame transformation equations

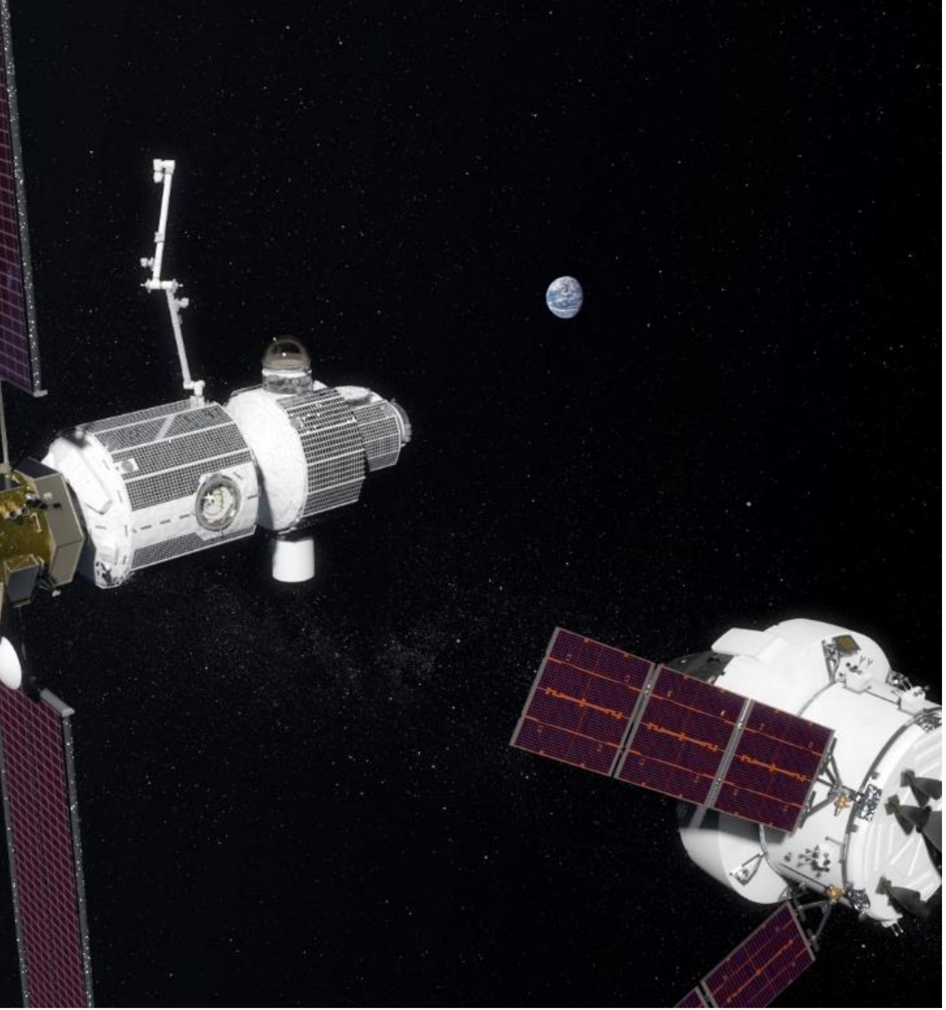




MIL & PIL testing

11:15 – 12:00

- Ascent	11:15 – 11:30
- Orbit transfer	11:30 – 11:45
- Rendezvous	11:45 – 12:00



Ascent

MIL & PIL testing. Ascent

MIL testing. Nominal case

Guidance parameters

- First Vertical Rise Limit: 20 [m]
- Altitude of Target PeriApsis: 30 [km]
- Altitude of Target ApoApsis: 100 [km]
- Target Orbit Inclination: 80 [deg]
- Maximum Angular rate during pitchover: 1.5 [deg/s]
- Maximum Angular rate after pitchover: 10 [deg/s]
- Maximum Angular acceleration: 1.6 [deg/s2]
- Threshold on inclination for ascent completion: 0.1 [deg]
- Threshold on perigee height for ascent completion: 3000 [m]
- Threshold on apogee height for ascent completion: 3000 [m]

Nominal sensor/actuator / MCI parameters. on-board software knows perfectly MCI properties and initial state

Perfectly vertical attitude

MIL & PIL testing. Ascent

MIL testing. Nominal case

Vertical Rise completed in 3.5 seconds. Actual altitude reached: 21.2 m

Pitch Over duration: 44.6 seconds

Overall ascent duration: 258.3 seconds

Final angular rate: [2.711, -0.091, 0.531] deg/s

Final orbital properties

	GUI internal (ascent flag -> 4)	Real World (ascent flag -> 4)	Real World (GUI mode -> 5)
Inclination [deg]	80.000	80.001	80.001
Altitude of apogee [m]	101906.448	102088.011	102759.570
Altitude of perigee [m]	29993.842	29993.855	30131.766

MIL & PIL testing. Ascent

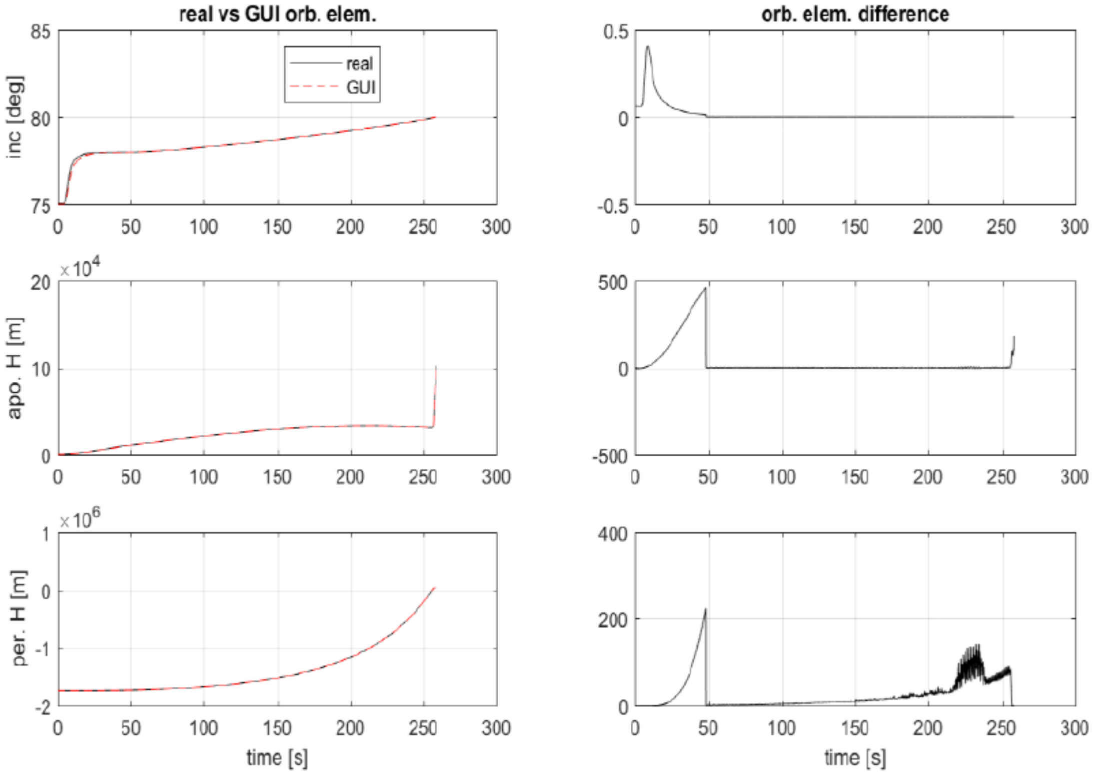
MIL testing. Nominal case

Orbital properties

Target altitude of apoapsis reached quickly at the end of the ascent (mean increase between two successive guidance steps ~ 3 km)

Altitude of periapsis and inclination reached more smoothly

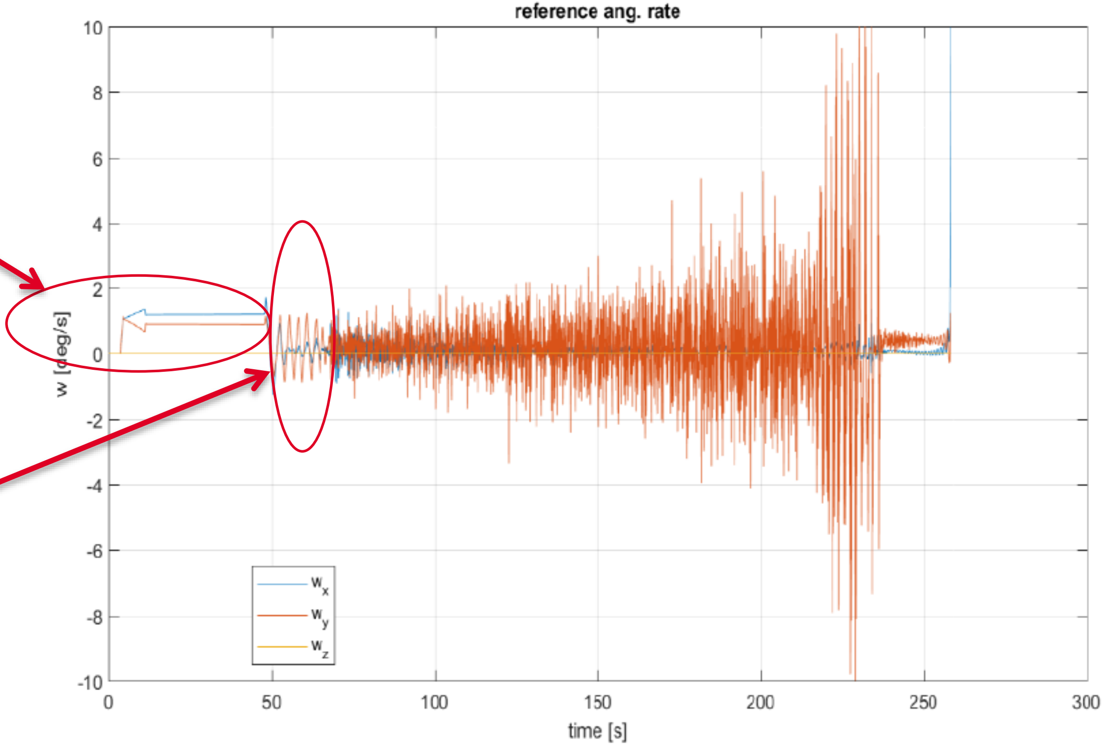
→ Large threshold on apoapsis for ascent termination



MIL & PIL testing. Ascent

MIL testing. Nominal case

Reference angular rate



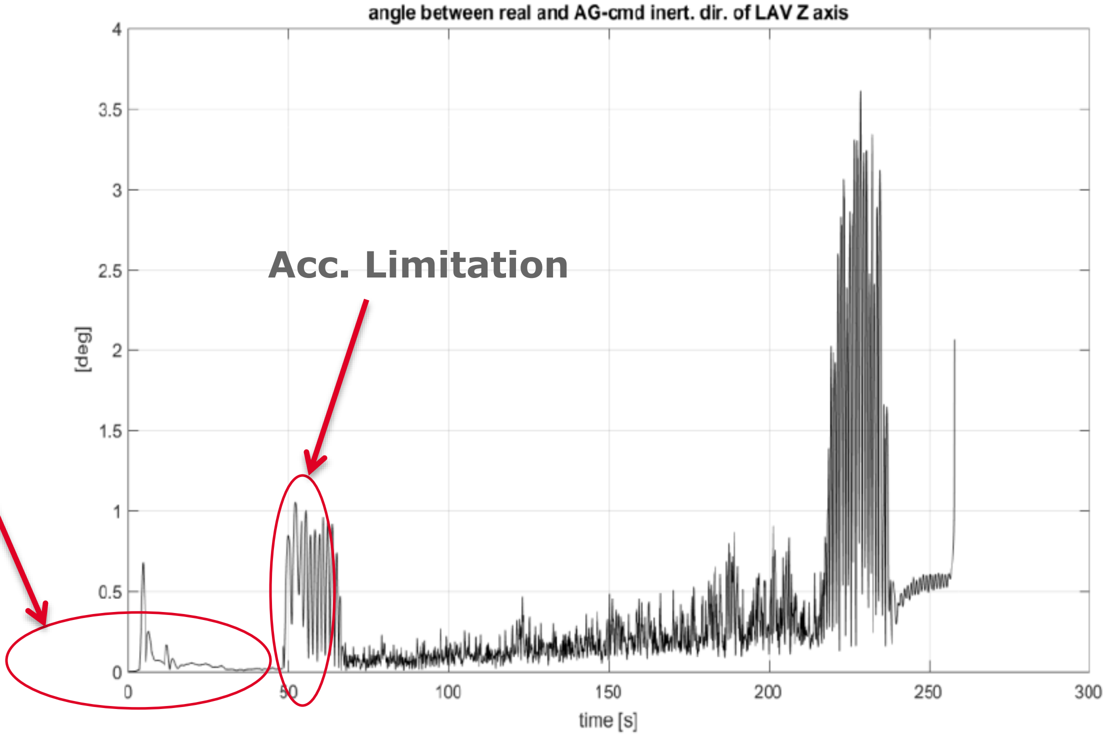
VR + Pitch Over

Acc. Limitation

MIL & PIL testing. Ascent

MIL testing. Nominal case

APE properties
mean 0.336 deg
max 3.608 deg
std 0.513 deg



VR + Pitch Over

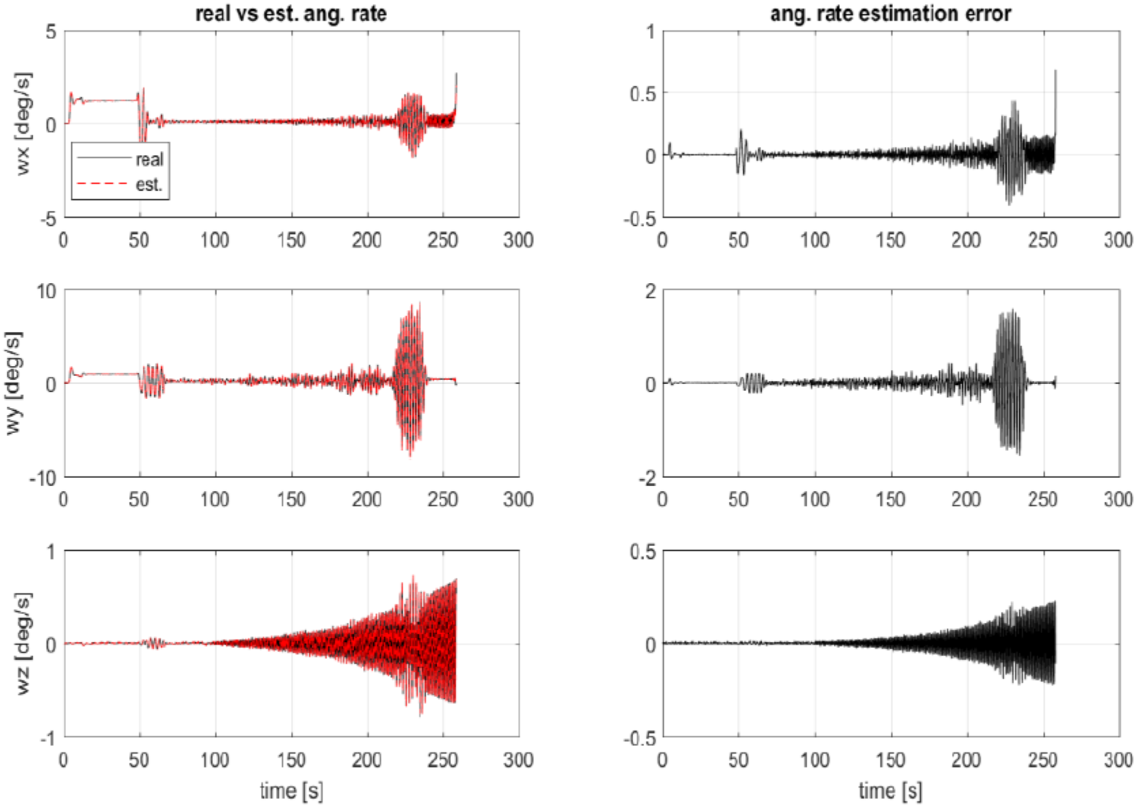
Acc. Limitation

MIL & PIL testing. Ascent

MIL testing. Nominal case

Real angular rate and angular rate estimation

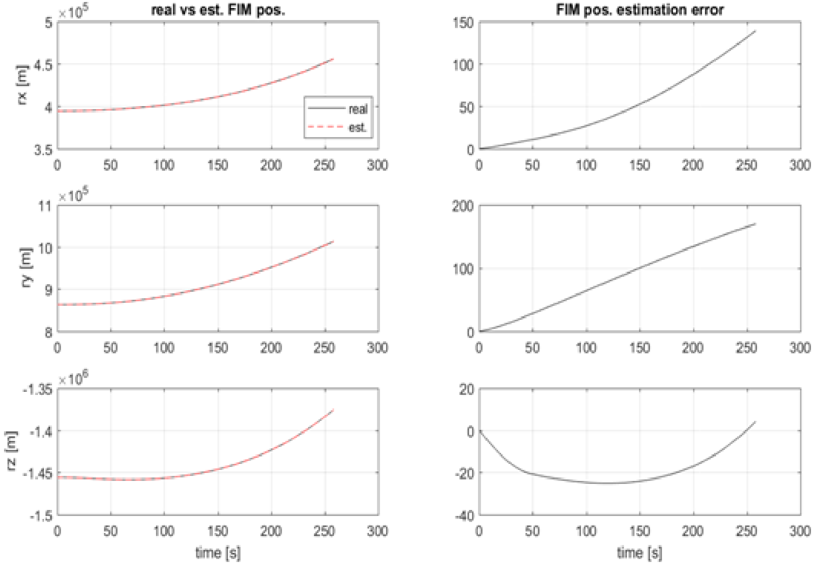
Peaks in estimation error only at end of ascent, when larger corrections are required



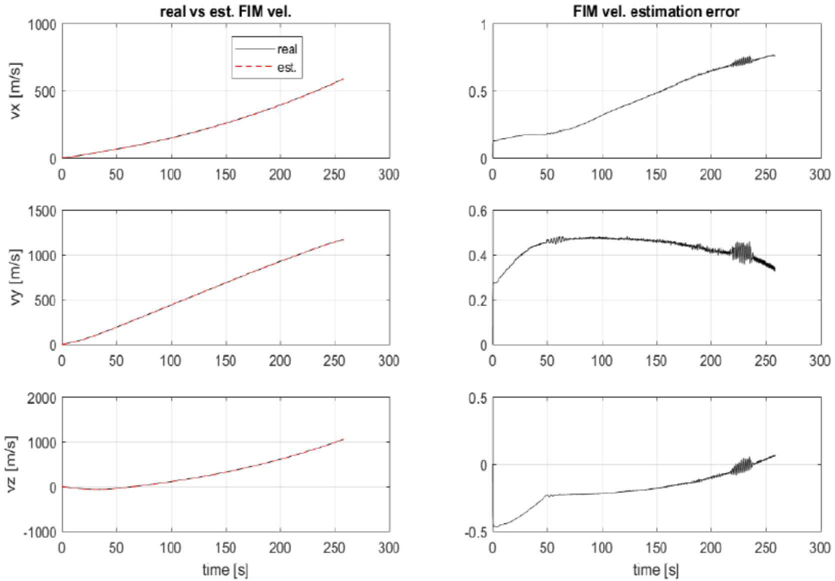
MIL & PIL testing. Ascent

MIL testing. Nominal case

Position estimation



Velocity estimation



MIL & PIL testing. Ascent

MIL testing. Monte Carlo analysis

2000 cases run

Main dispersed parameters:

- initial inclination (11 deg)
- dry ass: 40% uncertainty (nominal 451.83 kg)
- inertia: 25% uncertainty both on diagonal and off-diagonal terms
- propellant mass: 10% uncertainty (nominal 659 kg)
- sloshing properties (mass factor, frequebcy factor, damping)
- acc/gyr properties (bias, scale factor, misalignment)
- actuator properties (bias, misalignment)

Summary:

- All simulations completed successfully
- Altitude of apoapsis most sensitive parameter

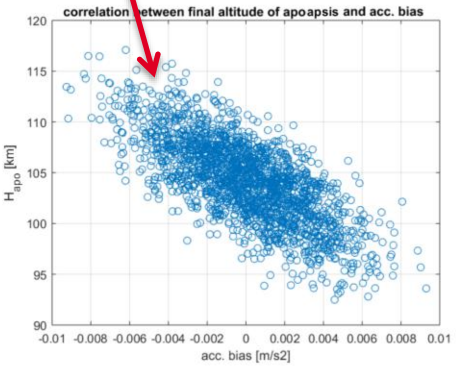
MIL & PIL testing. Ascent

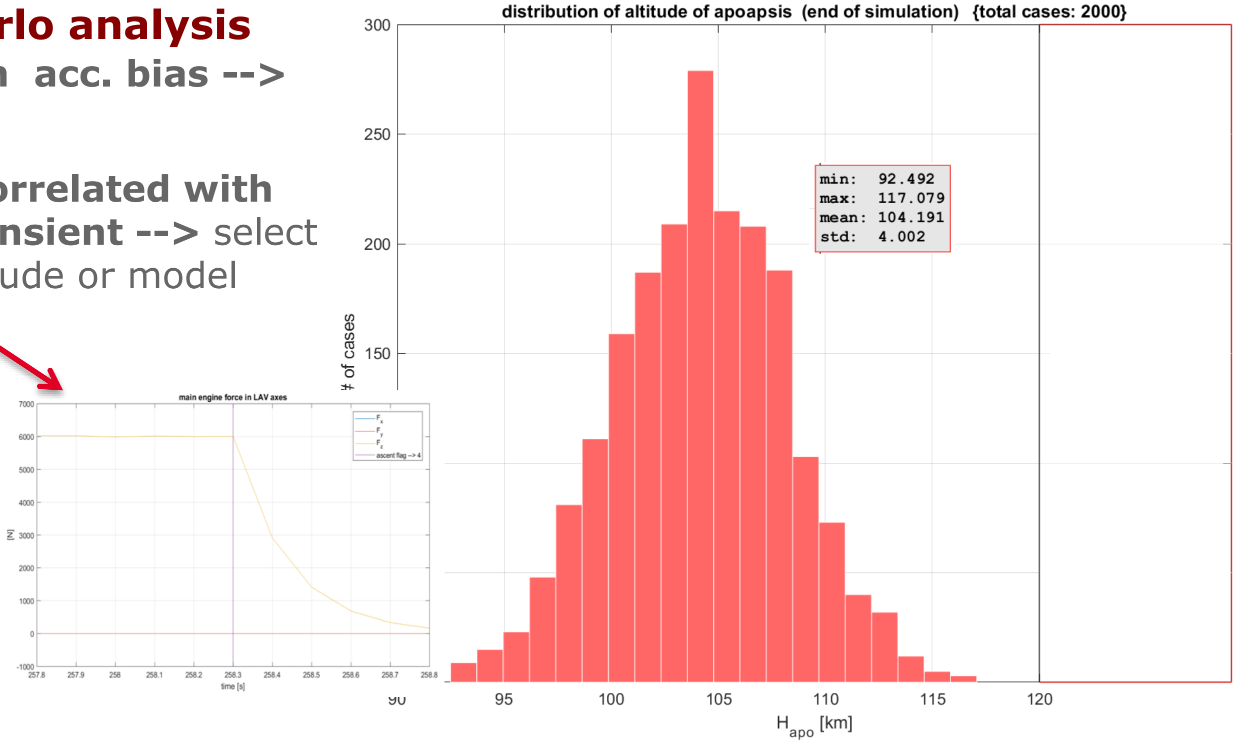
Distribution of altitude of apoapsis

MIL testing. Monte Carlo analysis

Large std correlated with acc. bias --> calibration

Mean value correlated with switch-off transient --> select alternative altitude or model transient

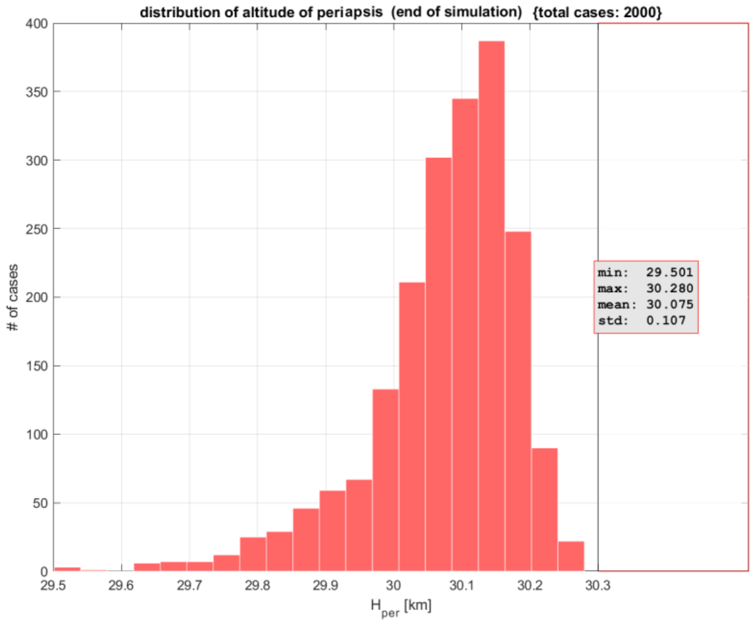




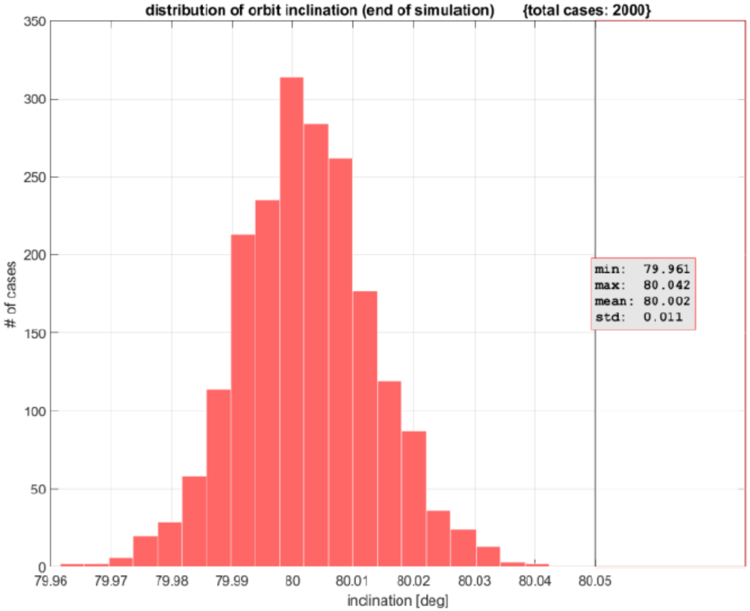
MIL & PIL testing. Ascent

MIL testing. Monte Carlo analysis

Altitude of periapsis



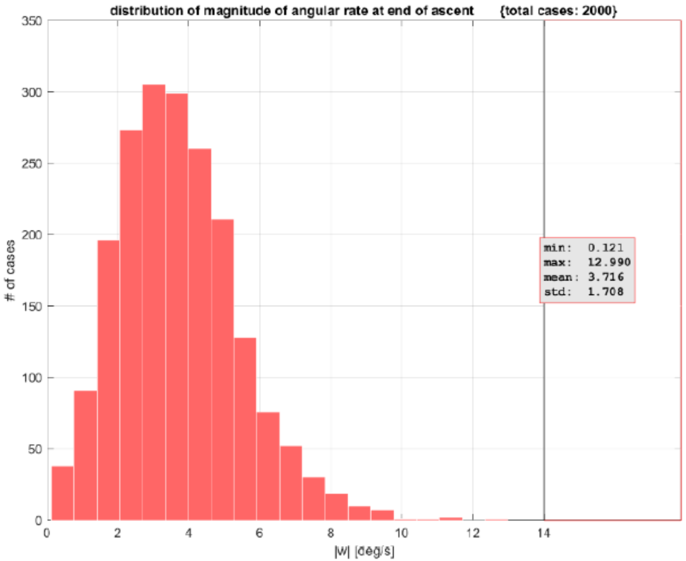
Orbit inclination

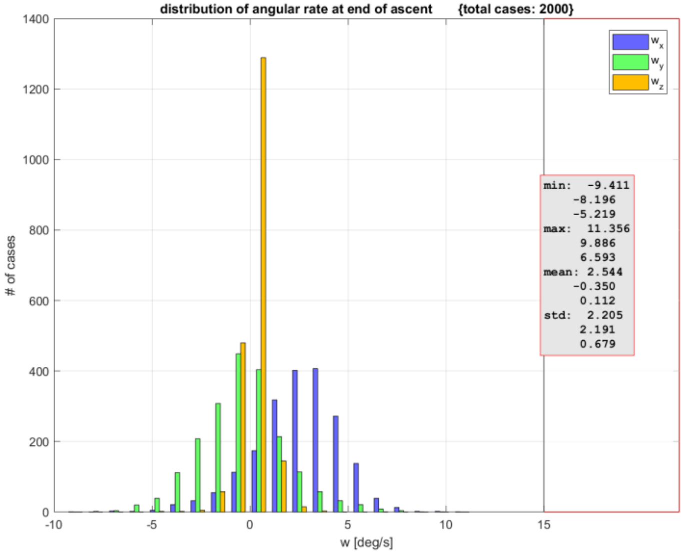


MIL & PIL testing. Ascent

MIL testing. Monte Carlo analysis

Angular rate at end of ascent

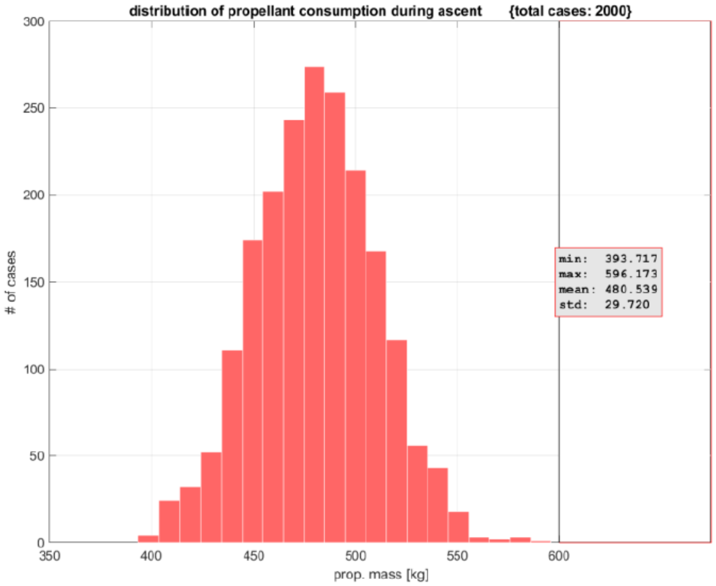




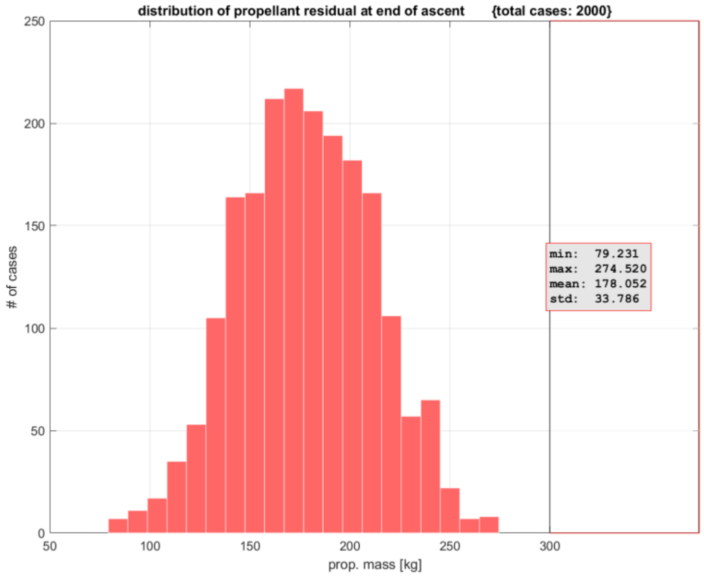
MIL & PIL testing. Ascent

MIL testing. Monte Carlo analysis

Propellant consumption



Residual propellant

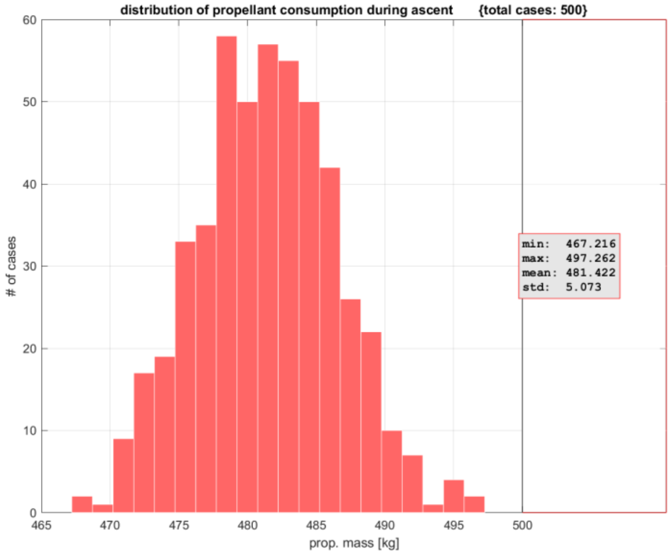


MIL & PIL testing. Ascent

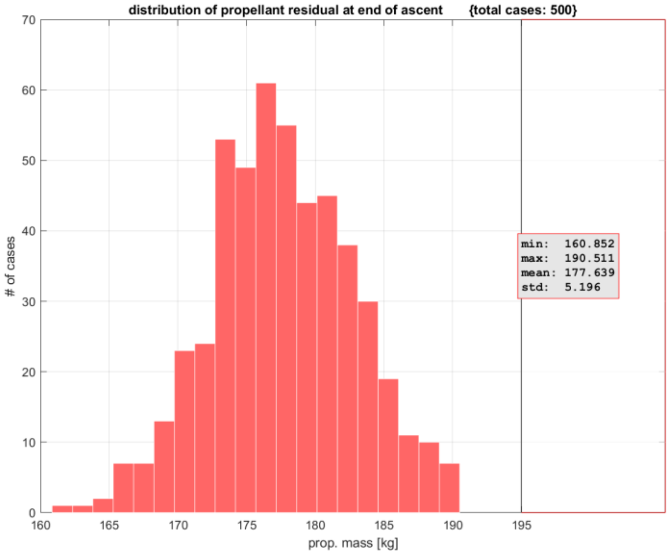
MIL testing. Monte Carlo analysis

MC campaign with reduced mass dispersion (+/- 3% dry mass; +/- 0.75% propellant)

Propellant consumption



Residual propellant

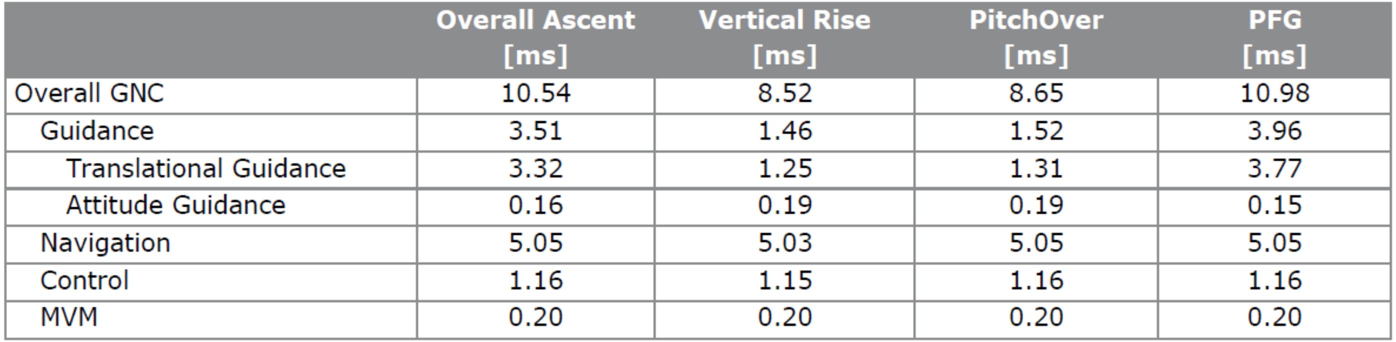


MIL & PIL testing. Ascent

PIL testing

PIL test for the ascent phase executed using an HW configuration that includes an Avionic Test Bench with AT697FT (LEON2) microprocessor

PIL test scenario: nominal ascent case

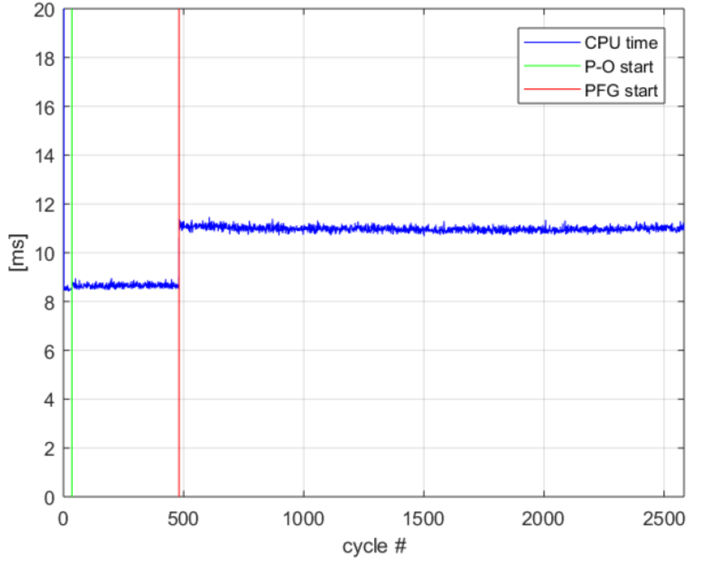


	Overall Ascent [ms]	Vertical Rise [ms]	PitchOver [ms]	PFG [ms]
Overall GNC	10.54	8.52	8.65	10.98
Guidance	3.51	1.46	1.52	3.96
Translational Guidance	3.32	1.25	1.31	3.77
Attitude Guidance	0.16	0.19	0.19	0.15
Navigation	5.05	5.03	5.05	5.05
Control	1.16	1.15	1.16	1.16
MVM	0.20	0.20	0.20	0.20

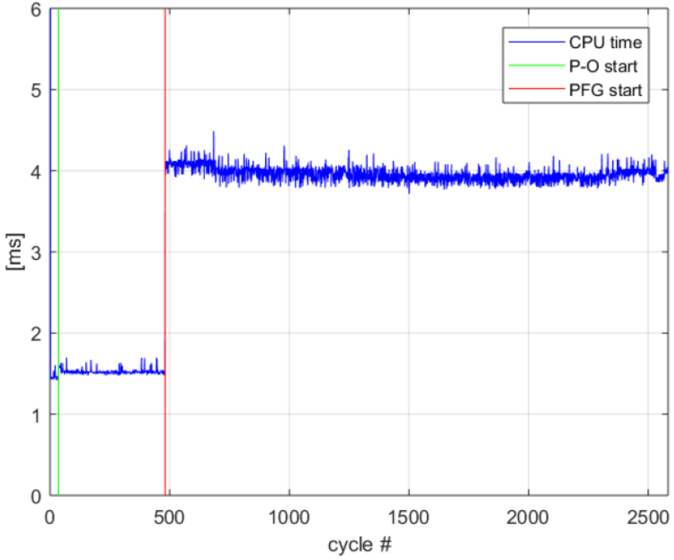
MIL & PIL testing. Ascent

PIL testing

Complete GNC execution time



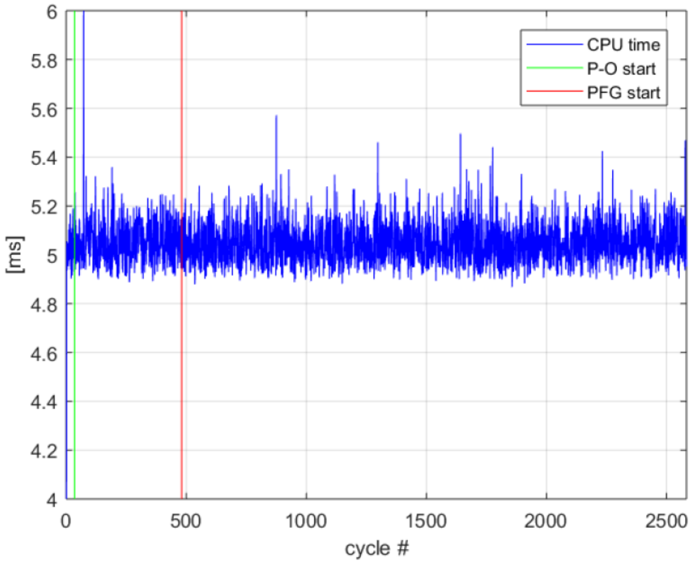
Guidance execution time



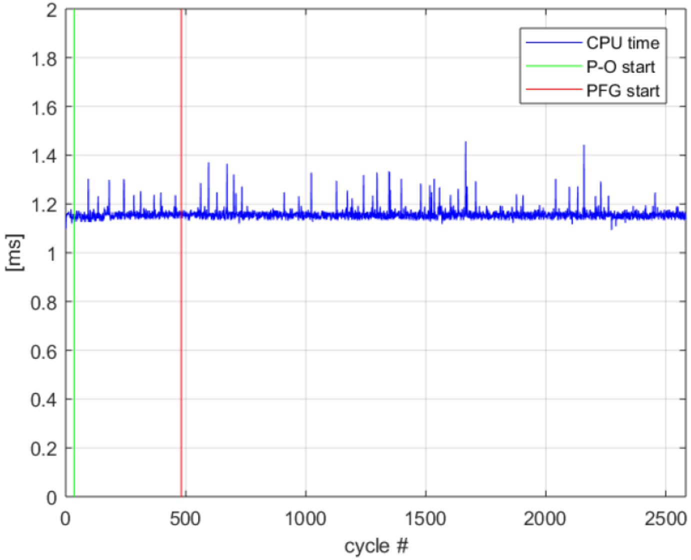
MIL & PIL testing. Ascent

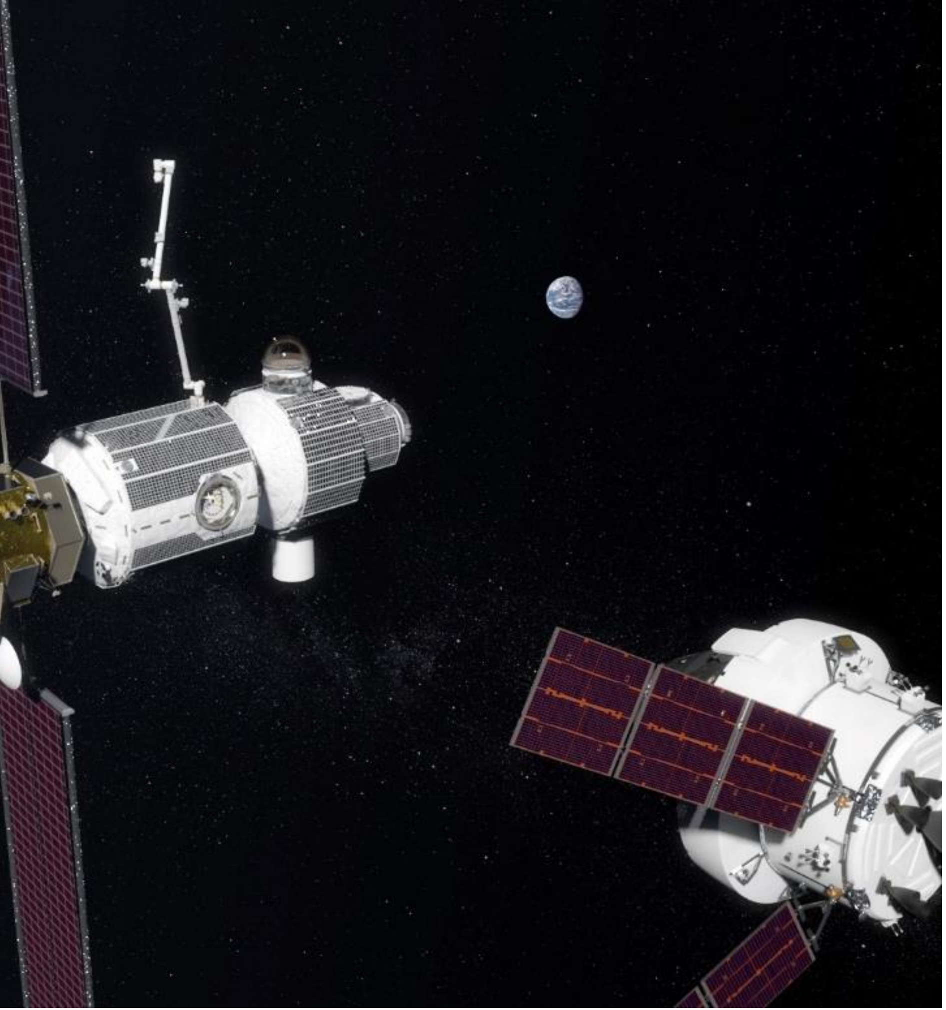
PIL testing

Navigation execution time



Control execution time





Orbit transfer

Orbit Transfer

MC ΔV consumption

Total consumption

- Small dispersion
- Acceleration dispersion reduced by cut-off control

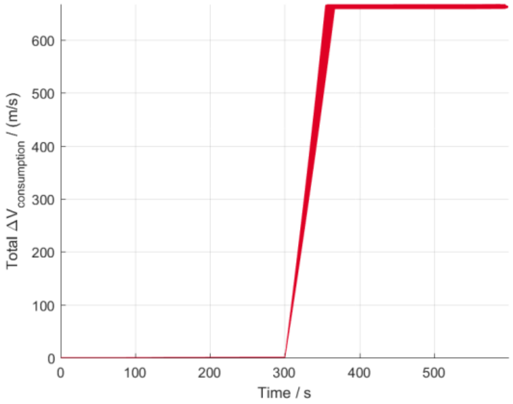
Auxiliary thrusters

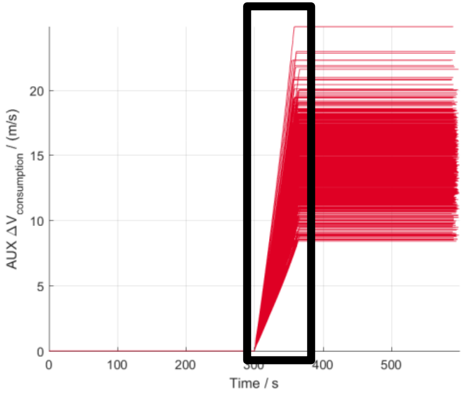
- Correction of main engine torque
- Large dispersion depending on main engine misalignment

RCS

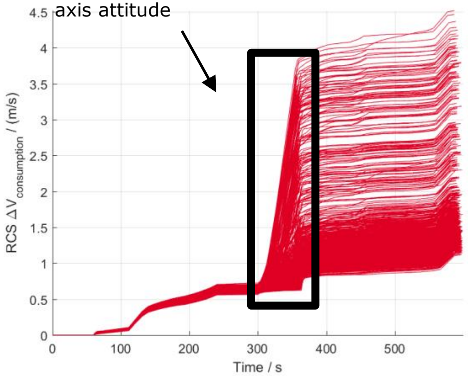
- Correction of rotations around Z axis
- Execution of attitude manoeuvres (spin, repoint)
- Most dispersion concentrated during OT man

Total





AUX



Dispersion during orbital manoeuvre to correct z axis attitude

RCS

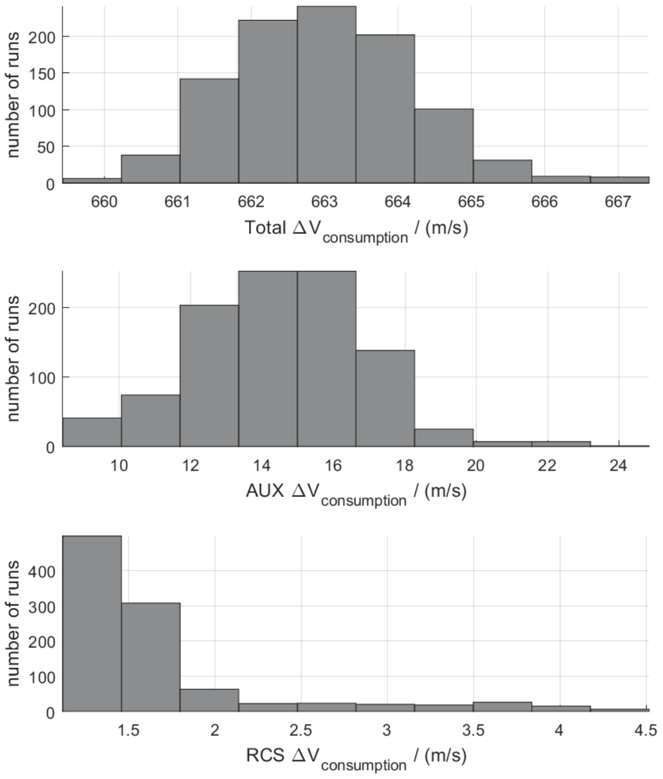
Orbit Transfer

MC ΔV consumption

ΔV consumption metric updated with definition per-phase

	Commanded ΔV / (m/s)	Total ΔV cons / (m/s)	AUX ΔV cons / (m/s)	RCS ΔV cons / (m/s)
Metric	-	768.6	61	42
Mean	660.862	662.963	14.475	1.685
Std. deviation	0.926	1.242	2.390	0.644
Success rate	-	100 %	100 %	100 %

ΔV histogram



Orbit Transfer

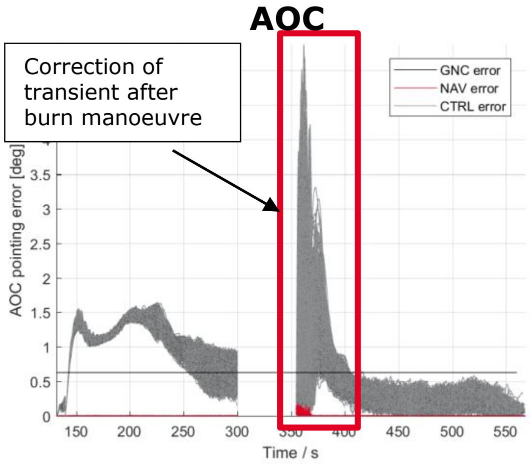
MC Pointing Performance

Attitude Manoeuvres

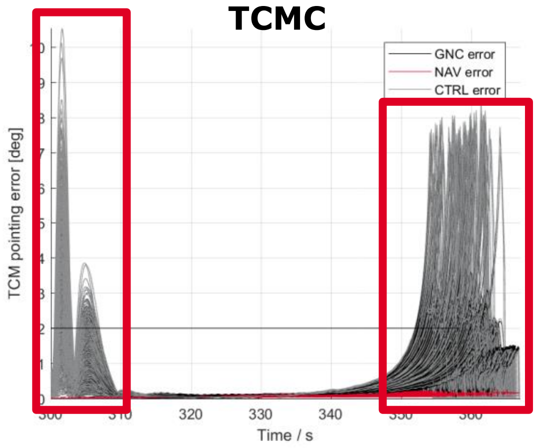
- Spin-down and spin-up performed correctly
- Low impact of repointing phase in TIM performance
- Successful continuity between attitude modes

TCMC

- Initial transient because of main engine misalignment
- Final transient caused by correction of accumulated residual ΔV
- Target ΔV obtained within requirements


AOC

Correction of transient after burn manoeuvre


TCMC

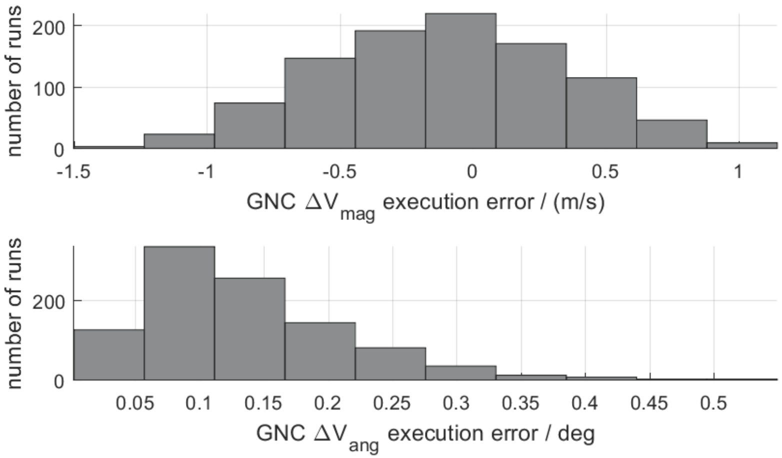
Orbit Transfer

MC TIM execution

Test results compatible with mission analysis requirements

Update of performance metric from manoeuvre execution to performance at arrival

Manoeuvre execution histogram



	ΔV_{mag} error GNC / ΔV_{mag} %	ΔV_{ang} error GNC / °
Metric	0.333	0.333
Mean	-0.016	0.135
Std. deviation	0.068	0.079
Success rate	100 %	100 %

Trajectory Correction Manoeuvre

MC ΔV consumption

Total consumption

- Stochastic manoeuvre
- Large dispersion of base commanded manoeuvre

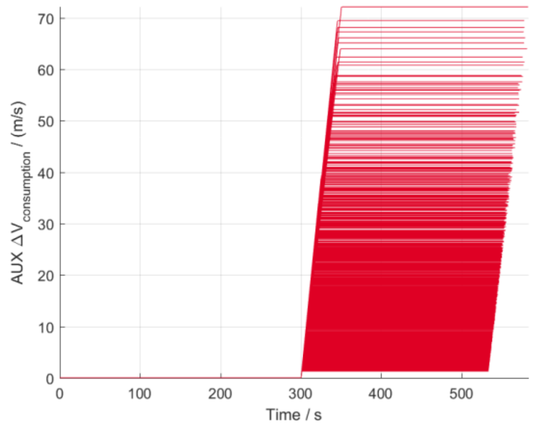
Auxiliary thrusters

- Execution of manoeuvre

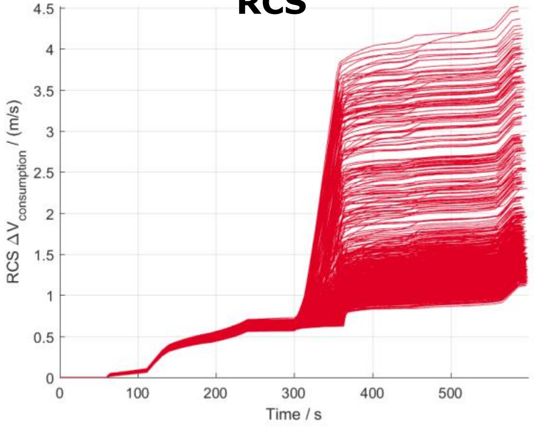
RCS

- Correction of rotations around Z axis
- Execution of attitude manoeuvres (spin, repoint)
- Most dispersion concentrated during OT man

Total



RCS



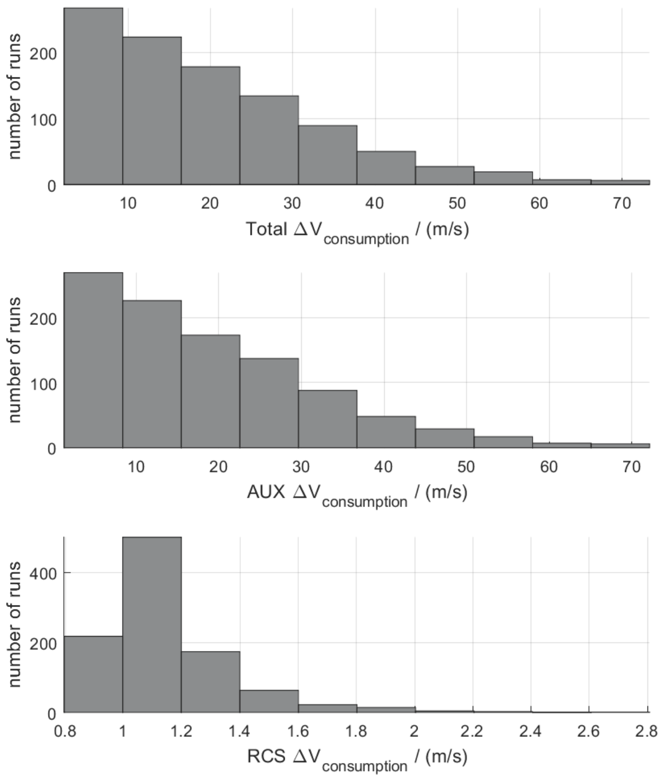
Trajectory Correction Manoeuvre

MC ΔV consumption

ΔV consumption metric updated with definition per-phase

	Commanded ΔV/(m/s)	Total ΔV cons / (m/s)	AUX ΔV cons / (m/s)	RCS ΔV cons / (m/s)
Metric	-	-	61	42
Mean	18.480	19.892	18.746	1.146
Std. deviation	13.281	13.613	13.481	0.216
Success rate	-	100 %	100 %	100 %

ΔV histogram



Trajectory Correction Manoeuvre

MC Pointing Performance

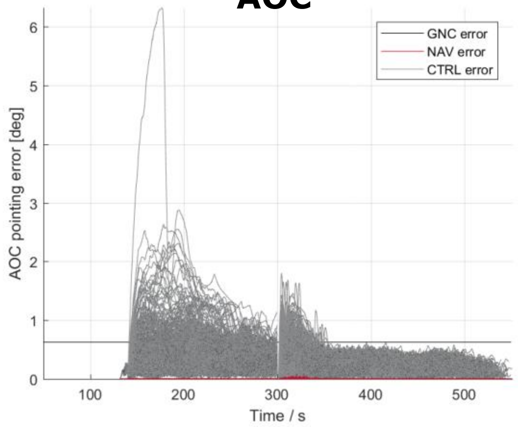
Attitude Manoeuvres

- Spin-down and spin-up performed correctly
- Larger variability of manoeuvre profiles
- Smaller transient between attitude modes

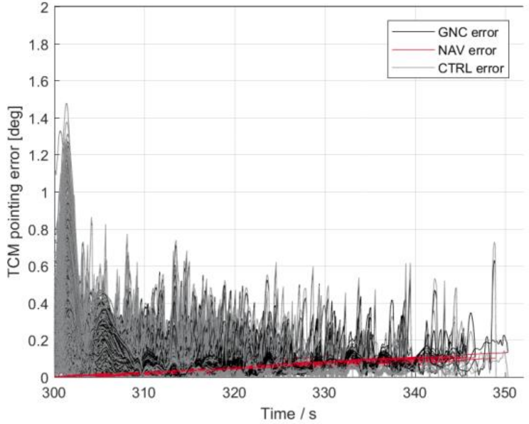
TCMC

- Smaller transient at start and end of manoeuvre
- Large manoeuvre duration variability

AOC



TCMC



Trajectory Correction Manoeuvre

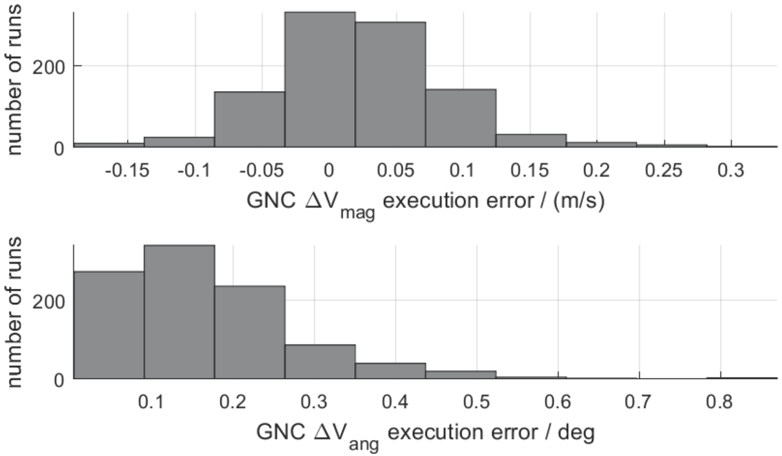
MC TIM execution

Test results compatible with mission analysis requirements

Smaller reference manoeuvre

- Smaller manoeuvre error in size
- Larger manoeuvre error defined as %
- Better performance at arrival than with TIM results

Manoeuvre execution histogram



	ΔV_{mag} error GNC / ΔV_{mag} %	ΔV_{ang} error GNC / °
Metric	0.333	0.333
Mean	0.205	0.169
Std. deviation	0.724	0.109
Success rate	90.5 %	100 %

Orbit Transfer

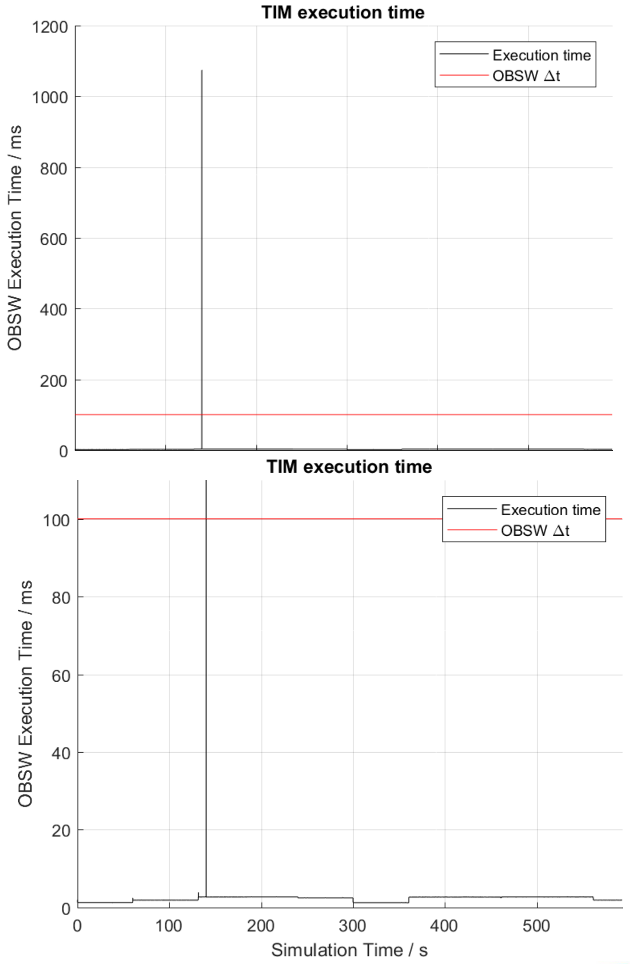
PIL testing

Execution time

- OBSW Δt set to 0.1 s (10 Hz)

General

- Execution time consistently below 4% OBSW Δt
- Large spike during computation of orbit transfer manoeuvre
    - NAV propagates chaser state to TIM time (once)
    - GUI propagates transfer arc and STM to compute manoeuvre (repeated until convergence)
    - Mitigation by breaking up into multiple cycles

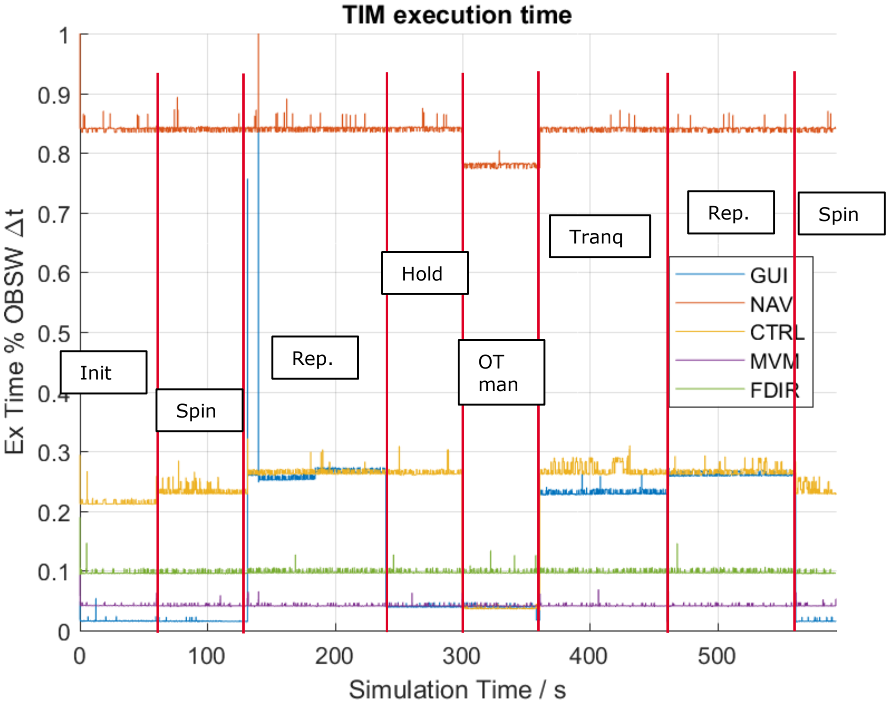


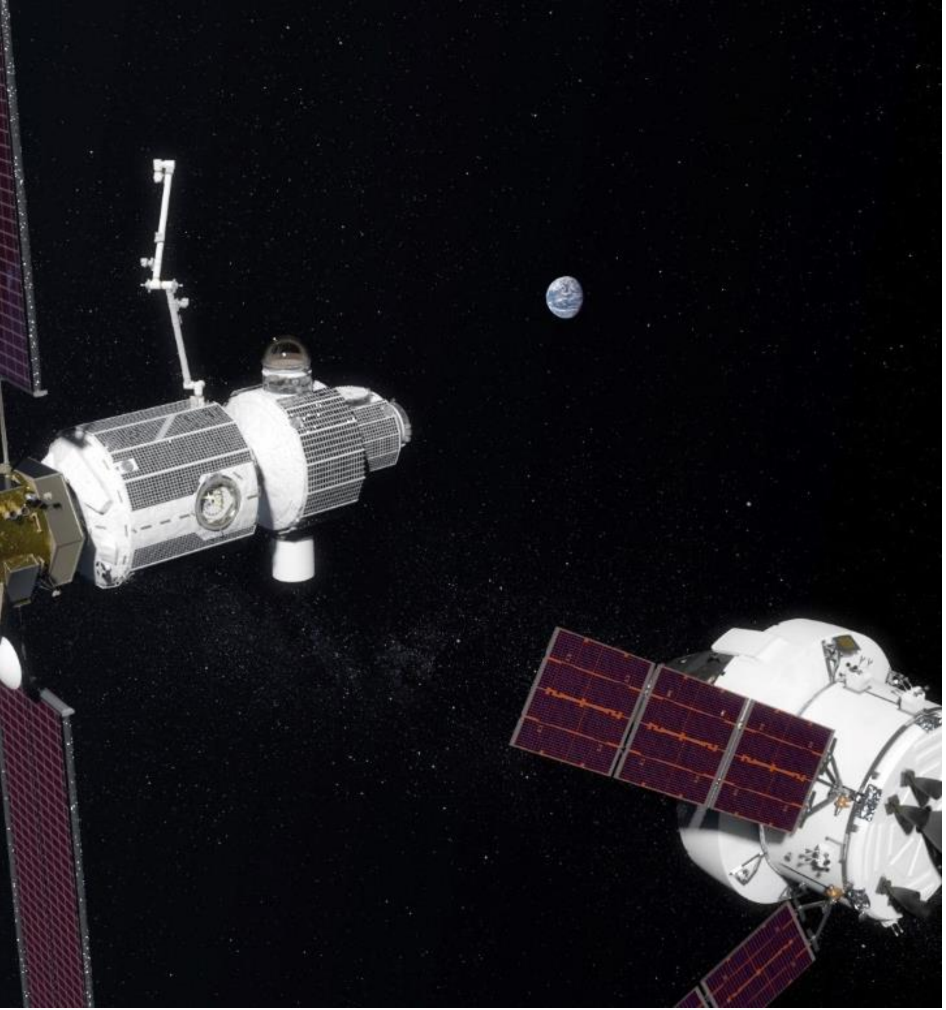
Orbit Transfer

PIL testing

GNC functions

- **MVM** 0.05% (constant)
- **FDIR** 0.1% (constant)
- **CTRL** <0.3%
  - Variability with size of controller matrices
  - Large impact of simplex (TMF)
- **NAV** <0.9%
  - Spike in orbit transfer computation
  - Cost reduced with gyro vs STR
- **GUI** <0.3 %
  - Spike in OT computation
  - Impact of quaternion interpolant during repointing





Rendezvous

Long Range Rendezvous

Nominal Scenario

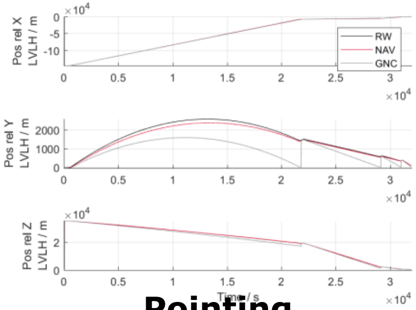
Objectives

- Execution of sequence of impulsive manoeuvres to traverse from 150 km to 200 m

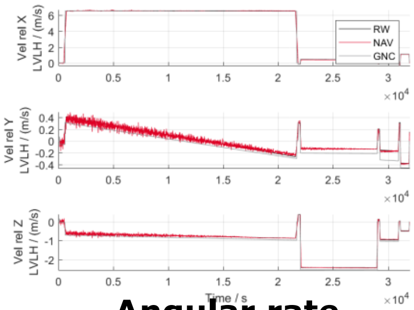
Propellant consumption caused by impulsive manoeuvres and target pointing

Pointing stability compatible with long range camera integration requirements

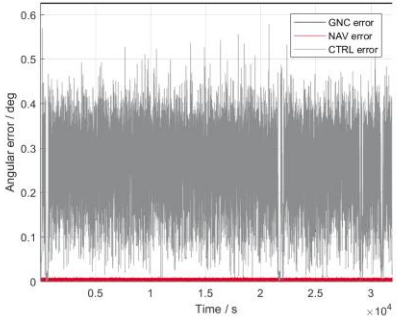
Trajectory



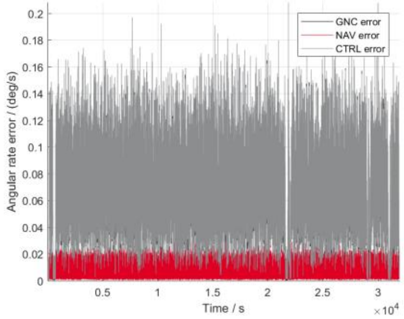
Velocity



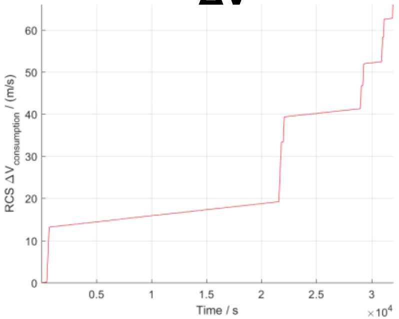
Pointing



Angular rate



ΔV



Long Range Rendezvous

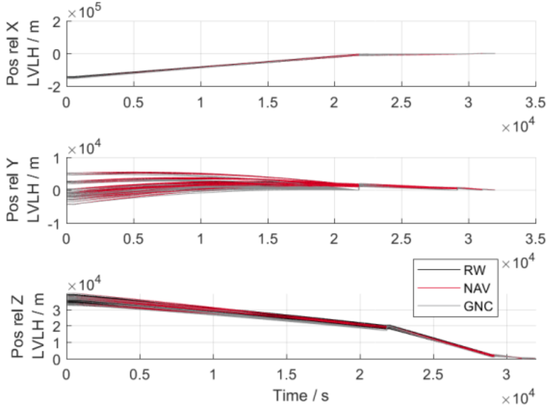
MC Analysis

Small dispersion at arrival, correcting large initial orbital dispersion

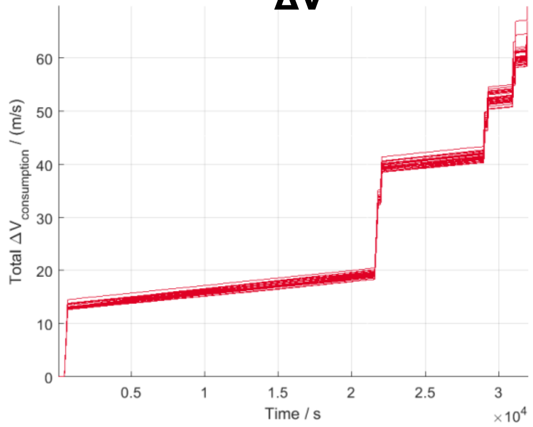
Handover to SRN compatible with boundary conditions

Small ΔV consumption dispersion

Trajectory



ΔV



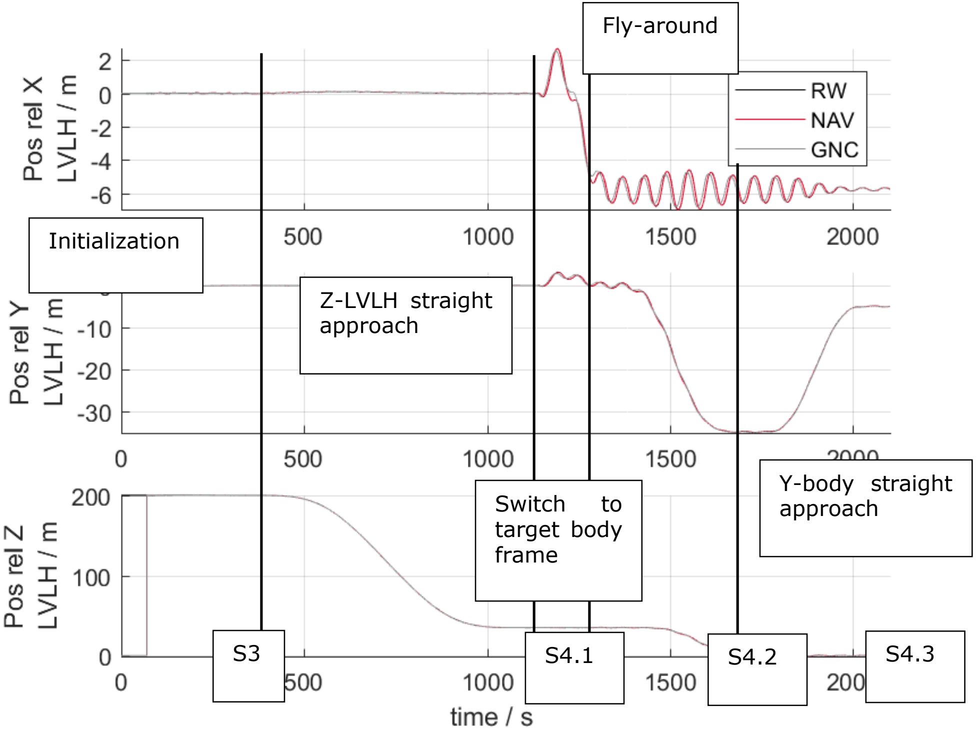
Short Range Rendezvous

Nominal Case

Forced motion to achieve berthing conditions

Segments

- Accommodation from previous phase
- Straight line approach in R-bar
- Switch to Target Body Frame
- Fly-around
- Straight line approach to berthing box



Short Range Rendezvous

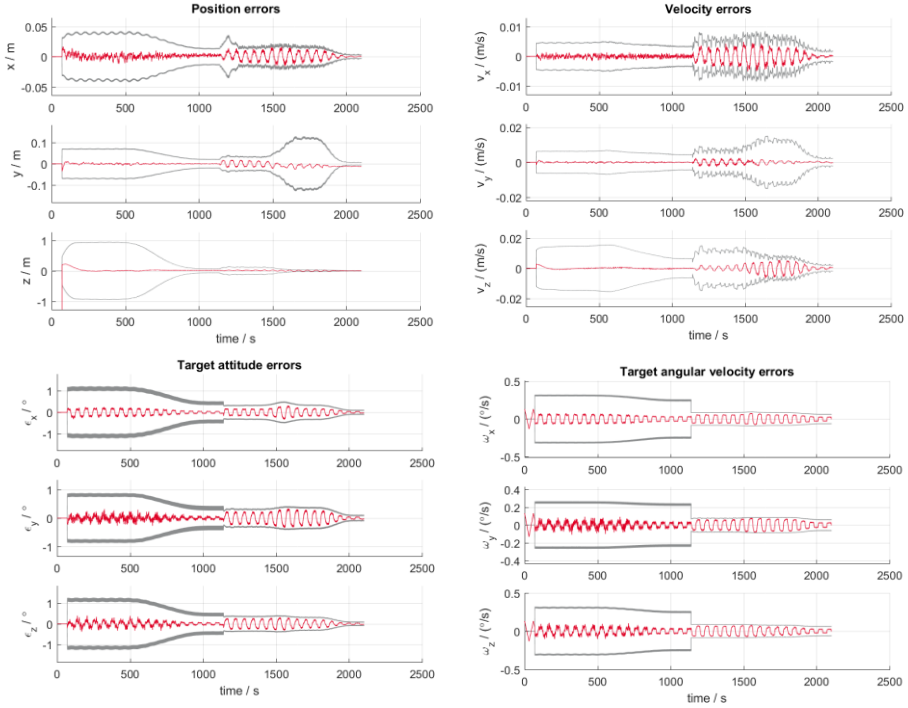
Navigation in SRR

Influence of approach direction and pattern

- Chaser approaches over z-axis
- Estimation of the x-coordinate is not as good as the estimation of the y-coordinate
  - size of the pattern of markers is larger in the y-direction than in the x-direction

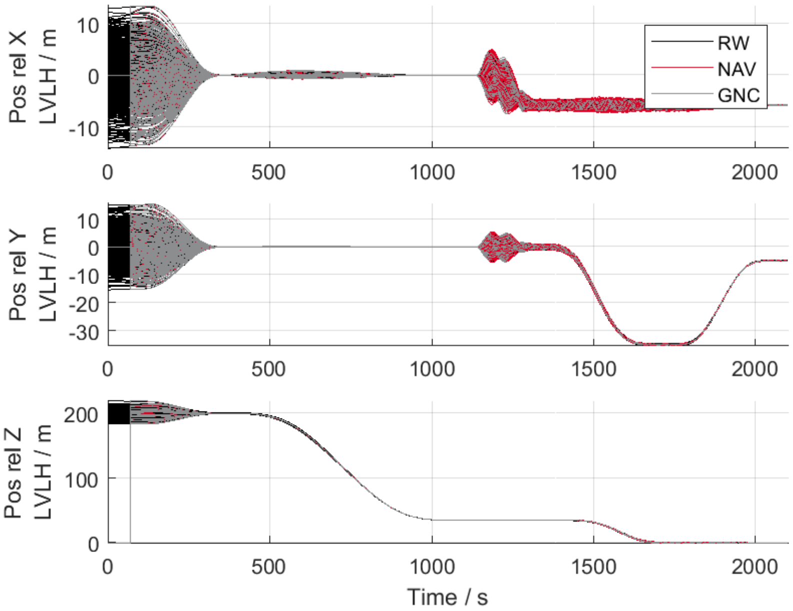
SRN does not model target angular acceleration

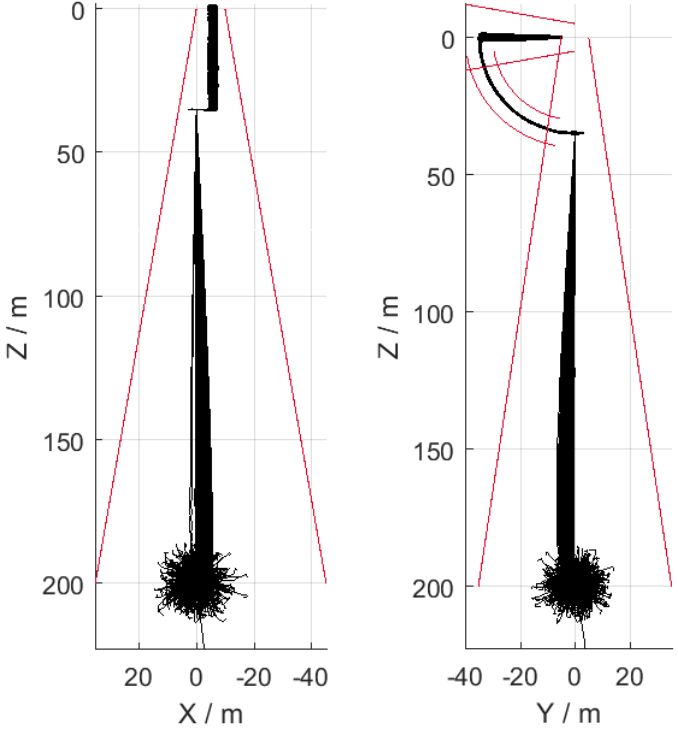
- Position / velocity estimates show oscillation with amplitude of 2 cm in position and 0.5 cm/s in velocity
  - Directly related to attitude motion of the target



Short Range Rendezvous

MC analysis





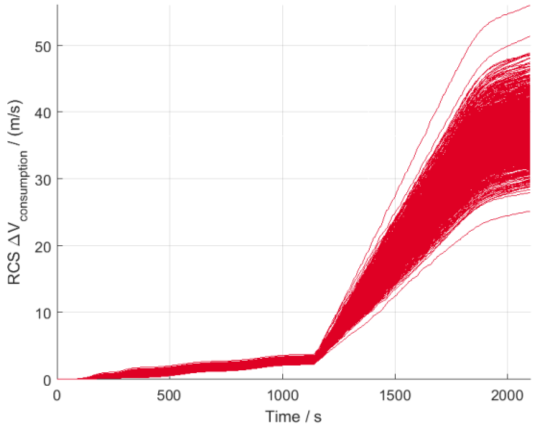
Short Range Rendezvous

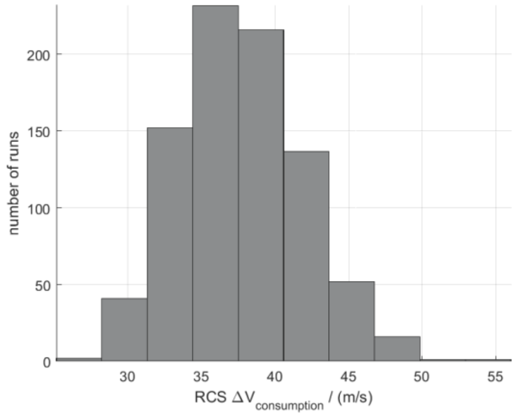
MC Analysis

Consumption increase when switching to target body frame

Scenario with challenging manoeuvres (fly-around and body frame motion) to test GNC capabilities

	RCS ΔV cons / (m/s)
Metric	-
Mean	37.9
Std. deviation	4.3
Success rate	-





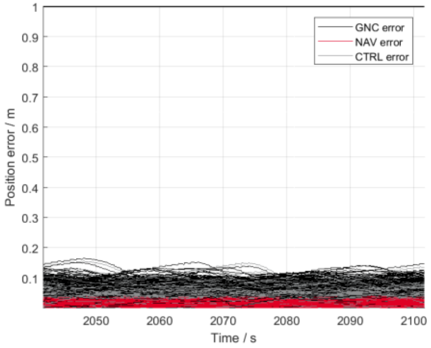
Short Range Rendezvous

MC Analysis

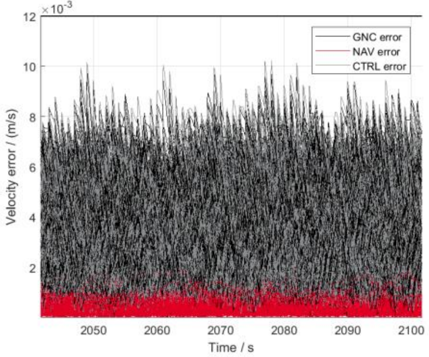
Performance metric evaluated in berthing box

- Great performance in position, velocity and attitude errors
- Angular rate performance compatible with past activities results and requirements (ORCO)

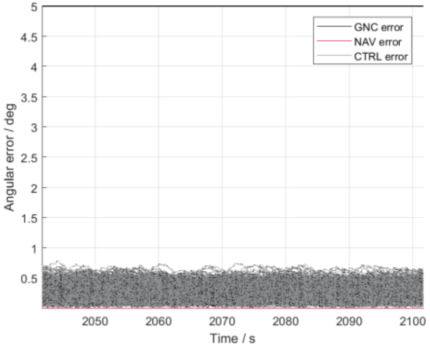
Position



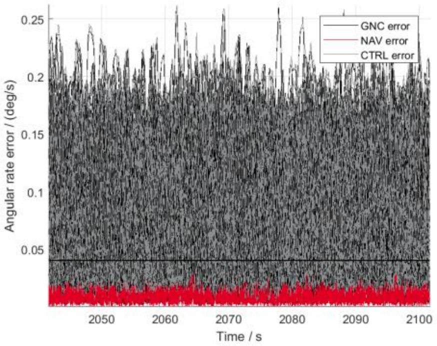
Velocity



Attitude



Ang. rate



Rendezvous

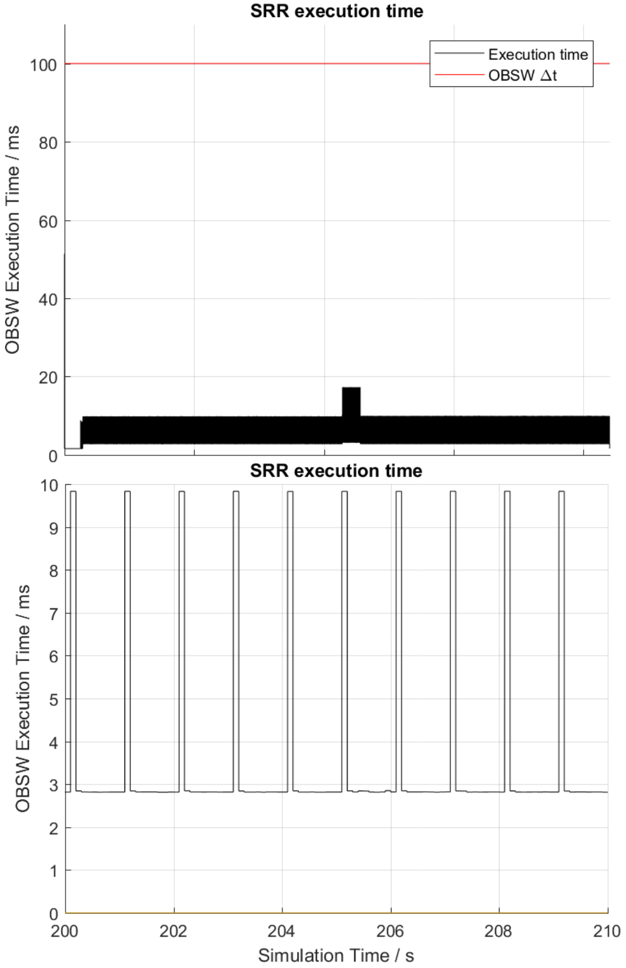
PIL testing

Execution time

- OBSW Δt set to 0.1 s (10 Hz)

General

- Consistently below 10%
- Segment ~20% (NAC and WAC nav)
- Spikes of 1 Hz, IP data arriving to NAV
- Propagation between images <3%
- Cost of IP not analysed

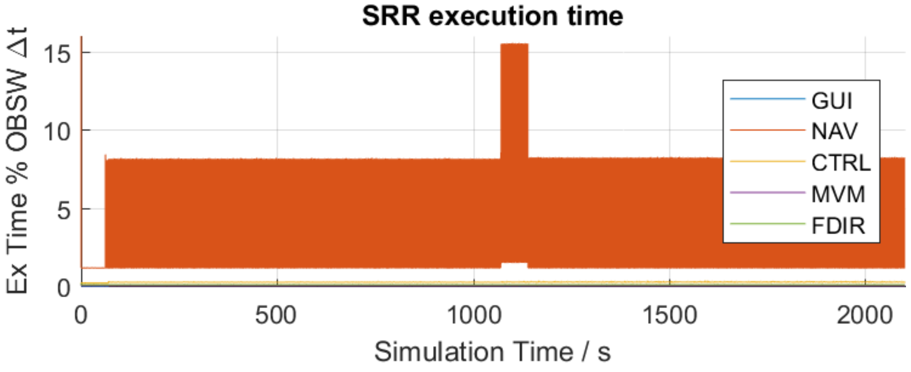


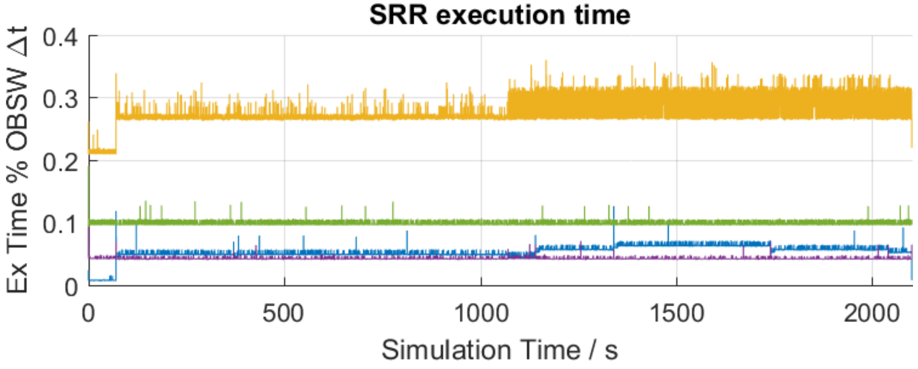
Rendezvous

PIL testing

GNC functions

- **NAV** largest cost
    - Spikes at 1Hz to update based on IP
    - Segment ~20% with both NAC and WAC
    - Rest <2%
- **CTRL** 0.3% (constant)
- **MVM** 0.05% (constant)
- **FDIR** 0.1% (constant)
- **GUI** 0.07%
    - Small variability caused by frame changes





HIL testing

12:00 – 12:15

Rendezvous

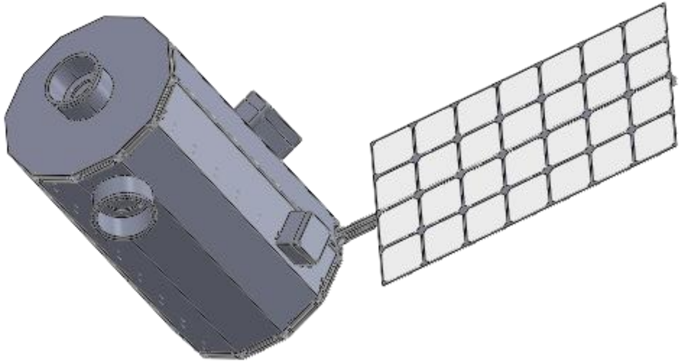
HIL testing

Objectives

- To demonstrate feasibility of SRN concept
- To validate IP algorithm performance in an open-loop test
- To assess SRN performance with inputs from an IP function processing real camera images
- To assess performance of overall GNC system in closed-loop using real camera images processed by IP function as input to the SRN

=> all in a low-accuracy set-up

- Mock-up is 1:10 scale model of LOP-G module
  - Height 655.9 mm,
  - width 386.27 mm,
  - Panels width 103.5 mm
- Mock-up already built; available for immediate use
- CAD model of mock-up has been made => simulator trajectory can be tested using synthetic images



Rendezvous

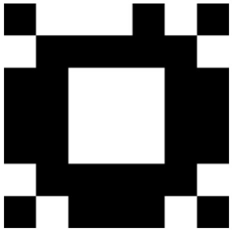
HIL testing

Camera

MANTA G-419
- used in previous activities between ESA and GMV (iGNC, NEO-GNC2-IP) to take pictures for IP activities
- high level space representative camera

Kowa LM16JC MP C-Mount Lens
- Focal length 16 mm
- FoV cropped to 30° (40° full FoV)

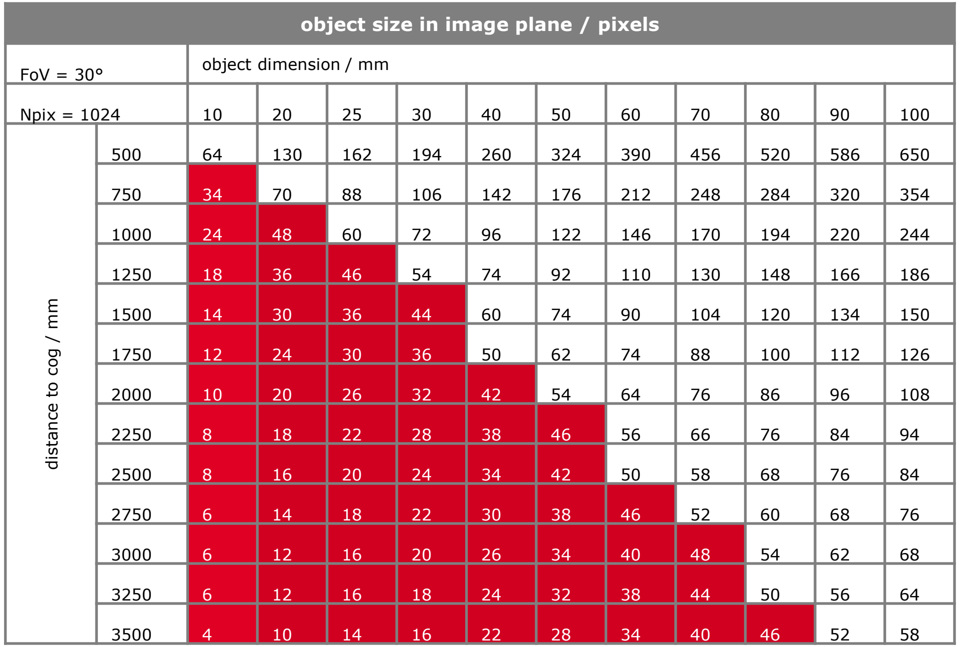
Rendezvous



HIL testing

Markers and detection
- **Previously Concentric Contrasting Circles (CCC) were considered**
- **Aruco markers or AprilTags more practical:**
  - Markers have in-plane orientation
  - Markers have ID, making them easier to track
  - IP algorithm already coded and immediately available
- **Some disadvantage:**
  - Finer details make marker harder to detect at large distance

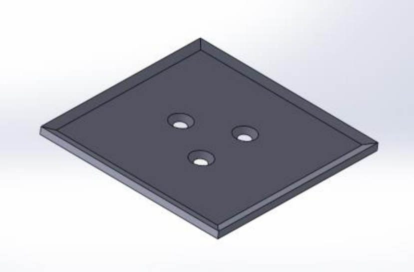
Marker detectability as a function of distance and marker size

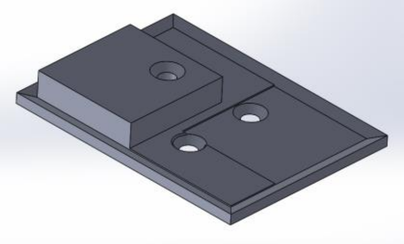


		object size in image plane / pixels										
FoV = 30°		object dimension / mm										
Npix = 1024		10	20	25	30	40	50	60	70	80	90	100
distance to cog / mm	500	64	130	162	194	260	324	390	456	520	586	650
	750	34	70	88	106	142	176	212	248	284	320	354
	1000	24	48	60	72	96	122	146	170	194	220	244
	1250	18	36	46	54	74	92	110	130	148	166	186
	1500	14	30	36	44	60	74	90	104	120	134	150
	1750	12	24	30	36	50	62	74	88	100	112	126
	2000	10	20	26	32	42	54	64	76	86	96	108
	2250	8	18	22	28	38	46	56	66	76	84	94
	2500	8	16	20	24	34	42	50	58	68	76	84
	2750	6	14	18	22	30	38	46	52	60	68	76
	3000	6	12	16	20	26	34	40	48	54	62	68
	3250	6	12	16	18	24	32	38	44	50	56	64
	3500	4	10	14	16	22	28	34	40	46	52	58

Rendezvous

HIL testing





Test setup

- **Markers placed on 3D printed base plates mounted on existing holes on mock-up, originally used for calibration**
  - Minimal & reversible change to mock-up
- **markers arranged in circular arc covering pointing direction camera during fly-around**
- **Smaller markers include raised section to enhance observability**

Rendezvous

HIL testing

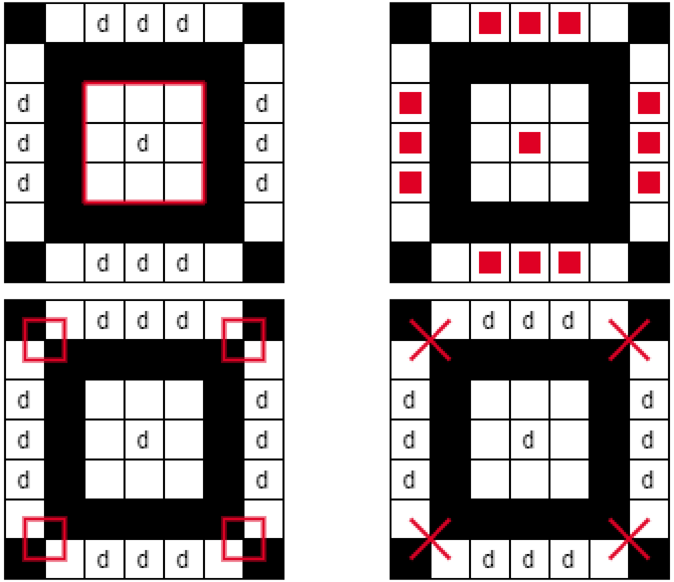
Software

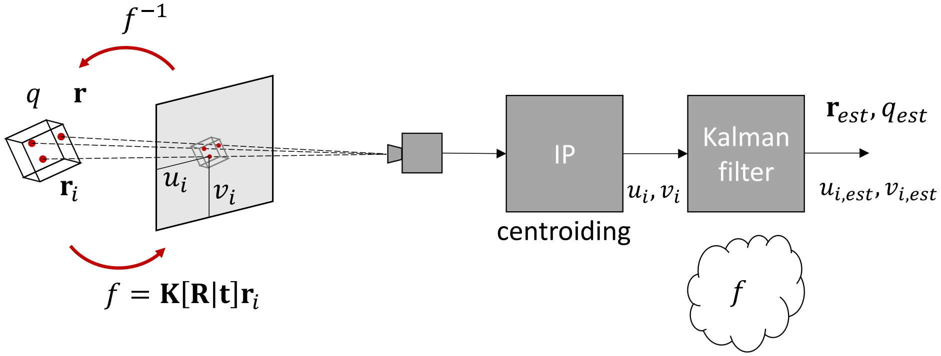
IP

- AprilTag Marker detection with custom marker design
- High-contrast square enhances accuracy

Filter

- Kalman filter featuring projection equation





Rendezvous

HIL testing

Modifications

Kalman filter

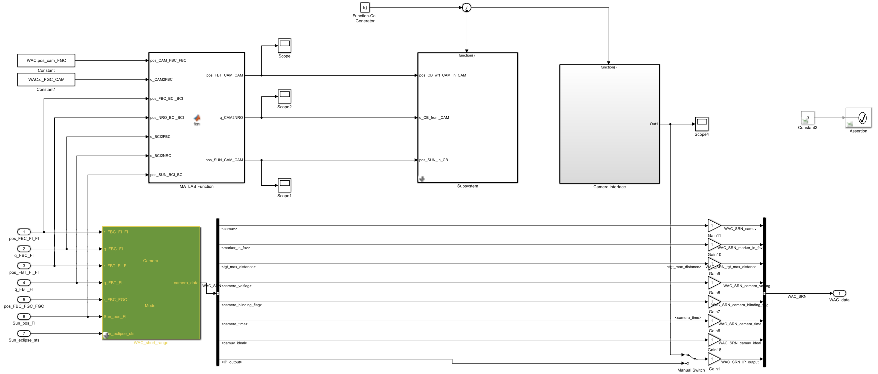
- Use actual marker set
- Use actual camera intrinsic matrix K
- use 4 markers maximum , total of 16 detected corners /tracked points
- generate statistics (measurement covariance matrix, state – measurement cross covariance matrix, Kalman gain matrix) only for those markers (with a limit of up to 4 markers used) that are known to be visible
- update the state estimate using only the measurements of the visible markers

Camera model

- include function that determines which markers are visible (i.e. in field of view of camera)
- present output in same format as actual IP output
- use actual marker set
- use actual camera intrinsic matrix K

Simulator

- Add ***platform-art*** interfaces

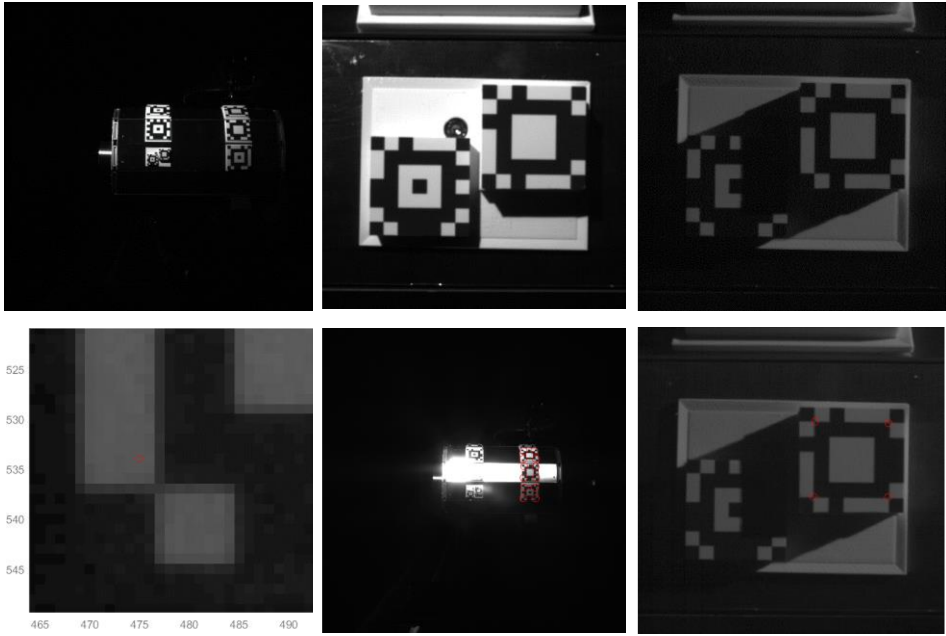


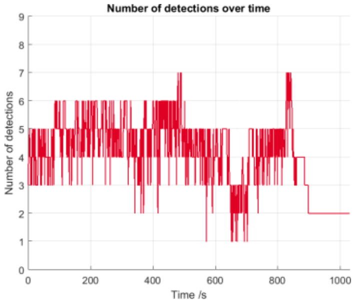
Rendezvous

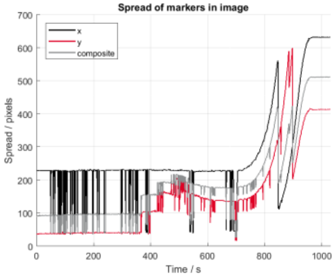
HIL testing

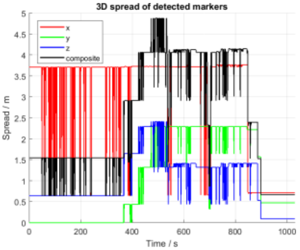
Marker detection

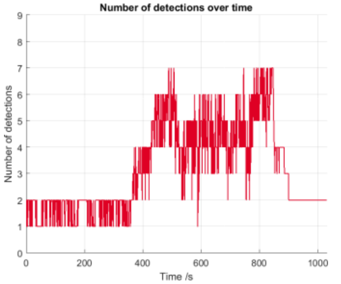
- **Dependent on lighting conditions**
  - Deep shadows can prevent detection
  - Glare can prevent detection
  - Can be (and has been) optimized
- **Spread of markers important**
- **IP Marker detection off by up to 5 pixels**











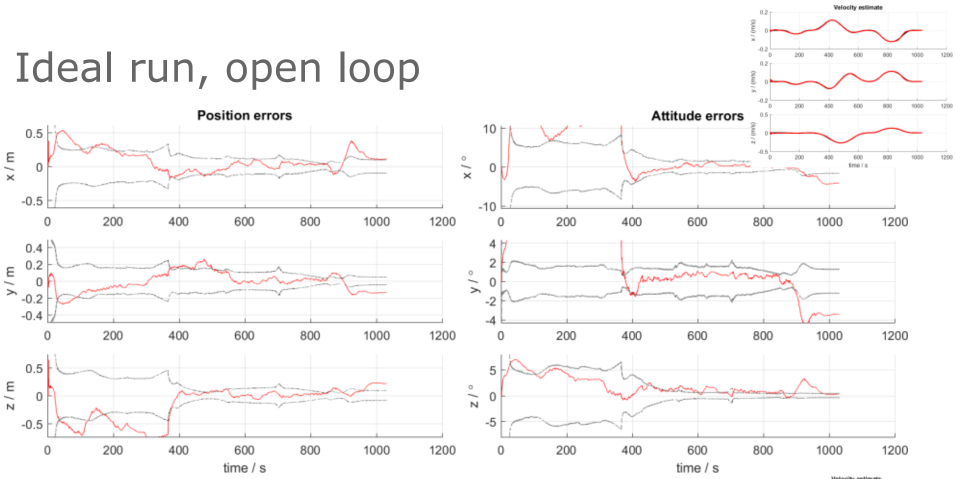
Rendezvous

HIL testing

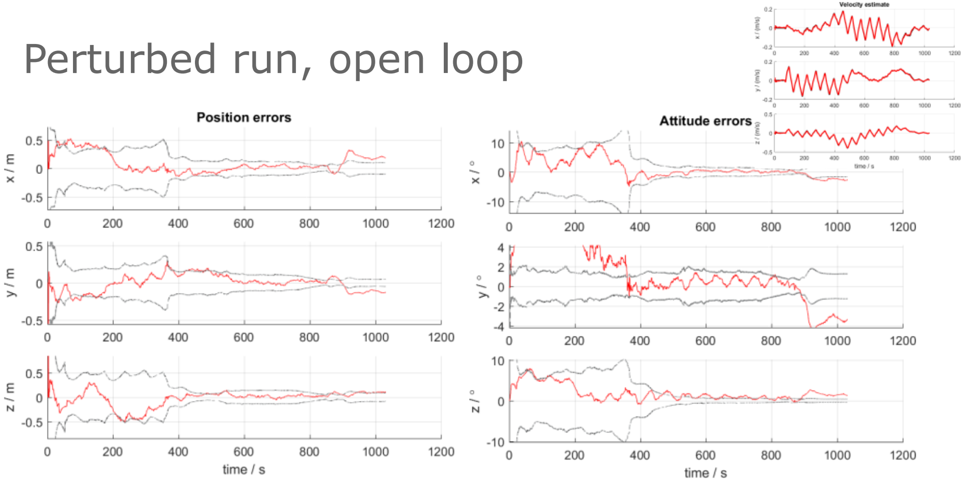
Open-loop navigation results

- **Navigation function works well**
  - Especially when large number of markers visible
- **Difficult to attribute errors to causes**
  - Motion representation errors visible in animated sequence
  - Systematic bias visible at end of trajectory

Ideal run, open loop



Perturbed run, open loop

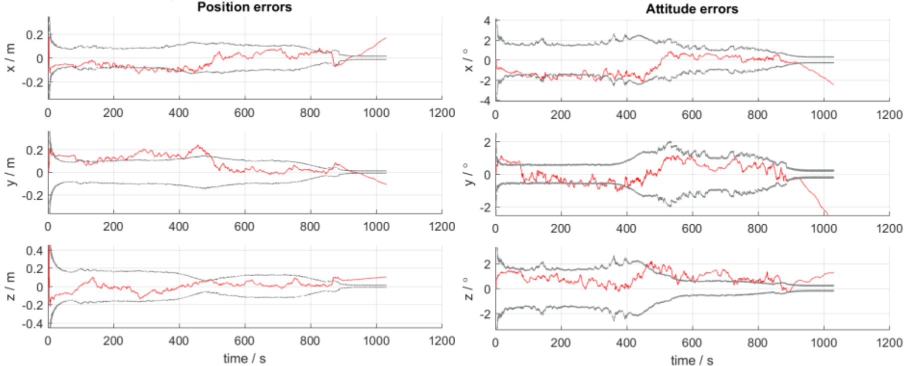


Rendezvous

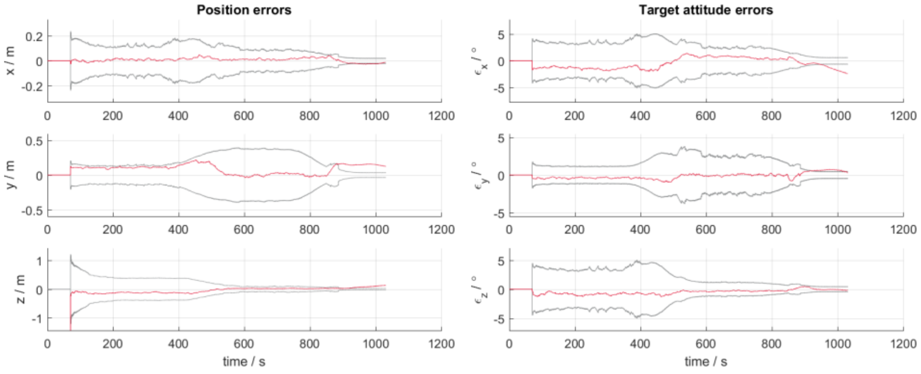
HIL tests

Closed loop tests

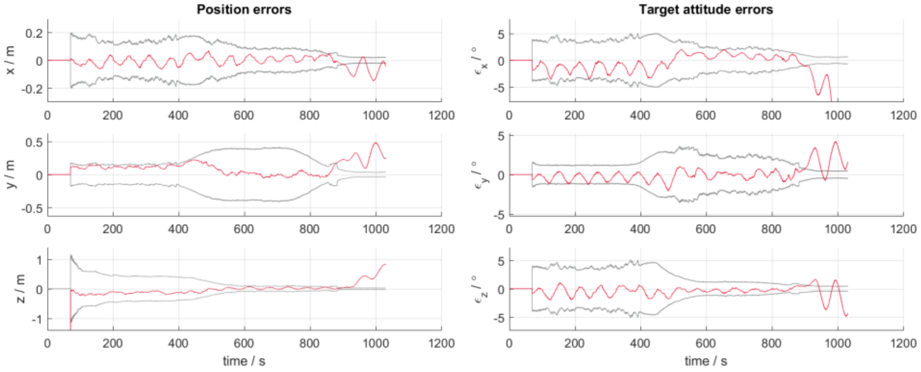
- **Behaviour of SRN in closed loop is good when four or more markers are visible**
  - Deterioration due to change in calculation of statistics
  - Confirmed by additional analysis of open-loop results:



Ideal run, closed loop



Perturbed run, closed loop



Conclusions, Evaluation and Roadmaps

12:15 – 12:30

Evaluation and Roadmaps

TRL

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. 11]
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. 12]
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.
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, velocity, attitude and attitude rate) during rendezvous**

Evaluation and Roadmaps

Development activity 1: GNC/SW

Specific points of attention:

Consolidate GNC for all phases

Mission analysis

- Improve MA tools:
  - Increase automation of timeline generation
  - Include perturbations

Modelling

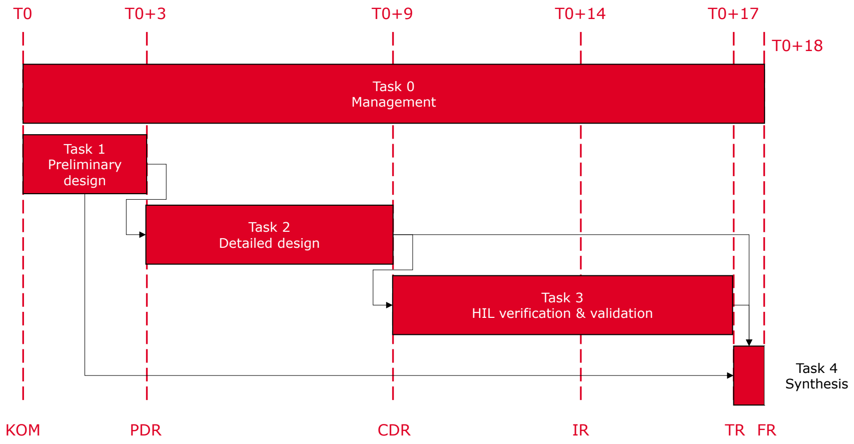
  - Increase model fidelity (behaviour and interfaces)

GNC

  - General revision of algorithms
  - Include sensor preprocessing

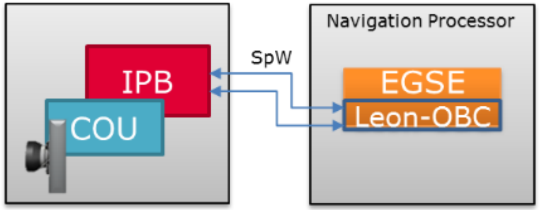
Testing

- Better calibration
- Higher quality mock-up models



Evaluation and Roadmaps

Development activity 2: Camera + IP



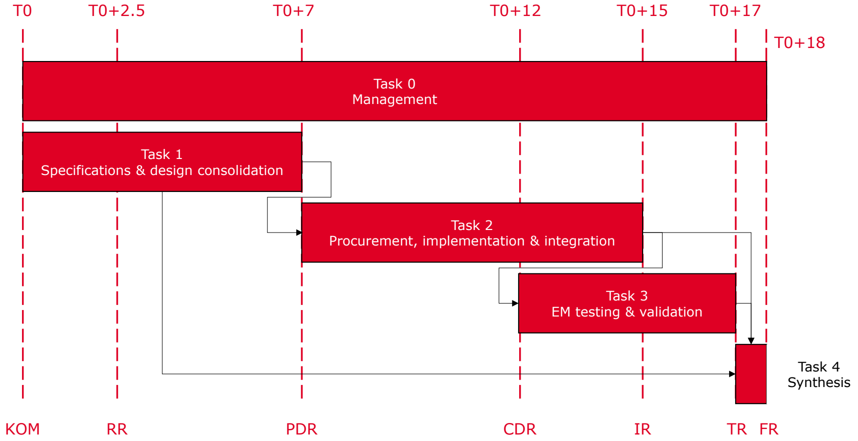
Specific points of attention to be covered during the development activity

Camera

- Development of camera specific to HERACLES LAE

IP

- Long Range: first phases of rendezvous, tracking LOP-G as point-source of light / small blob of pixels.
- Medium Range: using model-based tracking
- Short Range: final part till berthing, using marker tracking
- Study marker type and placement



Questions and Answers

12:30 – 13:00

Thank you

Thomas Peters
t.v.peters@gmv.com